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What the Death Star can tell us about Ergonomics Methods

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Abstract

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 in the film Star Wars. The first option presented in this paper is to employ traditional error identification methods of the sort contemporaneous with film's release in 1977 and still in widespread use today. The findings show the limitations of this deterministic world-view because the method selected did not predict the actual vulnerability exploited. The second option is to use a systems-based method and this did detect the film ending, and several others. What began as an amusing aside has turned into a highly effective means to communicate complex Ergonomic concepts across disciplines and enhance ergonomic teaching and learning.

Keywords: Star Wars, resilience, scale, variety, systems approaches, predictive efficiency

Introduction

It is unusual, although not unprecedented, to find an academic paper written on the topic of a fictional space-born orbital battlestation from the film franchise Star Wars. The reasons for this need to be explained. Three of the four authors are based in civil engineering departments at their respective institutions. This analysis, which began as an amusing aside, has grown considerably as it was discovered just how well-known the film franchise was across all disciplines but especially engineering. As a vehicle for communicating complex ergonomic ideas it has become unsurpassed in our experience and we are not alone in this. Researchers have used Star Wars to teach complex topics in psychiatry because it is “well known to students, registrars, and consultants alike” (Freidman & Hall, 2015, p. 432). It has facilitated an examination of how people interact with political philosophy (Geraci & 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 Vadar’s respiratory difficulties informs learning and teaching in pulmonology (Berg et al., 2014). If papers in 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 paper describing how Star Wars can be used to communicate complex ideas about ergonomics, resilience, and the burgeoning topic of civil engineering systems (e.g. Jowitt, 2004: 2010) begins to seem quite sensible.

What this entertaining case study has enabled us to do, without any doubt, is reach out across discipline borders in a way not previously experienced. Having showcased parts of this analysis at numerous events, and for numerous purposes, it is now time to present the full work. This Special Issue is the ideal outlet. Despite the paper’s filmic overtones and hints of levity we are able to put forward a powerful intergalactic demonstration of how to match ergonomic methods to ergonomic problems at a fundamental theoretical level. We hope this demonstration is able to inform professional practice, but we also hope it can serve as a useful resource for learning and teaching activities.

A long time ago, in a galaxy far, far away…

Star Wars Episode IV, the first in an original trilogy of films, was released into the US domestic market in May 1977, had a second launch in August of the same year, and a general release in UK cinemas from March 1978. Among other films, such as Jaws, Close Encounters, and Superman, it heralded the dawn of the Blockbuster genre (Stringer, 2003). It helped end the interregnum left by the widescreen Roadshow era of films common in the 1960's, and stem (albeit temporarily) the precipitous decline in cinema audiences through the 1980's (Haines, 2003). The centre piece of the original Star Wars film (Episode IV) was a planetoid sized orbital battle station referred to as the 'Death Star', around which much of the storyline centres.

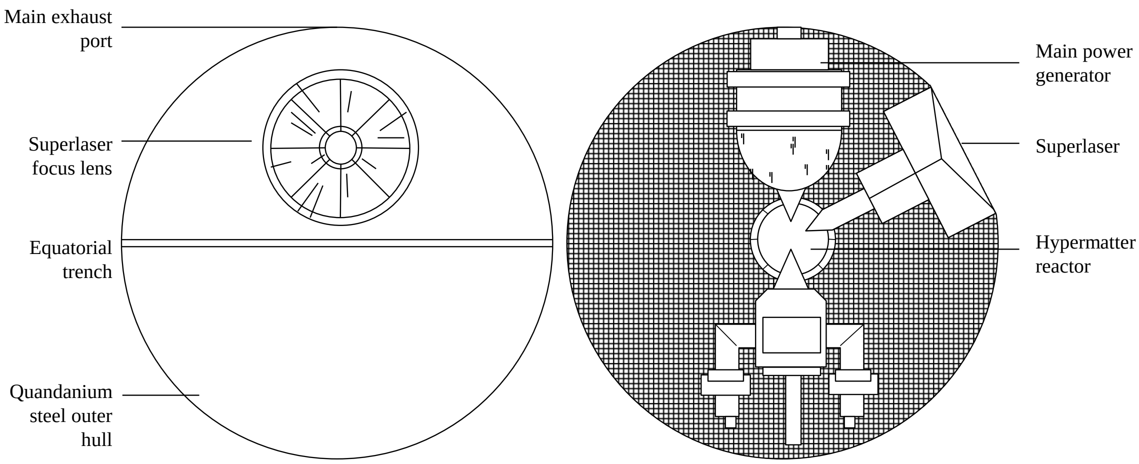

Figure 1 - High level schematic of the DS1 Orbital Battle station

The Mark I version of the battle station certainly had impressive civil engineering credentials. It was a 160km diameter spheroid constructed from Quandanium steel, a high strength material apparently mined from asteroids (Windham, Reif & Trevas, 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, defensive and offensive weapons systems. Principle among the latter was the Superlaser, possessing enough power to destroy entire planets. The large conical focusing nexus, positioned on the northern hemisphere of the station, is visible in Figure 1. The core is devoted largely to energy and offensive purposes meaning that accommodation and living space reside 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 – the protagonists - was a small thermal exhaust port located in the equatorial trench

(Windham, Reif & Trevas, 2013). This provided a route from the surface of the station directly to the core. It had clearly been risk assessed by the Imperial Empire – the antagonists and Death Star creators - as it was protected by a ray shield. It was also small, being only two meters in diameter, meaning that 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 turbolaser towers, and the Borstel SB-920 maned laser cannons, to name just three. Unfortunately, the perceived impossibility of exploiting this weakness was proved false. A proton torpedo was launched by the friendly Rebel forces from a small X-Wing fighter craft escorted to the surface of the Death Star by a wing of other similar craft. Manoeuvring in such close 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 the TIE Fighter squadrons, reducing the asymmetry to 'one-on-one' combat. In the event, a proton torpedo was launched into the thermal exhaust port and caused an explosive chain reaction which destroyed the Death Star. This is the critical vulnerability discovered in the film by analysing stolen Death Star plans, and the vulnerability that needs to be detected by the ergonomic methods applied in this paper.

