HANDBOOK OF SYSTEMS THINKING METHODS

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ROUTLEDGE

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Preface

Society faces many current and forthcoming challenges that represent significant threats to human health and wellbeing and, in some cases, even existential threats to humanity. The scale and complexity of these issues is such that there are few scientific theories and methods available to support effective preparedness, management, and mitigation. As a result, the response is too often inadequate resulting in substantial personal, societal, environmental, and economic costs.

Road trauma is one example of a long-standing issue that continues to kill and injure on an unacceptable scale, annually causing over 1.3 million deaths, approximately 50 million injuries, and costing countries around 3% of their gross domestic product (World Health Organisation, 2021). On top of other long-standing issues such as workplace injury, inadequate disaster management, and public health issues such as disease, obesity, and mental health disorders there are an emerging set of global threats for which we are ill-prepared. The ongoing COVID-19 pandemic provides a sobering example; at the time of writing, the pandemic has killed over 6 million people, destroyed entire industries, disrupted social norms, and has cost the global economy in the region of $28 trillion (International Monetary Fund, 2020). Looking into the future, Artificial General Intelligence (AGI) is the forthcoming next generation of Artificial Intelligence (AI) which, if not adequately managed and controlled, could wipe out humanity (Bostrom, 2014; Salmon, 2021). Worryingly, there is little indication to suggest that these pressing global challenges can be resolved or managed with current approaches. As such, new ways of thinking about global challenges and the adoption of alternate theoretical and scientific perspectives is needed.

Systems thinking is a way of thinking about the world that helps us understand the many components and dynamic interactions that create behaviour, and problems, in different contexts. It provides "a way of seeing and talking about reality that helps us better understand and work with systems to influence the quality of our lives" (Kim, 1999). Throughout our research we have applied a set of analysis methods which can be used to apply a systems thinking lens to help understand complex problems. Whilst these methods have their origins in a diverse set of disciplines, and often have differences in their specific theoretical underpinnings, they share the common trait of enabling analysts to describe and understand complex systems in terms of their components, interactions, and emergent properties.

The central premise of this book is that complex issues, such as road trauma and the COVID-19 pandemic, are best understood and managed through the use of what we will call ‘systems thinking methods’. Despite their utility, practical guidance on many of the methods can be hard to come by, and novice analysts are often deterred by their apparent complexity. Consequently, the methods are often underused, especially by practitioners working outside of academia. Accordingly, the aim of this book is to provide practical step-by-step guidance for a subset of systems thinking methods that the authors have used extensively in our own work. This guidance covers 12 methods categorised into four broad types: risk assessment, systems analysis and design, accident analysis, and computational modelling methods. The intention is to provide a ‘how to’ guide for each method, demonstrate how we have applied each method in practice, and encourage researchers, students, and practitioners to learn and apply them in their own work and studies.

Acknowledgements

Many colleagues and collaborators contributed to the case studies presented in this book. We would like to acknowledge specifically the contributions of Lisa Aiken, Melissa Bedinger, Tony Carden, Adrian Cherney, Clare Dallat, Amanda Clacy, Lauren Coventon, Dennis Desmond, Alison Gembarovski, Eryn Grant, David Lacey, Ben Lane, Jennifer Marks, Anjum Naweed, Rod McClure, Scott McLean, Sharon Newnam, Aaron Roberts, Erin Stevens, Nicholas Stevens and Patrick Waterson. Without these contributions it would not have been possible to write this book.

Author Biographies

Paul M. Salmon is a Professor in Human Factors and is the founding Director of the Centre for Human Factors and Sociotechnical Systems at the University of the Sunshine Coast. Paul has over 20 years' experience of applied Human Factors and systems thinking research in areas such as road and rail safety, aviation, defence, sport and outdoor recreation, healthcare, workplace safety, and cybersecurity. His research has focused on understanding and optimising human, team, organisational, and system performance through the application of Human Factors and systems theory and methods. He has co-authored 21 books, over 270 peer reviewed journal articles, and numerous book chapters and conference contributions. Paul's contribution has been recognised through various accolades, including the Chartered Institute for Ergonomics and Human Factor's 2019 William Floyd award and 2008 Presidents Medal, the Human Factors and Ergonomics Society Australia's 2017 Cumming memorial medal, and the International Ergonomics Association's 2018 research impacting practice award.

Neville A. Stanton is a Chartered Psychologist, Chartered Ergonomist and Chartered Engineer. He holds the Chair in Human Factors Engineering in the Faculty of Engineering and the Environment at the University of Southampton in the UK. He has degrees in Occupational Psychology, Applied Psychology and Human Factors Engineering and has worked at the Universities of Aston, Brunel, Cornell and MIT. His research interests include modelling, predicting, analysing and evaluating human performance in systems as well as designing the interfaces and interaction between humans and technology. Professor Stanton has worked on design of automobiles, aircraft, ships and control rooms over the past 30 years, on a variety of automation projects. He has published 45 books and over 350 journal papers on Ergonomics and Human Factors. In 1998 he was presented with the Institution of Electrical Engineers Divisional Premium Award for research into System Safety. The Institute of Ergonomics and Human Factors in the UK awarded him The Otto Edholm Medal in 2001, The President's Medal in 2008 and 2018, The Sir Frederic Bartlett Medal in 2012 and The William Floyd Medal in 2019 for his contributions to basic and applied ergonomics research. The Royal Aeronautical Society awarded him and his colleagues the Hodgson Prize in 2006 for research on design-induced, flight-deck, error published in The Aeronautical Journal. The University of Southampton has awarded him a Doctor of Science in 2014 for his sustained contribution to the development and validation of Human Factors methods.

Guy H. Walker is a Professor within the Centre for Sustainable Road Freight at Heriot-Watt University in Edinburgh. He lectures on transportation engineering and human factors. He is the author/co-author of over one hundred peer reviewed journal articles and 18 books. He has been awarded the Institute for Ergonomics and Human Factors (IEHF) President's Medal for the practical application of Ergonomics theory and Heriot-Watt's Graduate's Prize for inspirational teaching. Dr Walker has a BSc Honours degree in Psychology from the University of Southampton, a PhD in Human Factors from Brunel University, is a Fellow of the Higher Education Academy, a Fellow of the Chartered Institute of Ergonomics and Human Factors, and a member of the Royal Society of Edinburgh's Young Academy of Scotland. His research has featured in the popular media, from national newspapers, TV and radio, through to an appearance on the Discovery Channel.

Adam Hulme is a Research Fellow at the Centre for Human Factors and Sociotechnical Systems at the University of the Sunshine Coast. He has a bachelor's degree in sport and exercise science, an honours degree in Psychological Metacognition, a master's degree in Public Health, and a PhD in Sports Injury Epidemiology and Systems Human Factors and Ergonomics. Adam's current research is focused on the development and testing of a new integrated safety management toolkit that includes both proactive systems-based risk assessment and retrospective incident analysis methods. He has 47 publications including one edited book, five book chapters, 36 peer reviewed journal articles, and various international conference papers on safety. Adam is becoming increasingly passionate about closing the research-practice gap in human factors and safety science, ensuring that methods to enhance the safety of complex systems are usable and effective in real settings.

Natassia Goode is a Program Manager at WorkSafe Victoria, and Adjunct Fellow within the Centre for Human Factors and Sociotechnical Systems at the University of the Sunshine Coast. Natassia's PhD and honours research in Psychology investigated how people learn about complex systems. Over the last nine years, her work has focused on applying systems thinking to fundamentally change the way that organisations manage safety, and reduce incidents. She has worked with several industries to design more effective incident reporting and investigation systems, including healthcare, construction, and outdoor education. She has written book on designing incident reporting systems, and co-authored over 60 peer reviewed journal articles. Her roles at WorkSafe Victoria have involved providing expert advice on applying systems thinking to improve health and safety enforcement and compliance activities. She now coordinates WorkSafe Victoria's programs in the Healthcare and Social Assistance Industry.