Describing the Death Star

Formal Rationality

To be emblematic of an ultimate technological terror weapon circa 1977 the principles of Formal Rationality (Weber, 1930) needed to find particularly vivid expression. Formal rationality is a prominent part of an 'implicit theory' that has guided modern organizational design since the industrial revolution, and is one of many universal themes picked up tacitly or otherwise by the Star Wars franchise (Rinzler, 2007; Campbell, 2008). A formally rational organization is labelled a bureaucracy and the Death Star is an extreme example. Rationalizing organizations like this exhibit a tendency towards hierarchies and the maximization of the following attributes:

- Efficiency: The Death Star is "…the most efficient structure for handling large numbers of tasks…no other structure could handle the massive quantity of work as efficiently"
- Predictability: "Outsiders who receive the services the [Death Star] dispense know with a high degree of confidence what they will receive and when they will receive it [i.e. total destruction]"
- Quantification: "The performance of the incumbents of positions within the [Death Star] is reduced to a series of quantifiable tasks…handling less than that number is unsatisfactory; handling more is viewed as excellence"
- Control: the Death Star "may be seen as one huge nonhuman technology. Its nearly automatic functioning may be seen as an effort to replace human [and in this case moral] judgment with the dictates of rules, regulations and structures" (Ritzer, 1993, p. 20-21).

Organizations like the Death Star, designed along bureaucratic lines, can be seen as a way of imposing control theoretic behaviour on a large scale. In so doing, they are attempting to make inputs, processes, outputs, even humans (and other life-forms too) behave efficiently, predictably, quantifiably and under maximum control.

Scale

Another defining feature of the Death Star is its size. Why was it so big? There is an expedient engineering need to accommodate a large reactor core and super laser, but an analytical side effect of this are the changes that happen to the Death Star's behaviours when viewed at different scales (Bar-Yam, 2004). This is referred to as a complexity profile and it relates to "the amount of information necessary to describe a system as a function of the level of detail provided" (Bar-Yam, 2004, p. 1). In the case of the Death Star its primary behaviours are visible at very large scales indeed. Those behaviours include a planet shattering Superlaser, but they also include the squadrons of TIE fighters in close formation, the serried ranks of Imperial Stormtroopers, and the numerous other examples of the system behaving in highly rigid and coordinated ways. As we zoom in on the Death Star, decreasing our scale of observation to that of small groups of actors, that high level of coordination gives rise to a distinctive property. Although the effects of bureaucratic organization (the Superlaser, the close formation flying, the serried ranks) can be viewed from a great distance, the Death Star's fine scale behaviours are not always that complex. Role incumbents have strictly defined tasks in an equally strict hierarchy, and innovation is not rewarded. The Death Star, therefore, is an example of a complex organization, in terms of its control structures, rules, myriad procedures, patterns of vertical communication and, of course, technology, which nonetheless only permits agents within it to undertake comparatively simple tasks (Sitter, Hertog & Dankbar, 1997). This reflects a fundamental principle of systems shown in Figure 2. When parts of a system are acting together, the large-scale behaviours are clearly visible but the fine-scale complexity is small; when parts of a system are acting individually the large scale behaviours are not clearly visible but the fine scale complexity is large (Bar-Yam, 2004).

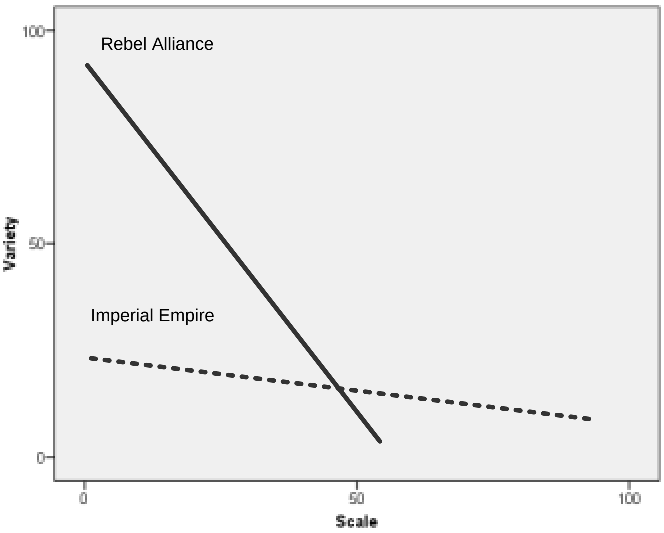

Figure 2 – Complexity profiles for the Evil Imperial Empire and the Friendly Rebel Alliance. The profiles arise from considering the number of distinct behaviours (i.e. variety) available to the organisation at different levels of observation (i.e. scale). The Imperial Empire has large scale but low variety while the Rebel Alliance has low scale but high variety

Variety

The second point about bureaucracies is their large scale behaviours cannot be more complex than the actors at the top of their organisational structure. The Emperor is the supreme overlord of the Death Star but even his complexity is limited (Bar-Yam, 2004). Bureaucracies like the Death Star, therefore, are large scale but also low variety. Ashby's Law of Requisite Variety tells us that:

"…only variety can destroy variety. [..] This principle has important implications for practical situations: since the variety of perturbations a system can potentially be confronted with is unlimited, we should always try to maximize its internal variety (or diversity), so as to be optimally prepared for any foreseeable or unforeseeable contingency." (Heylighen, 1992, p3).

In other words, a resilient system must have a sufficient repertoire of responses, and the agility to use them, such that it can track the dynamics of its environment and deliver stable outputs under all conditions. If not it becomes vulnerable. In Star Wars Episode IV, and to paraphrase Ashby, 'variety literally did destroy variety'. The Death Star had insufficient internal variety or diversity to be able to counter the threat posed by the Rebel Alliance. Its hierarchical organization was exceptional at amplifying the scale of the individual at the top of the hierarchy (i.e. the Emperor) but it was ultimately "not able to provide a system with larger complexity than that of its parts" (Bar-Yam, 2004). In contrast, the Rebel Alliance's attack was more complex than the person(s) at the top of its organizational structure. The focus here was on self-synchronizing teams, effects based operations, compatible awareness (via The Force), all of which created the conditions for variety to neutralise the effects of scale.

Analysing the Death Star

Of course, scale versus variety is a trade-off. There are situations which require sheer scale and others that require high organizational variety. As such it relies on organizations and analysts matching their 'approach' to their extant 'problems'. Table 1 distils this simple but important expedient into a matrix in which 'problem' and 'approach' are crossed, and the resultant system behaviours approximately defined.

Table 1 – Matrix of 'Approach' versus 'Problem' and a simple taxonomy of showing the outcomes that arise when Approaches and Problems are mapped onto each other

		PROBLEM	
APPROACH		**Blow up planets with Superlaser (Deterministic)**	**Launch agile asymmetric attack (Complex)**

Imperial Empire *(Bureaucratic/ deterministic/ hierarchical/ tightly coupled)*	**Match** The Death Star has sufficient scale to yield this outcome in a predictable way…	**Mismatch** Scale hinders ability to respond quickly and adaptively
Rebel Alliance *(Systemic/ probabilistic/ team-based/ loosely coupled)*	**Mismatch** Insufficient scale to yield the expected outcome	**Match** Organisational agility and speed sufficient to neutralise advantages of scale

What sort of ‘problem’, at a fundamental level, does the problem of destroying the Death Star with a small asymmetric force represent? A useful way to approach this is to gauge the extent to which it exhibits the property of emergence. Emergence describes behaviour that is not deducible from its low level properties; behaviour that does not adhere (at any reasonable or tractable scale of analysis) to the logic of causal determinism. It can be defined as follows:

Emergence is the phenomenon wherein complex, interesting high-level function is produced as a result of combining simple low-level mechanisms in simple ways” (Chalmers, 1990, p.1).

The combination of simple low-level mechanisms in simple ways to give rise to complex, interesting, high-level function describes the Rebel Alliance’s attack on the Death Star well. To quote the classic sociotechnical literature, “though [the Rebel Alliance’s] equipment was simple, their tasks were multiple”, the agent in this organization “…had craft pride and artisan independence” (Trist & Bamforth, 1951). The Rebel Alliance’s attack on the Death Star is an example of a simple organization undertaking complex tasks (Sitter, Hertog & Dankbaar, 1997), and it was this variety (rather than scale) which proved the deciding factor. The question to ask next is how to determine what ‘approach’ should be matched to what ‘problem’ to ensure similar successes in future? A useful guiding concept is Relative Predictive Efficiency (RPE, Crutchfield, 1994) which is expressed as follows:

$$RPE = E/C$$

E is ‘excess entropy’ or the extent to which a system can be adequately modelled. This can be based on a comparison between the system behaviours predicted by a model compared to those behaviours actually observed. Any disparity between ‘expected’ and ‘observed’, and in what quantity, represents an approximation to ‘excess entropy’, or ‘E’ in the formula. For example, the simple organization (the Rebel Alliance) which is able to do complex unexpected things not predicted by a normative analysis of how attacks on space-born battlestations ‘should’ be performed, would measure low on the parameter E. C, on the other hand, is ‘statistical complexity’. It is a measure of the size and complexity of the system’s model at any given scale of observation. This can be measured in a number of ways using metrics from complexity theory (e.g. Hornby, 2007). It is possible to consider the number of ‘build symbols’ in the system model (for example, the number of functions contained in a Work Domain Analysis), the sophistication of the model (i.e. the number of logical operators used in Hierarchical Task Analysis plans), or the model’s connectivity (the maximum number of links present in both) and so on. A highly complex model that does not predict the behaviours of the system has poor Relative Predictive Efficiency. The sought after outcome is the reverse: simple, efficient models of low complexity that nonetheless predict the system behaviours well.

Relative Predictive Efficiency gets to the heart of the current paper. The filmic subject matter of the Death Star serves as a surprisingly compelling demonstration of a particular type of system, and the approaches that can be adopted for neutralising it. In the remainder of the paper a replication based on the film will be undertaken. In the film a full technical read-out of the station was obtained and, based on this, 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. Two competing approaches will be attempted in this paper. The first approach is based on ergonomics methods contemporaneous with, and in widespread use at the time of the film’s original release in 1977. The second approach is based on an ergonomic method that has gained traction subsequently. The two approaches represent polar opposites in terms of their high level ‘approach’. The former is a deterministic and reductionist approach while the latter is systemic and holistic. This is an exploratory study, but it can be hypothesised that the ‘approach’ which more closely matches the extant nature of the ‘problem’ will exhibit higher relative predictive efficiency and, moreover, would have enabled the Rebel Alliance to perform the analysis task correctly and in the amount of time inferred by the film. Based on these insights some wider and more fundamental issues can be addressed. Principally, how ergonomists should select analysis methods in relation to the underlying properties of the system under analysis. The promise of these insights is that higher levels of predictive efficiency are available to ergonomists who pay attention to these issues which, in turn, will lead to better insights more quickly.

Method

To illustrate the practical and methodological issues around scale, variety and predictive efficiency a replication of the analysis of the Death Star's plans was undertaken. Two distinct approaches were used to try and detect the critical vulnerability exploited in the film. The first method is a reflection of the deterministic world-view dominant at the time of the original film's release in 1977. In this case a Hierarchical Task Analysis (HTA) of the Death Star was created and used to drive a HE-HAZOP (Human Error Hazard and Operability) analysis. HTA was originally developed in the early 1970s by Annet et al. (1971) and HAZOP can trace its origins to the pioneering work of ICI in the 1960's and Kletz in 1974. Both methods are thus contemporaneous with the year of the film's release and would have been (indeed, still are) in widespread use in earth-bound settings.