Jason Thompson holds a PhD in Medicine, masters in Clinical Psychology, and a Bachelor of Science with Honours. Dr Thompson's work is focused on the translation of research into practice across the areas of transportation safety, public health, post-injury rehabilitation, and health system design. Since 2014, Dr Thompson has published over 40 articles related to the investigation of injury and transport systems alongside methods machine learning and computational social science. His work has pioneered the use of agent-based models and convolutional neural networks in areas of traditional health system, urban design, and transportation safety research involving vulnerable road users.

Dr Thompson is an Australian Research Council Discovery Early Career Research Fellow. His DECRA project is focused on challenges associated with the introduction of autonomous vehicles on the operation and sustainability of Australia's $5 billion personal injury insurance market. In particular, how this transition will change injury rates and types, the operation of compensation and rehabilitation systems, and how these systems' responses will shape the autonomous vehicle market, itself.

Gemma J. M. Read is a Senior Research Fellow at the Centre for Human Factors and Sociotechnical Systems at the University of the Sunshine Coast. Gemma holds a PhD in Human Factors from Monash University and has undergraduate qualifications in psychology and law. She has worked in the field of transportation human factors since 2006 in both academic and government roles. She has co-authored two books and over 40 journal articles applying Human Factors and systems thinking approaches across areas associated with transport safety, workplace safety, and sport and outdoor recreation.

Section I

Introduction to Systems Thinking

1

Introduction to Systems Thinking in Human Factors and Ergonomics and Safety Science

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The call to action

A convergence of ideas and themes have led to this book. The main proposition is this: research and application are becoming disconnected. The science-base is increasing its focus on complex systems problems, yet the application of systems thinking methods is lagging behind (Holman et al., 2020; Leveson, 2017; Salmon et al., 2017; Woods and Dekker, 2000; Walker et al., 2010, 2017). This book is an attempt to correct this situation. It is about putting cutting-edge systems thinking methods into the hands of those who need to apply them in their practice.

Systems thinking methods are different from deterministic methods. Deterministic methods – broadly speaking – focus on reducing systems down to their component parts. The assumption is that if individual components can be understood, then so can the overall system (Walker et al., 2010). Deterministic methods have driven disciplines such as Human Factors and Ergonomics (HFE) and safety science forward for over half a century. They remain entirely appropriate for deterministic problems. They are not, however, appropriate for *all* classes of problem (e.g. Ackoff, 1973; Sterman, 2000; Lee, 2001, Sharma, 2006). Such problems include near-term, and profound, changes in global work and societal systems, artificial intelligence, new developments in information and communication technology, the fourth industrial revolution, the internet of things, ecological sustainability, climate change adaptation, food and farming systems, and many other global risks and existential threats. Problems such as these are increasingly recognised as 'systems problems' (Dul et al., 2012; Wilson, 2014; Salmon et al., 2017). A growing body of recent research highlights the limitations of applying reductionist methods to tackle them (Walker et al., 2010, 2016; Woods and Dekker, 2000; Salmon et al., 2017).

HFE and safety scientists are today confronted with an uncomfortable and disconcerting truth (Holman et al., 2021). The continued use of reductionist methods to tackle systems problems of great complexity are likely to fail. Worse, their use could be detrimental to the health and sustainability of those systems they seek to support. An exclusive reliance on deterministic methods could see HFE and safety science fail at a time when they are needed most. Something needs to be done.

Earlier work by the authors in Walker et al. (2010) provides a telling indication of the methodological issues we face. The term 'complexity' is a bellwether word that first occured in the title of a paper in the journal *Ergonomics* in 1958 (Chiles, 1958). Since then, well over 80 papers have featured either the word 'complex' or 'complexity' in their titles, with more than 90% having been published since 1990 (Walker et al., 2010). The key issue is not whether the traditional HFE and safety science domains have become more, or less, complex. It is that the problems 'left over' from the successful application of deterministic approaches are systemic and growing in number. In many domains the limits of deterministic approaches have exposed new classes of problem featuring a prominent, and complex, human dimension (e.g. EASA, 2010; Coury et al., 2010; CAA, 2011). Not just that, but in many sectors safety trends are plateauing as deterministic approaches reach the limits of their effectiveness (Salmon et al., 2017). In some sectors, safety performance is even worsening (Salmon et al., 2019, 2020). The methods that have yielded prior improvements in performance are becoming less effective when applied to the problems that remain: the complex, systemic ones. This, in turn, creates a corresponding pressure to find new methods and ensure they enter the practitioner mainstream (Salmon et al., 2017, 2022). This book is a direct attempt to address this issue.

The aim of this book is to provide the reader with practical guidance on how to apply a sub-set of methods that have their theoretical roots in systems theory, complexity science, and systems thinking. 'Systems thinking methods' are better matched to many extant HFE and safety science challenges and their uptake needs to be accelerated. In this book we will draw from an eclectic body of work to show what can be done, and how to do it. Before then, it is important to introduce the core elements of the systems thinking philosophy on which these methods are based.

A short introduction to Systems Thinking

Systems thinking represents "a way of seeing and talking about reality that helps us better understand and work with systems to influence the quality of our lives" (Kim, 1999). In this book the term 'systems thinking' is used to describe a philosophy which is applied to help understand and optimise behaviour in work and societal systems. An axiom of systems thinking is that behaviour, safety, and accidents are emergent properties arising from non-linear interactions between multiple components across sociotechnical systems (Rasmussen, 1997; Leveson, 2004). From this point of view, responsibility for behaviour and safety spans all levels of work systems, up to and including regulatory bodies, government, and international organisations. The overall ‘system’, therefore, becomes the unit of analysis when attempting to understand behaviour.

A system can be viewed as “any group of interacting, interrelated, or interdependent parts that form a complex and unified whole that has a specific purpose” (Kim, 1999). Meadows (2008) points out that a system must comprise three core components:

- Elements (or parts),
- Interconnections (or interactions), and
- A function or purpose (or goal).

We encounter and engage with many systems as part of our everyday lives. For example, this chapter was written at the University of the Sunshine Coast, in Queensland, Australia. Universities can be conceptualized as systems (see Perrow, 1984; Rouse, 2016). They comprise elements such as academic staff, administrators, students, lecture theatres, tutorial rooms, research laboratories, teaching and research materials, policies, and procedures, to name just a few. The system has purposes relating to the creation of new knowledge, educating society, and generating wealth. Interconnections between these university elements are required to achieve the purposes. There are interactions between academic staff and administrators, between academic staff and students, between research staff, participants, data, and between all staff and the materials required for their work. Whenever there are groups of interacting, interrelated, and interdependent parts that work together towards a specific goal, they can be considered a system. Analysing the components in isolation would not fully describe what a university is or how positive or negative outcomes emerge from the interactions between the components.

Systems are all pervasive. While the University of the Sunshine Coast can be considered a system in its own right, it is also a sub-component, or sub-system, of an even larger national education and research system. Australia’s other 43 Universities are also large systems, but at the level of the national ‘super-system’ they are a sub-system. Likewise, if the boundary is widened still further to include the global educational system, then the other co-author’s host institutions (the University of Melbourne, the University of Southampton, Heriot-Watt University, etc.) become sub-systems of their national educational systems, and the national educational systems are sub-systems of the global system. Working in the other direction the system boundary can be re-drawn yet again, this time around the lead author's research centre (the Centre for Human Factors and Sociotechnical Systems). This sub-system is also a system with its own components, interconnections, and core functions. A key task in analysing systems is to draw the boundaries around them and recognise that those boundaries are permeable, relying on a steady flow of resources, information, and other means of interconnection.