The second method is a reflection of the systems world-view which is becoming a key feature of the ergonomics 'offer' to stakeholders (e.g. Dul et al., 2012). It coincides neatly with the release in 2015 of a new Star Wars sequel. In other words, if a requirement emerges in the 2015 film to analyse a technical read-out of a Death Star it is just as likely that a Work Domain Analysis (WDA) would be performed. This is a systems method which enables key constraints and affordances of the Death Star to be systematically interrogated. WDA originates from the pioneering work of Rasmussen and the Riso Institute in the 1980's, but entered the Ergonomic mainstream (to a greater extent at least) in the 90's with the publication of Rasmussen, Pejtersen and Goodstein's book in 1994, and Vincente's in 1999. WDA is in use at the present time in numerous industrial settings (e.g. Naikar, 2013; Jenkins, 2009).

Both analyses were driven from technical data contained in the Haynes Workshop Manual for the DS-1 Orbital Battlestation (Windham, Reiff & Trevas, 2013). In the film, a full technical read-out of the Death Star was obtained by rebel spies, many of whom lost their lives in the attempt, and as such ethical approval for a true replication was not forthcoming from the host institutions. The time it took to complete each analysis was logged, as was the ability of the respective methods to detect the vulnerability actually exploited in the film. An expert workshop was also held to construct the HE-HAZOP outputs, review the WDA, and facilitate narratives on how the system could fail. It is important to note that the participants in the study were well aware of the actual vulnerability exploited in the film and the goal was to provide the best opportunity possible for each method to detect it. Participants were guided in detail on how to perform the analyses 'strictly by the book' (e.g. Stanton et al., 2013) and to pay close attention to whether the 'real' vulnerability was actually emerging. This very open and overt strategy also serves to attenuate any order effects. After the two analysis methods were complete, a Relative Predictive Efficiency score was calculated in order to gauge the fit of the two methodological approaches to the host problem.

Results Part 1: HE-HAZOP Analysis of the Death Star

The HE-HAZOP technique was first developed by ICI in the late 1960s in order to investigate the safety and operability of industrial plant. It has been used extensively in the nuclear power and chemical process industries since (Swann and Preston, 1995). HAZOP, and its derivatives (including HE-HAZOP) are a well-established approach originally applied to engineering diagrams (Kletz, 1974; Kirwan, 1992; Kirwan and Ainsworth, 1992). It involves the analyst applying guidewords (see Table 2) to each step in a process in order to identify potential problems. The following steps from Stanton et al. (2013) were followed in this analysis:

Step 1: Assemble HE-HAZOP Team

The most important part of any HAZOP analysis is assembling the correct HAZOP team (Swann and Preston, 1995). The HAZOP team needs to possess the right combination of skills and experience in order to make the analysis efficient. The HAZOP team leader should be experienced in HAZOP-type analyses so that the team can be guided effectively, and in this study the role was adopted by the first author. Death Star Subject Matter Experts

(SMEs) were recruited via social media, Edinburgh Comicon and a news item in the Edinburgh Evening News. Two individuals were specially selected to take part, a male and female both aged between 25-29 years with extensive knowledge of the so-called 'Star Wars Universe'. Both participants were asked to complete two pre-qualification tests. The first was a Star Wars Super-Fan Extent quiz (available on-line at: http://www.mirror.co.uk/tv/tv-news/4th-star-wars-quiz-23-3488391) and both scored in excess of 50%. The SMEs were also asked to answer a number of questions (available on-line at: http://www.dorkly.com/post/59766/the-8-types-of-star-wars-fans) to define their Super Fan Type. Both scored 9/10 for 'Original Star Wars Trilogy' preferences, which is the part of the Star Wars film franchise where the Death Star resides. Both SMEs have been watching the original Star Wars trilogy films since the mid 90's (between 73 and 81% of their total lifespans) and have seen the films in excess of 40 times each (an average of between 2.21 and 4.29 viewings per year). The SME workshop itself took place in Cult Espresso, a so-called 'hipster' coffee shop popular with Star Wars fans located in Edinburgh City Centre. As noted in the sections above, all members of the HE-HAZOP team knew the critical vulnerability that needed to be detected and were reminded by the HE-HAZOP team leader throughout the analysis. They were also reminded throughout on the rules and procedures governing the use of HE-HAZOP.

Step 2: Conduct HTA

Hierarchical Task Analysis (HTA) is perhaps the most widely used of all available ergonomics techniques (Annett, 2004; Stanton, 2006). Originally developed in response to the need for greater understanding of cognitive tasks (Annett, 2004) it involves exhaustively describing the activity under analysis as a hierarchy of goals, sub-goals, operations and plans. One of the main reasons for the enduring popularity of the technique is its flexibility and scope for further analysis. The majority of ergonomics analysis methods either require an initial HTA of the task under analysis as their input, or are made significantly easier through the provision of one (Walker et al., 2009). This includes HE-HAZOP, which operates on the lowest level tasks defined by the HTA. A further advantage of HTA, which this case study amply demonstrates, is that it is capable of representing any system provided a satisfactory description of it can be sourced. This includes systems that do not yet exist, such as DS-1 Orbital Battlestations. The following steps from Stanton et al. (2013) were used to construct the HTA:

Define Task(s) under Analysis

It was decided at an early stage to focus on breadth rather than depth. This is a reflection of the technical material available and the fictional nature of the artefact under analysis. Having said that, knowing the critical vulnerability exploited in the film (the precision launch of a proton torpedo into a thermal exhaust port located in the station's main equatorial trench) prompted much finer levels of detail in those parts of the analysis.