Systems thinking is interdisciplinary and has its roots in fields as diverse as biology, communications theory, systems theory, and complexity science. It does not reside in any one discipline. Within HFE and safety science, systems thinking is a core philosophy that informs various models, including sociotechnical systems theory (Trist and Bamforth, 1951), Rasmussen's risk management framework (Rasmussen, 1997), Leveson's Systems Theoretic Accident Model and Processes (STAMP; Leveson, 2004); Dekker's Drift into Failure (DIF) model (Dekker, 2011), and Grant et al.'s systems thinking safety tenets (Grant et al., 2018). From these diverse traditions emerge some core features we can expand upon here.

Open Systems

Systems theory first emerged within the biological and physical sciences. Von Bertalanffy (1950) outlined a set of open-systems principles with application to living organisms. Skyttner (2001) subsequently outlined the properties of general systems theory for open systems, based on the work of Von Bertalanffy, as well as numerous other systems theorists. According to Skyttner, open systems display the following characteristics:

- Interrelationship and interdependence of components and their attributes: the parts of the system are interconnected rather than disparate.
- Holism: the system exhibits emergent properties that cannot be identified from analysing the components; the whole is more than the sum of its parts.
- Goal seeking: the system has a goal or end state.
- Transformation processes: the system transforms inputs into outputs to attain its goal(s).
- Inputs and outputs: inputs are taken from the environment and transformed; outputs are returned to the environment.
- Entropy: systems tend towards disorder or randomness without intervention.
- Regulation: the interrelated components constituting the system must be regulated for goals to be obtained. Regulation can be achieved through control and feedback loops.
- Hierarchy: systems comprise sub-systems nested within one another in a hierarchical structure.

- Differentiation: specialised units performed specialised functions within a system.
- Equifinality: from the same initial conditions, systems have different alternative ways of achieving the same goal.
- Multifinality: from the same initial conditions, systems can obtain different goals and objectives.

These properties provide the basis for *adaptive capacity*. Systems that are able to achieve goals and avoid entropy are also those that can adapt to external environmental conditions (i.e. to changes to inputs) by using alternative means (i.e. having the property of equifinality). Matters such as how regulatory mechanisms within the system operate, and the amount of differentiation available within the system, can affect its capacity to adapt and achieve its goals.

Complexity Theory

The defining feature of systems thinking is, arguably, complexity. Complexity science is concerned with attempting to understand and respond to problems that are dynamic and unpredictable, multi-dimensional, and comprise various interrelated components. Fundamental to complexity science, and thus systems thinking, is a focus on the interactions among elements within the 'complex system', rather than on the role and contribution of those elements in isolation (Ottino, 2003; Batty and Torrens 2005; Senge 2006). Complexity is difficult to define (Cilliers, 1998). Various authors have outlined characteristics exhibited by complex systems (e.g. Von Bertalanffy, 1968; Cilliers, 1998; Skyttner, 2005; Holland, 2014). According to Luke and Stamatakis (2012), complex systems exhibit the following properties:

> ...they are made up of a large number of heterogenous elements; these elements interact with each other; the interactions produce an emergent effect that is different from the effects of the individual elements alone; and, this effect persists over time and adapts to changing circumstances.
>
> (p. 2)

Cilliers (1998) outlined the following characteristics of complex systems:

- *Complex systems comprise multiple components*. Complex systems comprise many components that interact dynamically with one another. The existence of many components is necessary, although this is not sufficient to denote complexity – dynamic interactions between components are also required (Cilliers, 1998).

- *Interactions between components are multiple, rich, and non-linear.* Interactions between components are abundant and can be non-linear in nature, meaning that there is asymmetry between input and output, and that small events can produce large outcomes and vice versa (Dekker, 2011). Emergent properties arising from interactions mean that "the action of the whole is more than the sum of its parts" (Holland, 2014, p. 2). Holland (2014) explains emergence by discussing the 'wetness' of water. Wetness is not something that can be assigned to individual water molecules, rather it is an emergent property arising from the interaction of water molecules.
- *Interactions are short-range in nature.* Information received by components mainly comes from neighbouring components and long-range interactions are limited. However, as there are many interactions between components, it is possible to influence non-neighbouring components through just a few interactions. For example, most workers are not likely to interact with the CEO of their employing organisation; however, they interact with their supervisors who in turn interact with managers and senior managers who in turn interact with the CEO.
- *There are recurrent loops in the interactions.* The effect of an activity can feed back onto itself either directly or through other components. These feedback loops can be positive (reinforcing) or negative (balancing), and both are necessary.
- *Complex systems are open systems.* Complex systems are open systems meaning that it is difficult to define their boundaries and that they interact with their environment. As a result of these interactions complex systems have an influence on their environment and are influenced by their environment in return (Cilliers, 1998).
- *Components are ignorant of the system and its behaviour.* Components within the system often only have access to local information and hence do not fully comprehend the behaviour of the overall system, nor the effects of their actions on the behaviour of the overall system.
- *Complex systems are dynamic and do not operate in a state of equilibrium.* Systems must have constant inputs to maintain functioning. Without constant inputs, complex systems are unable to function (Cilliers, 1998).
- *Complex systems have a history and path dependence.* Within complex systems there is a dependence on initial conditions whereby past behaviour is co-responsible for present behaviour. This means that decisions and actions made previously (even many years previously) influence the here and now (Cilliers, 1998).

Evolution of Systems Thinking

The field of complexity science is extensive, involving multiple traditions, disciplines, methods, techniques, and analytical tools. For instance, Castellani's (2018) 'Map of the complexity sciences' (Figure 1.1) spans several decades and visualises the historical progression of five major intellectual traditions:

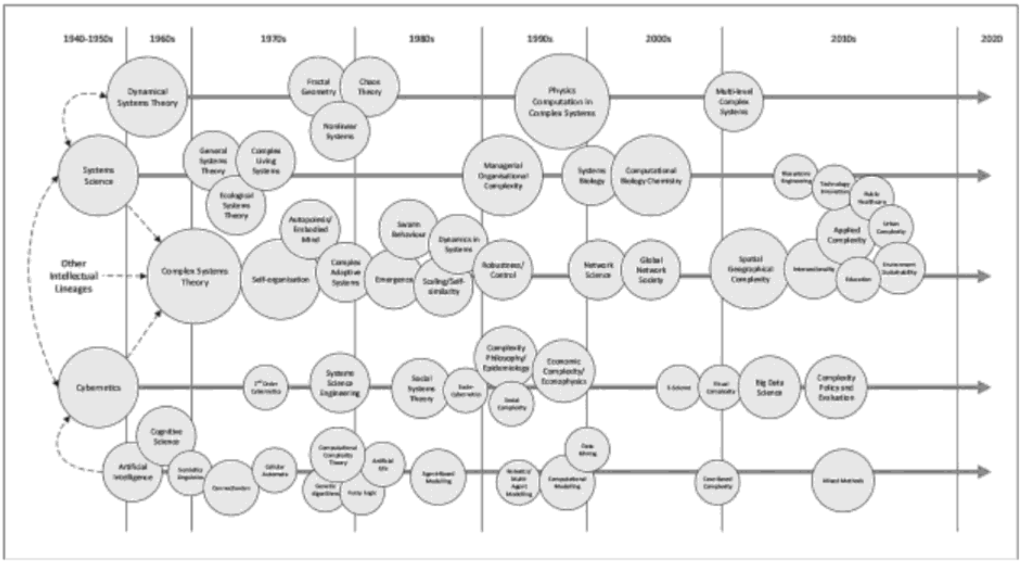

Figure 1.1 Historical evolution of complexity science. (Adapted from Castellani, 2018).