Data Collection

The primary source of technical data on the Death Star was the Haynes Workshop Manual: DS-1 Orbital Battlestation (Windham, Reiff & Trevas, 2013). This is a 123 page pictorial and textual description of the station, officially sanctioned by the film's creators, and purporting to be "the most thorough technical guide to the Death Star available". This was supplemented later in the analysis with SME interviews.

Overall Goal of the Task

This was defined simply as "Operate DS-1 orbital battle station". This highest level goal was kept deliberately broad in order to capture the full range of tasks while recognising that ultimate depth of analysis was limited by the available technical material.

Determine Task Sub-Goals

The task sub-goals were largely determined by the break-down of Chapters contained in the main technical reference (Windham et al., 2013). Thus the top level of the HTA appears as:

0 Operate DS-1 orbital battle station
Plan 0: Do 1 AND 2 AND 3 AND 4 AND 5 AND 6 AND 7

1 Operate weapons and defensive systems
2 Operate energy and propulsion systems
3 Operate docking and hangar bays
4 Operate life support systems
5 Provide station security
6 Undertake service and technical operations
7 Undertake command operations

Sub-Goal Decomposition

Goals 1 and 2 were decomposed up to the limits of what the technical material could support. This is consistent with the analysis goals set out in Step 1, which is to focus on the critical vulnerability actually exploited in the film and provide the best possible chance of this vulnerability being detected via the subsequent HE-HAZOP analysis. Goals 3 to 7, which were not directly related to the critical vulnerability, were decomposed to one further sub-goal level. This gave rise to an analysis that extended to a maximum depth of seven levels, and comprised 161 goals and operations. An extract is shown in Figure 3.

2 operate energy and propulsion systems
Plan 2: do simultaneously

2.1 operate hypermatter reactor
Plan 2.1: WHILE 1 do 2 and 3

2.1.1 control and monitor reactor subsystems
Plan 2.1.1: do simultaneously

2.1.1.1 control and monitor stellar fuel bottles
2.1.1.2 control and monitor capacitor panels
2.1.1.3 control and monitor redundant subsystems
Plan 2.1.1.3: do 1 AND 2
2.1.1.3.1 control and monitor redundant engine subsystems
2.1.1.3.2 control and monitor redundant electrical subsystems

2.1.1.4 distribute power
2.1.1.5 expel excess energy
2.1.1.6 control and monitor thermal exhaust port ray shield generators

Figure 3 - HTA of the DS-1 Orbital Battle Station with the two critical tasks highlighted

Step 3: HE-HAZOP Guideword Consideration

The HE-HAZOP method works by applying the guidewords shown in Table 2 to each bottom level task step in the HTA, individually and in turn. To provide the participants with the best possible chance of detecting the ‘real’ vulnerability exploited in the film, and provide a test that could be accomplished within a reasonable timescale, they were asked to focus on the following two tasks:

2.1.1.5: Expel excess energy
2.1.1.6: Control and monitor thermal exhaust port ray shield generators

These were chosen because they were the only tasks that explicitly referred to the Thermal Exhaust Port which, as we know, was the critical vulnerability exploited by the Rebel Alliance in the film. The two analysts were well aware of this vulnerability and the task was to fully explore the analysis outputs, following the instructions explicitly, to see if it emerged. To do this the HE-HAZOP guidewords for the task steps under analysis were applied. This involved in depth discussions on whether the guideword could have any effect on the task step or not, and also what type of error would result. If any of the guidewords were deemed credible by the HE- HAZOP team, Step 4 was performed.

Table 2 – HE-HAZOP Guidewords (Stanton et al., 2013)

Less Than	Later Than
Repeated	Other Than
More Than	Mis-ordered
Sooner Than	Part Of
As Well As	Omitted

Step 4: Error Description

For any credible guidewords, the HE-HAZOP team provided a description of the form that the resultant error would take. The facilitator reminded the participants of the actual vulnerability exploited in the film, and ensured that its presence or absence in the HE-HAZOP outputs was fully considered.

Step 5: Consequence Analysis

Once the HE-HAZOP team described the potential error its consequence was then determined. The HE-HAZOP leader helped to facilitate clear and explicit descriptions which were logged.

Step 6: Cause Analysis

After considering the consequences, the HE-HAZOP team then determined the cause(s) of the potential error. The cause analysis is crucial to the remedy or error reduction part of the HE-HAZOP analysis. Any causes associated with the identified error were logged.

Step 7: Recovery Path Analysis

Any recovery paths the Death Star might potentially take after the described error has occurred were recorded. The recovery path for an error is often another task step in the HTA (where this is available) but in this case a detailed description based on SME knowledge of the Death Star was sought and provided.

Step 8: Error Remedy

Finally, the HE-HAZOP team took the previous inputs and proposed any number of design or operational remedies that could be implemented. This is based upon the subjective judgement of the analysts and their domain expertise.

Key Findings from the HE-HAZOP Analysis

The analysis of these two critical tasks with a HE-HAZOP team comprised of three members took 56 minutes to complete. Extrapolating to the full 161 HTA tasks leads to a total analysis time of 75 hours and 4 minutes. This could be quicker in the face of familiarity, duplication of tasks and practice; but it could also be longer in the face of new and more complex tasks elsewhere in the HTA. It should also be noted that a full HTA of the Death Star, with all sub-goals taken down to an equal and maximum level of decomposition, would take orders of magnitude longer to complete. Adding to the time needed to perform the HE-HAZOP analysis is the time taken to construct, error check and validate the HTA. A conservative estimate for this is ten hours of working time, bringing the total HTA/HE-HAZOP analysis time up to 85 hours. It is beneficial to have the same analysts working on the HE-HAZOP and thus if we assume an 8 hour working day (acknowledging that working practices may differ in other parts of the galaxy) this leads to a total analysis time of 10.5 days. This is well over double the time available to run the analysis as described in the film, and even despite this, the HE-HAZOP method did not detect the 'real' vulnerability'.