- Dynamical systems theory,
- Systems science,
- Complex systems theory,
- Cybernetics, and
- Artificial intelligence.

These traditions share several philosophical and theoretical similarities, as well as practical commonalities in terms of the approaches used to study and examine complex phenomena. Figure 1.1 indicates that there is no single, unified understanding of what exactly complexity is from an operational standpoint. When invoking the term systems thinking it can refer to distinct, as well as shared features embedded in Figure 1.1. Researchers and practitioners have a multitude of highly capable scientific approaches and modelling techniques at their disposal to understand complexity and complex problems so long as a suitable justification for their selection is offered. This is key. This book aims to help researchers and practitioners make those conceptual groundings, and analytical decisions, transparent.

The Systems Thinking tenets

The work of Grant et al. (2018) brings some much-needed order to the current state of systems thinking in HFE and safety science. It does so by synthesising a set of key tenets from a range of systems thinking models (Rasmussen, 1997; Leveson, 2004; Dekker, 2011). This has led to the specification of a set of work system features which interact to create both safe and unsafe performance. Labelled the systems thinking tenets, they encapsulate much of the current state of thinking in this area and include 15 characteristics of work systems that are believed to create both safe and unsafe performance (Grant et al., 2018, see Table 1.1). These tenets graphically illustrate the uncomfortable truth we are now living with in the HFE and safety science arenas. It is no longer safe to assume that our targets of analysis are simple, predictable, stable, and characterisable. Decomposing problems comprised of these tenets, analysing the component parts, and reassembling the whole does not guarantee the insight required. Indeed, by severing the interconnections which bind systems together it becomes just as likely that an erroneous analysis outcome will emerge. Instead, we need to think in systems.

Table 1.1 Grant et al. (2018) Systems Thinking Tenets

Tenet	**Definition**	**Unsafe System Description**	
Vertical integration	Interactions between elements within and across levels of the system hierarchy.	Decisions and actions do not filter through the system and impact behaviour. Information regarding the current status of the system across levels is not used when making decisions.	
Constraints	System elements that impose limits on, or influence, other system elements.	A constraint that has failed to perform its function and/or restrict an appropriate response, behaviour, or the desired variability in performance.	
Normal performance	Routine behaviours that are typically performed within a system, regardless of formal rules and procedures.	Routine and expected behaviours that played a contributory role (i.e. were a 'normal' part of the aetiological mechanism).	
Performance variability	System elements vary their behaviour in response to changing conditions in the system and its environment.	Behaviours are adjusted to cope with changing circumstances; however, the outcome of the adjustment is not desirable.	
Emergence	Outcomes that result from interactions between elements in the system that cannot be fully explained or reliably predicted in advance by examining the elements in isolation.	Emergent behaviours or outcomes that are unsafe or undermine the goals of the system.	
Tight and loose coupling	The degree of interdependence that exists between system elements.	Tight coupling: Cascading failures that propagate quickly and widely through the system when one element breaks down.	Loose coupling: Loss of control regulating behaviours. Too much independence between elements.
Linear and non-linear interactions	Interactions that produce effects that are either proportional or not proportional to the causes.	Linear: Interactions are readily predictable, predefined, and fixed with no allowances for adaptation when alternatives are required.	Non-linear: Seemingly inconsequential events have small or large effects which cannot necessarily be predicted.

Tenet	Definition	Unsafe System Description
Feedback loops	Self-reinforcing and self-correcting forms of feedback between system elements which influence the system's behaviour.	Feedback mechanisms are not controlled and amplify through the system, increasing risk and accident potential.
Modularity	Sub-systems and elements that are designed to operate independently of one another.	The system is tightly integrated and complex, substitutions cannot be made (e.g. no contingencies).
Sensitive dependence on initial conditions	Characteristics of the originally designed system that influence system behaviour at a later point in time.	Initial conditions and their influence on the system create unsafe behaviours.
Decrementalism	Minor and accepted modifications to system elements that gradually create a significant change in system behaviour.	Constant small changes eventually create unsafe behaviours and practice through migration and drift.
Unruly technologies	Unforeseen and unpredictable behaviours of technologies that are introduced into the system.	Technologies that behave in unanticipated ways.
Contribution of the protective structure	The contribution of the formal and organised structure that is intended to protect and optimise system safety.	Protective structure competes for resources with negative effects on behaviour and safety.

How to blow up the Death Star

This book is all about systems thinking methods. A common criticism is that systems thinking methods are hard to pin down, a little ephemeral, and can seem uncertain in their outcomes. This makes communicating systems thinking methods a challenge. It explains a large part of why the uptake of systems thinking methods has been slow. To convey their utility, in this book we present numerous examples drawn from our own experience of applying them to a multitude of domains all around the world. From submarines, aeroplanes, automated vehicles, and darknet marketplaces, to hospitals, railway level crossings, led outdoor activities, and even entire road transport systems: all feature in this book. To aid understanding of what systems methods can do no singular example has surpassed our analysis of the Death Star from the film franchise Star Wars (Walker et al., 2016). Originally developed as a teaching aid, out of all our previous work it was this inter-galactic canter through systems thinking methods which was featured in National Geographic. When all other approaches to communicating the benefit of systems thinking methods fail, we need to be radical. An entirely sober and scientific treatment of systems thinking methods is covered in the following chapters, but if you, as a reader, are still a little unsure what a systems thinking method actually is, or what it can do, a Star Wars-based case study may help (Figure 1.2).

NATIONAL GEOGRAPHIC

The real science inspired by 'Star Wars'

From Darth Vader's breathing to the dual sunsets of Tatooine, we take a look back at the real studies inspired by the "Star Wars" universe.

BY **MICHAEL GRESHKO**

PUBLISHED DECEMBER 1, 2019 • 13 MIN READ

Walker applied real-world techniques to the notoriously explosion-prone Death Star as an example for his civil engineering students of analyzing flaws in big engineering projects. After obtaining its plans from an official technical manual, he and his colleagues gave themselves the equivalent of four days—the amount of time the Rebel Alliance had with the plans—to test two different flaw-finding techniques.

Figure 1.2 Originally designed as a learning and teaching aid, Walker et al.'s (2016) application of systems methods to detect flaws in the Death Star from the Star Wars film franchise led to unexpected impacts in science communication. This article appeared in National Geographic, https://www.nationalgeographic.com/science/article/151209-star-wars-science-movie-film.

We are not alone in using the occasional Star Wars metaphor in the service of science communication. Researchers have used Star Wars to teach complex topics in psychiatry because it is "well known to students, registrars, and consultants alike" (Freidman and Hall, 2015, p. 432). It has facilitated an examination of how people interact with political philosophy (Geraci and Recine, 2014), it has contributed to a better understanding of the behavioural processes underlying immersion in virtual worlds (Guitton, 2012), and a surgical assessment of Darth Vader's respiratory difficulties informs learning and teaching in pulmonology (Berg et al., 2014). If other disciplines are happy to provide a clinical diagnosis of lead character Anakin

Skywalker's borderline personality disorder (e.g. Tobia et al., 2015), and to use Jabba the Hutt as a visual metaphor for nuclear migration in cellular biology (e.g. Morris, 2000), then a quick case study describing how Star Wars can be used to communicate complex ideas about systems thinking methods begins to seem quite sensible. Indeed, it flushes out several important key issues which do not necessarily emerge from 'real' case studies.