The results obtained from the HE-HAZOP are shown in Table 3 and Table 4. It will be noted that despite the analysed tasks being the closest and most explicitly related to the thermal exhaust ports, and thus of proximal interest to the vulnerability actually exploited in the film, the HE-HAZOP did not identify it. Indeed, it will be noted that one of the design improvements was to increase the size of the thermal exhaust port. On the plus side, the method came close by referring to unwanted matter (such as debris) that could enter the thermal exhaust port and the possible benefits to be accrued by fitting a grate over it. It also enabled the participants to construct rich narratives about how the system could fail, and all were surprised at where the method took them in terms of their previous understandings of the system. Comments from the SMEs suggested that the HE-HAZOP, unsurprisingly, foregrounded technical risks: "more focussed on the build-up of heat." The participants also noted that the method was challenging and "not easy" but it did make "you thorough and detailed".

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Table 3 – HE-HAZOP Analysis of Task Step 2.1.1.5: Expel Excess Energy

Task Step	Guide-word	Error	Consequence	Cause	Recovery	Design Improvements
Expel excess energy	Less than	Amazing it works in the first place. Giant amount of energy.	Kill's 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 on exhaust port and source of radiation. Blow up more planets to test function. More test firing. Learn lessons/data from smaller guns on star destroyer. **Make port bigger 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 thermal exhaust. Cooling/extractor fans. **Put a grate over the port.** Re-route flows to other exhaust ports
	Other than	n/a	n/a	n/a	n/a	n/a
	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.	Over zealous with the super laser. Over use of the weapon creates too much thermal energy/radiation – needs a cool down period.	Stop over using it. Full shut down. Re-boot Death Star	Designated cool down period (procedural change). Back up for life support.
	Sooner than	Poor control.	Wasting energy and output.	Lack of sensing capability.	Human (alien) intervention of some sort	Better monitoring system. Control room improvements. Improve SCADA system. Improve operator vigilance. Diagnostic capability via remote desktop or similar technology.
	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.			
	Misordered	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 re boot.	Mechanical/system interlock. Automatic fail safes.

Table 4 – 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		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 generator. Life support at risk.	Delays in monitoring system – not in real time.		Safe zone – system optimization. Engineered level.
	Later than			Other warnings and control room ergonomics. Other demands and priorities. Workload and teamworking. Under staffing.		
	Mis-ordered	Distraction, concurrent demands, operator forgets what they are doing, error of commission.				Liason between forcefield and exhaust port monitoring teams. Get the droids to do it…but don't trust them completely.
	Part of					

Results Part 2: Work Domain Analysis of the Death Star

Work Domain Analysis (WDA) is a component of Cognitive Work Analysis (CWA), a larger analysis framework comprised of multiple methods (Vincente, 1999). The CWA framework is used to provide a description of the constraints which shape behaviour within a given domain. Unlike HTA and HE-HAZOP, which are normative descriptions of a system, CWA is formative: the constraints shape all possible behaviour within the system rather than script those that are observed to take place and/or designed to take place. This constraints-based approach can be used to address specific research and design aims, including an exploration of all the affordances or possibilities for action contained in a system, and indeed, the possible ways in which it could fail. The following steps from Stanton et al (2013) were performed in order to deliver the required analysis outputs. As before, the group facilitator guided the participants through the analysis and reminded them of the critical vulnerability to be detected:

Step 1: Define the Nature of Analysis

The first step in a CWA is to clearly define the purpose of the analysis. In this case the analysis is designed to provide the optimum chance to discover the Death Star's critical vulnerability which led to its destruction.

Step 2: Select Appropriate CWA Phases and Methods

Having defined the analysis purpose, the most appropriate phase of the CWA framework was selected. In this case it was the first phase, Work Domain Analysis (WDA). This enabled the required focus on functions and their interconnections, and the ability to visualise affordances between low level physical objects (such as thermal exhaust ports) and higher level functional purposes (such as ruling the galaxy unchallenged).

Step 3: Work Domain Analysis (WDA)

WDA provides a description of the constraints that govern the purpose and function of the system under analysis. The analysis is not specific to any particular technology: WDA seeks to represent the entire domain. The top three levels of the WDA consider the overall objectives of the domain, and what it can achieve, whereas the bottom two levels concentrate on the physical components and their affordances. Through a series of 'means-ends' links it is possible to model how individual components impact on the overall domain purpose. The WDA is constructed by considering the work system's objectives (top-down) and the work system's capabilities (bottom-up). The WDA was constructed using the same materials employed to construct the other analyses (e.g. Windham et al., 2013). This involved reviewing the document in depth and highlighting system functions that could later be extracted and categorised into the different levels of abstraction. To aid this process Naikar's (2013) WDA prompts were used. Extracts of the completed WDA analysis are shown in Figure 4. It comprises 115 functional nodes and 354 means-ends links. One analyst led the production of the WDA, with two others providing technical oversight and review over several iterations. The functional purposes of the Death Star, as defined by the source documents, are as follows:

- To present the galaxy with a powerful symbol
- Subjugate worlds
- Enable the galaxy to be ruled unchallenged
- Enact the Tarkin Doctine 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 superlaser'. As noted above, WDA is technologically agnostic and all of these functions and priority measures could potentially be achieved with a wide variety of technical means. As it is, the Death Star combines a wide range of specific Physical Objects such as Phylon Q7 tractor beam projectors, Taim & Bak xx-9 heavy turbo laser towers, the main power generator, the quandenium steel armoured hull and, of course, the thermal exhaust ports, in the service of these functions.

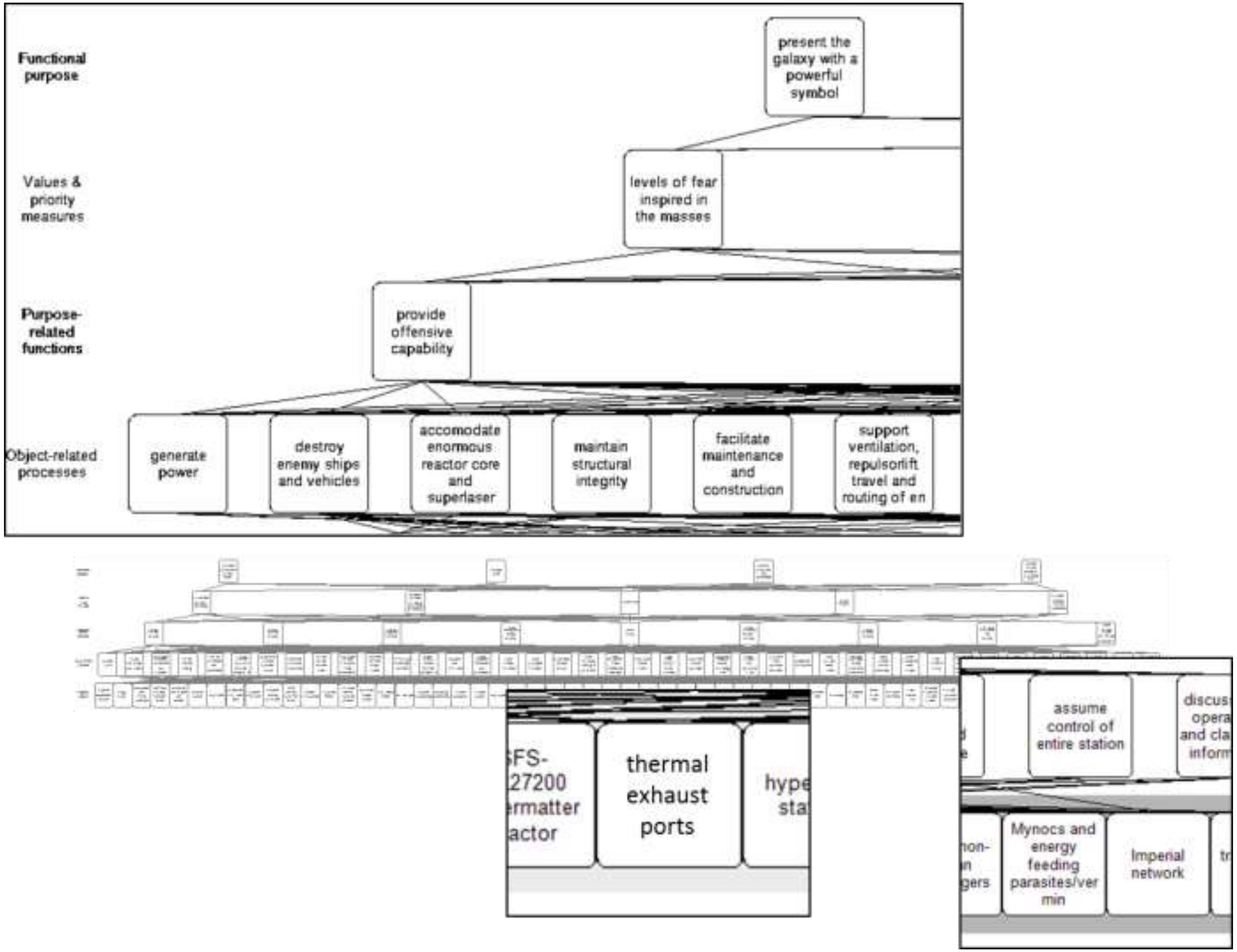

Figure 4 – Extract of the Work Domain Analysis (WDA) of the DS-1 Orbital Battle Station

Key Findings from the WDA Analysis

The two Death Star SMEs used in the HE-HAZOP analysis were also employed in the WDA validation and insight extraction process. This occurred after the HE-HAZOP analysis had been completed, yet they possessed equal awareness of the critical vulnerability to be detected and thus were not unfairly biased in favour of one or the other method. The first phase of the analysis was to scrutinise the complete WDA and identify any missing elements or links. Both SMEs were satisfied that the WDA contained all relevant components. The next phase of the workshop invited the SMEs to trace through the WDA, examining functions and 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, despite numerous of these already having already emerged from the HE HAZOP method. The participants judged the WDA as being less good compared to HE-HAZOP in terms of “fine detail” but was better at “providing a good overview”, “better for strategizing” and perhaps most importantly, “a lot quicker”. The WDA took a similar amount of time to develop as the HTA, requiring approximately 10 hours input by the lead authors, and a further two hours for the SMEs to validate and use to generate outputs. This is a total of 12 hours or 1.5 working days compared to 10.5 days required to run the HE-HAZOP analysis. It is important to remember that the WDA is a representation of the entire system, and it took comparable time to analyse the entire system as it took to analyse just two out of 160+ tasks using HE-HAZOP. Not only was it significantly quicker but it also succeeded in detecting the actual vulnerability, 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 latter vulnerability informed the narrative in the 1994 film ‘Independence Day’, but of course the first such virus was released into the wild in 1983 and so was not available for use in the original 1977 Star Wars. Nevertheless, despite not existing the ‘possibility for action’ is still present in the WDA and available for scrutiny. In summary the outputs of the analyses, combined with the time it took for both to be completed, suggest that Relative Predictive Efficiency for the WDA was higher than the comparable HE-HAZOP analysis in this case. This can be established a little more formally as follows.