Our case study example focused on pro-active risk assessment methods. Risk assessment is a critical and mandated component of safety management (Kirwan and Ainsworth, 1992; Reason, 1997; Hollnagel, 2004; 2008; ISO, 2018; Dallat et al., 2019; Hulme et al., 2019; 2021). The intention is to proactively identify and manage risks by developing controls which either prevent them from occurring or mitigate their effects once they do occur. Formal risk assessment involves the use of structured methods to proactively identify potential hazards and vulnerabilities that may create adverse outcomes during work tasks (Chemweno et al., 2018).

For those readers who have not seen Star Wars, imagine having to identify a critical flaw in a highly complex planetoid sized orbital battle station, under extreme time pressure, and with no clear idea at the outset where the vulnerability will lie. This was the challenge faced by the Rebel Alliance, the film's protagonists. Risk assessment methods could be used to identify critical vulnerabilities, only this time the purpose was not to develop risk controls, it was to develop strategies to exploit the vulnerabilities.

In Walker et al. (2016) we compared how a traditional deterministic risk assessment method would compare against a systems thinking method in discovering the Death Star's vulnerabilities. The first option was to employ a traditional error identification method of the sort contemporaneous with the film's release in 1977 and still in widespread use today (Hazard and Operability Study, HAZOP). Methods like HAZOP tend to focus on the work of human operators at the sharp end. They seek to identify the different kinds of errors they could make and the risks that might arise, usually at an atomistic level of task decomposition. The second option was to use a systems thinking method (the Work Domain Analysis phase of Cognitive Work Analysis). This approach is different. Rather than focus on the sharp end, this method, like most systems thinking methods, attempts to describe the overall work system, the interactions that occur, and the emergent properties arising from these interactions. Despite the filmic overtones and hints of levity, this case study enabled us to put forward a powerful demonstration of how to match systems thinking methods to complex problems at a deeper, more fundamental level. In doing so, it provides a powerful demonstration of what systems thinking methods can do, and challenges equally powerful beliefs about how difficult or time consuming such methods are to apply.

The Death Star

Back to Star Wars and how to destroy a Death Star. As orbital battle-stations go, the Death Star certainly had impressive civil engineering credentials. It was a 160km diameter spheroid constructed from Quadanium steel, a high strength material allegedly mined from asteroids (Windham et al., 2013). The internal superstructure was devoted to a large Sienar Fleet Systems SFS-CR27200 Hypermatter Reactor and its ancillary systems. This supplied all the power needs for propulsion, life support, and defensive and offensive weapons systems. Principle among the last item here was the Super Laser, possessing enough power to destroy entire planets. The core of the Death Star is devoted largely to energy and offensive purposes. This means accommodation and living space resides on the surface, protected by turbo-laser towers and a magnetic shield system. In the film, the critical vulnerability that was discovered and exploited by the Rebel Alliance was a small thermal exhaust port located in the equatorial trench (Windham et al., 2013). This provided a route from the surface of the station directly to the main reactor core.

The exhaust port had clearly been risk-assessed by the Imperial Empire – the antagonists and Death Star creators – as it was protected by a ray shield. The port was small, being only two metres in diameter, meaning the weapon system required to breach the ray shield defences could not be launched remotely with sufficient accuracy. It would instead have to be launched from a small, agile weapons platform (such as a one-person fighter) operating in extremely close proximity. This was something the evil Imperial Empire considered near impossible in view of the other layers of defence in operation. These included squadrons of close fire support TIE (Twin Ion Engine) Fighters, the Taim and Bak xx-9 heavy turbo-laser towers, and the Borstel SB-920 maned laser cannons, to name just three (Figure 1.3).

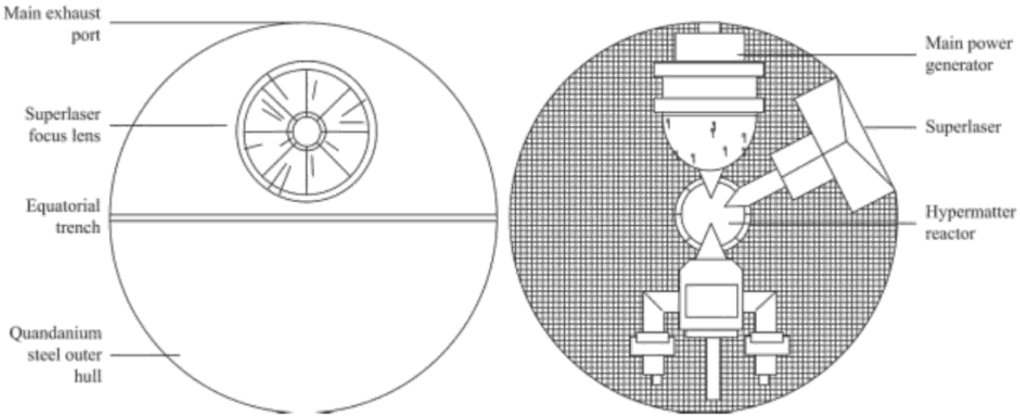

Figure 1.3 High-level schematic of the DS1 Orbital Battle station.

The Star Wars plot hinges on the Imperial Empire's hubris and the perceived impossibility of exploiting this weakness, a perception that proved (explosively) false. In the closing scenes of the film, the hero and budding Jedi Knight, Luke Skywalker (no relation to author Prof Guy Walker), managed to launch a proton torpedo into the thermal exhaust port resulting in an explosive chain reaction which destroyed the entire battle station. The friendly Rebel forces achieved this feat by escorting a small X-Wing fighter craft to the surface of the Death Star. Manoeuvring a small weapons platform in such proximity neutralised the effects of the Death Star's main weapon, and also its surface weapons, which could not fire for risk of damaging the Death Star's hull. This left just the enemy TIE Fighter squadrons, reducing the asymmetry of the conflict to 'one-on-one' combat in which the Rebel Alliance emerged victorious. Prior to the attack the risk assessment activity needed to be run on a set of stolen plans, and in very short order. The Death Star was en route to the planet Yavin 4 to destroy the base from which any attack would be launched from. In a race against time and system complexity, which type of analysis method will win through? 1. A deterministic method, or 2. A systems thinking method?

> We'll be safe enough once we make the jump to hyperspace.

The first issue this fictitious case study exposes is that one size does not fit all. Systems thinking methods do not suit every type of problem, just as deterministic methods do not. All methods need to be matched to the extant problem they are targeting. This is a bigger issue than disciplines such as HFE or safety science tend to admit.

In the case of HFE, which is used to understand and optimise human health and wellbeing, there is an implicit guarantee in the use of HFE methods that, provided they are used properly, they will produce certain types of useful products. All methods should provide structure and the potential for repeatability. In addition, they should provide a route into making the discipline more accessible to all (Stanton and Young, 2002; Wilson, 2014). Given there are hundreds of HFE methods to choose from (Stanton et al., 2013), and little explicit guidance on how to choose between alternatives, it is easy to understand why practitioners and organisations often develop their own or else find their favourites and continue to use them (Stanton and Young, 1998).

The benefits of this pragmatism are clear. Familiarity with a particular methodology can cut costs, decrease training times within organisations, and make knowledge transfer much smoother (Crawford et al., 2016). Over time, the continued application of particular methods creates a legacy. Within high hazard industries, for example, regulations begin to specify them and further solidify their usage. As a result, it is not uncommon for an organisation to have just two or three commonly used methods, often developed decades previously, despite the discipline having 200 or more, many of which are more up to date.

There are currently three broad ways in which HFE methods are selected:

1. Legacy and preference;
2. Methods selection processes; and
3. Method integration/triangulation.

In the first case, developers of a particular method will establish its effectiveness and diffuse those benefits more widely, either through the academic literature, academic or industry training and/or the provision of consultancy services. Many significant methods in the discipline follow this path. Many practitioners continue to apply the methods they know well, which is understandable given constraints on their time to complete analyses and learn new approaches (Shorrock and Williams, 2016; Salmon et al., 2020). It is also common for methods to arise as a response to specific regulatory prerequisites. The advantage of this approach is that methods are made to leave the laboratory and be subject to the rigours of practical application. The disadvantage is that by inventing a particular approach, every problem begins to look like a suitable candidate. The further disadvantage is that some regulatory prerequisites may themselves not be fit for purpose in a rapidly changing world.

The second, and much less well-developed path, is the decision support meta-method approach. This describes semi-formal approaches used to match a wide(r) range of HFE methods to a client or sponsor's needs (e.g. Wilson and Sharples, 2015; Williams and Salmon, 2016). Stanton and Baber (1996) attempted to formalise this by putting forward a meta-method process based on establishing the reliability, validity, and utility of methods, which was latterly extended by Stanton and Young (1999a, 1999b, 2002) in the development of a decision-support flowchart shown in Figure 1.4. This presents method selection as a closed loop process with three feedback loops. The first feedback loop validates the selection of the methods against the selection criteria. The second feedback loop validates the methods against the adequacy of the intended intervention. The third feedback loop validates the initial criteria against the adequacy of the intervention. The process is logically sound, but each step is open to interpretation, especially when selecting methods under time pressure.

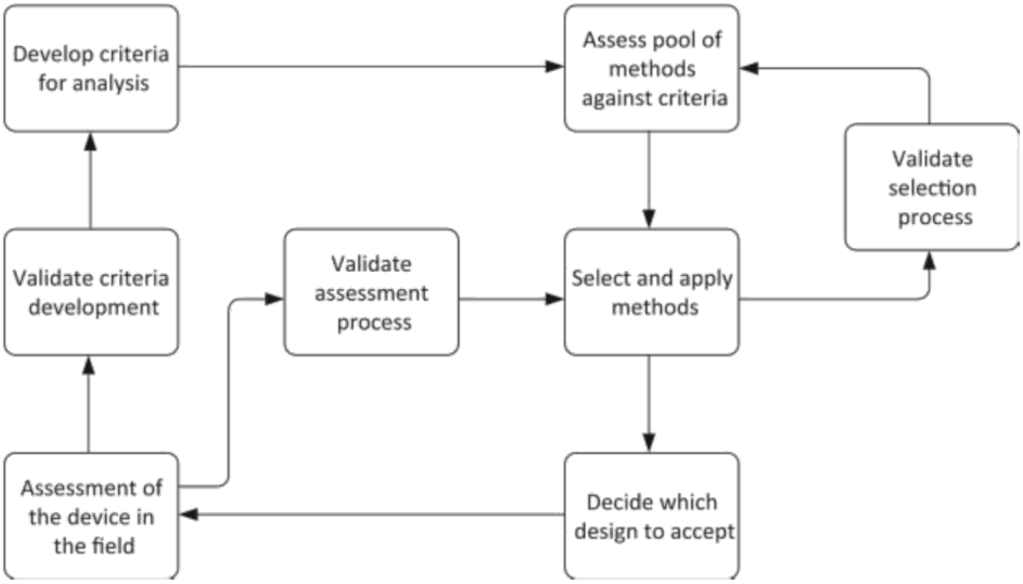

Figure 1.4 Stanton and Young's method selection flow chart. (Adapted from Stanton and Young, 1999b).

The final approach is method triangulation and integration. Through triangulation, weaknesses in one method can be mitigated by the strengths of another (Corlett et al., 1995) and vice versa. Methods can be combined like this in any way which would suit the work system under analysis, so long as theoretical compatibility between the methods is maintained (Stanton et al., 2013; Salmon and Read, 2019). Method triangulation reinforces the point that methods do not, nor do they have to, exist in isolation. This tends to be a feature of several systems HFE methods and is reflected in this book.

An analysis of the plans provided by Princess Leia show...

The three approaches to method selection illustrate the difficulties faced by practitioners in a new world of increasing systems problems. Method selection is contingent, and the primary contingency factor – in our view – are the systems attributes of the target problem. Grant et al.'s systems thinking tenets (2018) makes these systems attributes explicit. The more that a target problem exhibits these features – and destroying a Death Star is a good example – the more that methods covered in this book become well suited.

A more formal way of expressing this contingent approach to method selection is via Relative Predictive Efficiency (RPE; Crutchfield, 1994). The formula is:

$$RPE=E/C$$

E is 'excess entropy' or the extent to which a system can be adequately modelled using any HFE method. An approximation of E can be derived from a comparison between the system behaviours predicted by an HFE method compared to those behaviours actually observed. Any disparity between ‘expected’ and ‘observed’, and in what quantity, represents an approximation to ‘excess entropy’. For example, in the Star Wars case study, the simple organisation (the Rebel Alliance) was able to perform complex unexpected actions not predicted by any normative analysis of how attacks on space-borne battle-stations ‘should’ be performed. It would therefore measure low on the parameter E. The Rebel Alliance’s agility makes its behaviours unpredictable and difficult to model.

C is ‘statistical complexity’. It is a measure of the size and complexity of the system’s model (or method output) at any given scale of observation. This can be measured in several ways using metrics from complexity theory (e.g. Hornby, 2007). It is possible to consider the number of ‘build symbols’ in the system model, the sophistication of the model, or the model’s connectivity (the maximum number of links present in both), and so on.

A highly complex model – either deterministic or systems-based – that does not predict the behaviours of the system under analysis has poor RPE. It represents either wasted time and effort for sub-optimal outcomes, or an analysis of a system that is so large it becomes unwieldy. The sought-after outcome is the reverse. What we hope this book can help readers achieve is simple, parsimonious, efficient models of low complexity that nonetheless generate deep insight. In other words, high RPE.

> Any attack made by the Rebels against this station would be a useless gesture, no matter what technical data they've obtained

Returning to the Death Star, the engineering plans were obtained (read ‘stolen’) and a critical vulnerability was discovered and exploited. Estimates vary, but according to ‘Wookipedia’ the time available for the Rebel Alliance to undertake this analysis was four days. In Walker et al. (2016) we pitted the two competing approaches against each other. The two methods represent opposites in terms of their high-level approach. The former is deterministic and reductionist while the latter is systemic and holistic. Application of the RPE algorithm would suggest that the method which more closely matches the extant nature of the ‘problem’ will exhibit higher predictive efficiency. It would be the one that allows the Rebel Alliance to perform the analysis correctly and within the short amount of time inferred by the film.

The HAZOP and CWA analyses were driven from technical data contained in the Haynes Workshop Manual for the DS-1 Orbital Battle station (Windham et al., 2013). The time it took to complete each analysis was logged, as was the ability of each method to detect the vulnerability exploited in the film. An expert workshop was also held to construct the HE-HAZOP outputs, review the Work Domain Analysis phase of the CWA method, and facilitate narratives on how the Death Star could be destroyed. It is important to note that the participants in the study were aware of the actual vulnerability exploited in the film. After all, everyone (or nearly everyone) has seen it. The goal was to provide the best opportunity possible for each method to detect it. To that end, participants were guided in detail on how to perform the analyses 'strictly by the book' (in this case Stanton et al., 2013) and to pay close attention to whether the 'real' vulnerability was emerging. After the two analysis methods were complete, an RPE score was calculated to gauge the fit of the two methodological approaches to the host problem. What was found?