Calculation of Relative Predictive Efficiency

As noted above, a crude approximation of Relative Predictive Efficiency (RPE) can be derived from proxy measures of system entropy and complexity. Complexity can be accessed using metrics from complexity theory, such as the number of build symbols, grammar size and the connectivity inherent in the models of the system (i.e. the HTA used to drive the HE-HAZOP, and the WDA itself). Entropy, or the extent to which the models of the system provided explanations for all attendant facts, can be measured in a simple and crude way by ascribing a binary value to the extent to which the method achieved its aim of detecting the critical vulnerability (1 for yes and 0 for no). This is a very simplistic interpretation of the RPE concept, but both methods in the study are being judged equally on these terms. It is clear that when applied to the problem of destroying a Death Star with a proton torpedo fired into a thermal exhaust port at close range by a strongly asymmetric force, that WDA has higher predictive efficiency. It could also be completed well within the time available. It is thus the method recommended to the Rebel Alliance should the need arise to destroy (yet) another Death Star, and to the Imperial Empire should a more resilient and jointly optimised Death Star become necessary in future. This may or may not require grates to be fitted over all thermal exhaust ports.

Table 5 – Calculation of Relative Predictive Efficiency for the underlying models of the Death Star (HTA and WDA) and the extent to which they succeeded in detecting the critical vulnerability. A value of RPE=1 indicates the most parsimonious model of a system that provides explanations for all attendant facts. A value of 0 indicates a complex model that nonetheless does not detect the target feature(s) of interest.

		Complexity		Entropy		RPE	
Complexity Metric	Description	HTA	WDA	HTA	WDA	HTA	WDA
Number of Build Symbols	The number of tasks (HTA) or functions (WDA) which produce the overall goal/high level function.	161	115	0	1	0	0.009
Grammar Size	The total number of logical operators (e.g. IF, THEN, AND, OR) that are used in the HTA* plans in order to generate the overall goal, or the link types in the WDA**	6*	1**			0	1
Connectivity	The number of edges/links that hold the system model together.	170	354			0	0.003
Height	The maximum number of links between HTA sub-goals/ WDA functions from the bottom to the top of the analysis.	7	5			0	0.2

* This value denotes the main plan types in the HTA which were Linear (THEN), Non-Linear (ANY ORDER), Simultaneous (AND), Branching (IF THEN), Cyclical (REPEAT UNTIL) and Selection (OR)

** This value denotes the linkage type in the WDA, which are all identical means-ends links of the form 'how-what-why'

Conclusions

The aim of analysing the Death Star from the film franchise Star Wars is not to trivialise the issue of selecting optimum ergonomics methods. 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 to professionals. Systems thinking is a core part of the ergonomic offer and it is likewise becoming a core topic in other disciplines too. Novel approaches to bridging these gaps and demonstrating value are to be welcomed and encouraged, especially in view of the relatively poor uptake of ergonomic ideas that has long been concerning the discipline. Indeed, novel and unusual approaches for communicating ergonomic ideas would not be needed if existing strategies were fully effective. Sadly they are not. With these caveats in place we can move on to the substance of the paper, which is that not enough thought is currently given to the selection of ergonomic methods, as this amusing case study illustrates very well.

Did ergonomics methods detect the critical vulnerability in the Death Star that was portrayed in the 1977 film Star Wars? In the case of HE-HAZOP, a method contemporaneous with the film's release and still in widespread use to this day: no. The component-level analysis provided by HE-HAZOP revealed a very large quantity of potential system failings and human-error potential, but none of these component risks related strongly to the actual risks exploited in the film. The infamous Thermal Exhaust Port, down which proton torpedoes were fired leading to the battle station's complete destruction, activated very few HE-HAZOP guidewords, certainly far fewer than other system components. This was despite the participants being guided explicitly on how to apply these methods strictly 'by the book', and reminded continuously of the actual vulnerability to be detected. Under these most favourable of conditions the HE-HAZOP was well able to predict that the Thermal Exhaust Port might fail or expel too much or too little heat, however, it could not predict the proton torpedo strike or the knock-on effects of this at higher levels of the system. Indeed, given what we know about the film, a design recommendation put forward by the HE-HAZOP approach to increase the size of the exhaust port is surprising and highly paradoxical. The second fundamental problem was the time needed to complete the analysis which, in the current demonstration, far exceeded the time available between the Death Star plans being received and the Death Star itself arriving over the fourth moon of the planet Yavin ready to destroy the rebel base it hosted. In other words, to complete a detailed HTA and HE-HAZOP of the size and complexity needed for the Death Star would have place the Rebel Alliance at critical risk of destruction. From a Health and Safety point of view this is clearly unacceptable. The third fundamental problem – the most fundamental of all – is that because of all the above 'Excess Entropy' was high and Relative Predictive Efficiency low. The HE-HAZOP analysis, in this application, was large and complex yet for all that did not succeed in detecting the critical vulnerability.

The Work Domain Analysis, on the other hand, did detect the actual film ending. There were explicit and uncontroversial affordances between the Thermal Exhaust Port and Object-Related Processes around 'accommodating the enormous reactor core and super-laser', 'generate power' and 'expel excess heat and radiation'. These in turn were linked to key Death Star capabilities such as 'provide offensive and defensive capability' and 'energy and propulsion'. These in turn directly affected all of the higher-level Functional Purposes. A graphical depiction of these functional interconnections would certainly lead an astute Rebel planner to the conclusion that degrading these links would have a significant impact on the Death Star's functioning. The SMEs in the present study did exactly that. Surprisingly, given the criticism often rounded on CWA/WDA for its time consuming nature, the method was relatively quick. Not only was there time to consider the critical vulnerability already known about from the film, but numerous others also emerged. The critical point here is that the constraints and affordances are present and observable in the system, and if analysts are not able to explore them for all conceivable eventualities there exist other methods, such as the Strategies Analysis Diagram (Cornelissen , 2014), which will perform this function in an exhaustive and systematic manner. Potentially, every pathway to failure, and indeed success, can be elicited. As demonstrated here, techniques like these apply to civil engineering systems of all shapes and sizes.

What this comparison of methods illustrates is the fundamental role of scale, variety and predictive efficiency in making contingent decisions about what 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 paper 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. Considerations of variety, scale and predictive efficiency are tractable means to think afresh about sociotechnical problems and direct our analysis efforts in cost-effective ways. May The Force (of this contingent approach to Ergonomics method selection) be with you…

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