The Empire Strikes Back

HAZOP and its derivatives (including Human Error-HAZOP) are a well-established approach originally applied to engineering diagrams (Kletz, 1991; Kirwan, 1992; Kirwan and Ainsworth, 1992; Swann and Preston, 1995). It involves the analyst applying guidewords to each step in a task analysis to identify potential problems. It is the very definition of deterministic. It takes a complete entity (the system used to operate and defend the Death Star) and reduces it down to its component tasks. These tasks are individually analysed in order to construct detailed narratives about how the system could fail, and how to prevent it from doing so. Collecting these narratives together – in effect, recombining the system in its entirety – enables clusters of failure mechanisms and design solutions to be identified.

The most important part of any HAZOP analysis is assembling a HAZOP team with the right combination of skills and experience (Swann and Preston, 1995). Two Death Star Subject Matter Experts (SMEs) with extensive knowledge of the 'Star Wars Universe' were recruited via social media, Edinburgh Comicon, and a news item in the Edinburgh Evening News. An example of the detailed HE-HAZOP analysis outputs they produced is shown in Tables 1.2 and 1.3.

Table 1.2 HE-HAZOP Analysis of Task Step 2.1.1.5: Expel Excess Energy

Task Step	Guide-Word	Error	Consequence	Cause	Recovery	Design Improveme
Expel excess energy	Less than	Amazing it works in the first place. Giant amount of energy.	Kills everyone on board. Too hot/cold in a giant metal ball. Functions out of balance. General wear on essential part of station. Compounding problem of fixing problem might cause more exhaust emissions.	**Exhaust port too small.**	Better sensing capabilities and control.	More sensors c exhaust port a source of radia Blow up more planets to test function. More firing. Learn lessons/data f smaller guns o star destroyer. **Make port big to aid flow.**
	More than	Optimum amount of energy balance is required, so becomes out of balance.		Power source.		
	As well as	Channel for something unwanted to enter like vermin or rubbish. Material properties of port constrains design. Bits of port fall off. Bits melt off and re-harden somewhere else.		Floating space debris – but there is a force field. Poor design. Substandard materials. Cost cutting. Planning for maintenance in the future.	Do a cognitive work analysis (Melissa). Roberts to maintain everything.	Control of ther exhaust. Cooling/extra fans. **Put a gra over the port.** route flows to other exhaust ports.
	Other than	n/a	n/a	n/a	n/a	n/a

Task Step	Guide-Word	Error	Consequence	Cause	Recovery	Design Improveme
	Repeated	Access gate to exhaust port activating too much.	Kill's everyone on board. Too hot/cold in a giant metal ball. Out of balance. General wear on essential part of station. Compounding problem of fixing problem might cause more exhaust emissions. Destroys main power generator. Puts life support at risk.	Overzealous with the Super-Laser. Overuse of the weapon creates too much thermal energy/radiation – needs a cooldown period.	Stop overusing it. Full shutdown. Reboot Death Star.	Designated co down period (procedural change). Back for life suppor
		Sooner than	Poor control.	Wasting energy and output.	Lack of sensing capability.	Human (alien) intervention o some sort.

Task Step	Guide-Word	Error	Consequence	Cause	Recovery	Design Improveme
	Later than	Don't want too much energy in the core. Might slow things down, effect system performance. Strains systems if too much being demanded.				
	Mis-ordered	Energy for laser being expelled out of exhaust port and wasted.	Don't want energy for laser to shoot out of exhaust port and be wasted. Diminishes ability of the Death Star to fire main weapon system.	Faulty mechanics. Something not opening. Faulty sensors.	Shut it all down and reboot.	Mechanical/sy interlock. Automatic fail safes.

Table 1.3 HE-HAZOP Analysis of Task Step 2.1.1.6: Control and Monitor Thermal Exhaust Port Ray Shield Generators

Task Step	Guide-Word	Error	Consequence	Cause	Recovery	Design Improvements
Control and monitor thermal exhaust port ray shield generators	Less than	Malfunction.	Not strong enough. Allows unwanted matter into exhaust port.		Reset strength of forcefield – quick disablement of port. Isolate problem.	Control dial. Touchscreen interface.
	More than		Heat and radiation prevented from getting out – ray shield too strong.	Fried equipment due to heat.		
	As well as	Controls set incorrectly. Malfunction. Push dial too far due to inattention or slip.	Make problem worse. Make port vulnerable. Or make port less effective in dissipating heat.	Sabotage. Incompetence.		Threshold warning system. Condition monitoring. System feedback.
	Sooner than		Kills everyone aboard. Too hot/cold in a giant metal ball. Out of balance. General wear on essential part of station. Compounding problem of fixing problem might cause more exhaust emissions. Destroys generator.	Delays in monitoring system – not in real time.		Safe zone – system optimisation. Engineered level.
	Later than			Other warnings and control room ergonomics. Other demands and priorities. Workload and teamworking. Understaffing.		
	Mis-ordered	Distraction, concurrent demands, operator forgets what they are doing, error of commission.				Liaison between forcefield and exhaust port monitoring teams. Get the droids to do it...but don't trust them completely.

Task Step	Guide-Word	Error	Consequence	Cause	Recovery	Design Improvements
	Part of		Life support at risk.			

Don't be too proud of this technological terror you've constructed.

CWA (Vicente, 1999) is a systems analysis and design framework that is typically used in applications that aim to understand and/or optimise complex systems (Bisantz and Burns, 2008; Stanton et al., 2017). The framework comprises five phases and provides a series of modelling approaches that focus on identifying the constraints imposed on behaviour within the system under analysis (Vicente, 1999). The first phase, Work Domain Analysis (WDA), is used to develop an event- and actor-independent model of the system under analysis (Vicente, 1999; Naikar, 2013). This involves using the abstraction hierarchy method to describe the system across five levels of abstraction in order to identify the primary goals of the system, the processes and functions that are undertaken within the system, the values and criteria used to determine whether the system is achieving its goals, and the objects used when undertaking processes and functions. This constraints-based approach can be used to explore all the possibilities for action contained in a system, and indeed, the possible ways in which it could fail.

Extracts of the completed WDA analysis are shown in Figure 1.5 (Walker et al., 2016). It comprises 115 functional nodes and 354 means-ends links. The functional purposes of the Death Star, as defined by the source documents, are as follows:

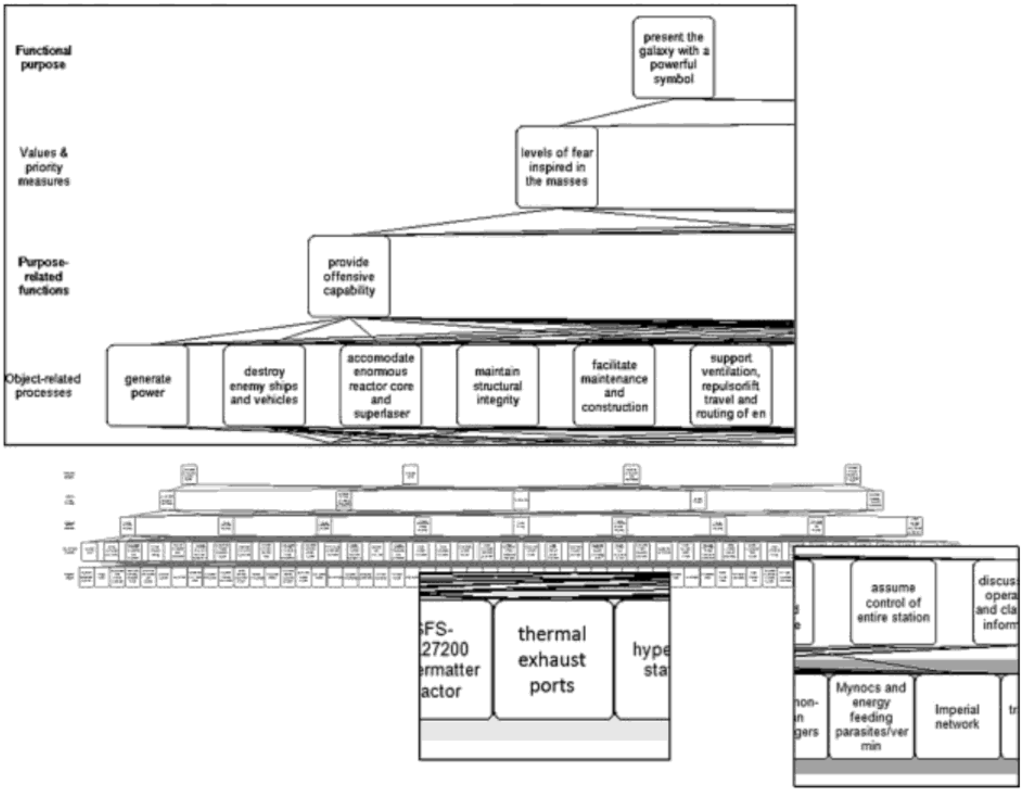

Figure 1.5 Extract of the Work Domain Analysis (WDA) of the DS-1 Orbital Battle Station. (Adapted from Walker et al., 2016).

- Present the galaxy with a powerful symbol;
- Subjugate worlds;
- Enable the galaxy to be ruled unchallenged; and
- Enact the doctrine of ‘rule through fear’.

The values and priority measures, which can be used to determine the extent to which the system is meeting those purposes, include the ability of the Death Star to exhibit ‘operational autonomy and self-containment’, the ‘relative firepower’ it can muster, and the overall ‘levels of fear inspired in the masses’. Purpose-related functions include: ‘provide offensive and defensive capabilities’, ‘provide energy and propulsion’ and ‘provide command capability’. The object related processes which underlie these more general functions include: ‘generate power’, ‘destroy enemy ships’, ‘capture, shift or redirect space-born objects’ and ‘accommodate enormous reactor core and super-laser’. All of these functions and priority measures could potentially be achieved with a wide variety of technical means. Currently (or rather previously), the Death Star combines a wide range of specific physical objects such as Phylon Q7 tractor beam projectors, Taim and Bak xx-9 heavy turbo-laser towers, the main power generator, the Quadanium steel armoured hull and, of course, the thermal exhaust ports. All of these, and more, service the higher-level functions.

A WDA validation and insight extraction process was undertaken. The first phase involved the SMEs scrutinising the WDA and identifying any missing elements or links. Both SMEs were satisfied that the WDA contained all relevant components. The next phase invited the SMEs to trace through the WDA, examining functions, processes, and their interconnections, and using these to drive further narratives for how the system could fail. The WDA had a significant effect on the ability of the SMEs to do this. They judged the WDA as being inferior compared to HE-HAZOP in terms of “fine detail” but felt it was better at “providing a good overview”, “better for strategising”, and perhaps most importantly, “a lot quicker”.

A common misconception is that systems thinking methods take a long time. This belief alone is often enough to prevent systems methods being used. In this case study (as well as numerous other real-world case studies) the WDA took a similar amount of time to develop as the Human Error-HAZOP. It required approximately 10 hours’ input by the lead investigators, and a further two hours for the SMEs to validate. This is a total of 12 hours, or 1.5 working days, compared to the 10.5 days required to run the complete Human Error-HAZOP analysis with the same resources. In fact, the WDA is a representation of the entire system, whereas the HE-HAZOP analyses just *two* out of 160+ tasks.

> I used to bullseye womp rats in my T-16.

Not only was the systems thinking method significantly quicker, it also succeeded in detecting the actual vulnerability exploited in the film (i.e. the exhaust port), along with many others. These included seizing control of the navicomputer and steering the Death Star into a planet or star; poisoning its atmosphere; or uploading a destructive computer virus. This last vulnerability informed the narrative of the 1994 film ‘Independence Day’, but of course, the first such virus was released into the wild in 1983 and was not available for use in the original 1977 Star Wars plot. Despite computer viruses not existing in 1977, the ‘possibility for action’ was very much present in the WDA and available for scrutiny.

The outputs of the two analyses, combined with the time it took for both to be completed, suggest that RPE for the WDA was higher than the comparable HE-HAZOP analysis in this case (Walker et al., 2016). Further, when applied to the problem of destroying a Death Star with a proton torpedo fired into a thermal exhaust port, the WDA had a higher predictive efficiency than the deterministic Human Error-HAZOP (Walker et al., 2016). Not just that, but the WDA could also be completed well before the Death Star hovered into view over the horizon of Yavin 4, ready to destroy the Rebel base with its Super-Laser. It is thus the method recommended to the Rebel Alliance should the need arise to destroy another Death Star…which of course they did in 1983 (Return of the Jedi) and 2015 (The Force

Awakens). Ever alert to a commercial opportunity, HFE and safety science can be of equal service to the Imperial Empire should they wish for a more resilient and jointly optimised Death Star in future. This may or may not involve a recommendation to fit grills over all the thermal exhaust ports.

The aim of analysing the Death Star from the film franchise Star Wars is not to trivialise the issue of systems thinking methods and their application in HFE and safety science. It arises from science outreach activities in which cross-disciplinary insights need to be communicated in effective ways to a wide range of different stakeholders, from students and first-time users of system thinking-based methods, through to seasoned professionals. Systems thinking is a core part of HFE and it is likewise becoming a core topic in other disciplines too. We believe that novel approaches to bridging these gaps and demonstrating value are to be welcomed and encouraged. The relatively poor uptake of systems thinking methods suggests that existing ways of advocating systems thinking may not be working, so we hope readers will forgive us for attempting a novel and unusual approach. With these caveats in place, we can move on to the substance of what we are trying to say with this case study, and indeed this book.

What this comparison of methods illustrates is the fundamental role of systems properties in making contingent decisions about which methods to apply to what problems. This is an increasingly important question because a) the paradigm has shifted towards greater use of systems concepts, b) many research grand challenges occur at the non-linear intersection of people and technology, and c) every time a method is used tacit assumptions about the nature of the problem to be solved are made. This is why our introduction to systems thinking methods has travelled to outer space to demonstrate that, sometimes, those assumptions can be at odds with what we are trying to achieve, with potentially disastrous consequences.

A real-life thermal exhaust port to find

Back on Earth we undertook a very similar comparison (Walker et al., 2014). Instead of a fictional space-born battle station the setting was a UK Magnox nuclear decommissioning site (Walker, et al., 2014). Instead of a Rebel Force seeking to destroy it, the challenge was to risk-assess decommissioning activities that had never been carried out on this site before. The risk was rather extreme. The activity being risk-assessed was the removal of two High Dose Rate Items (HDRIs) from a disused cartridge cooling pond. Both HDRIs were giving radiation dose readings of 14 Sieverts (Sv), which is the equivalent of a 5.25 second unshielded exposure time before the annual legal allowable dose uptake of 20mSv is exceeded. This reinforces the need to make *absolutely sure* that all risks were assessed. Instead of Human Error-

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