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RISK MANAGEMENT IN THE PETROCHEMICAL INDUSTRY – A GAME THEORETIC ANALYSIS

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Nomenclature

Abbreviations

ALARP	As low as reasonably practicable
API	American Petroleum Institute
C	Contractors
CEO	Chief Executive Officer
DB	Direct Benefit
DC	Direct Costs
FACTS	Failure and Accidents Technical information System
GET	Generative Equilibrium Threshold
GBP	Great Britain Pound
HFIP	Human Factor Incident Percentage
HSE	Health, Safety and Environment
HSE MS	Health, Safety and Environment Management System
LTI	Lost Time Injury
LTIF	Lost Time Injury Frequency
LSR	Life-Saving Rule
LWDC	Lost Work Day Case
M	Management
MARS	Major Accident Reporting System
MS	Management System
MTC	Medical Treatment Case
N	Nature
NAICS	North American Industry Classification System
OES	Occupational Employment Statistics

OGP	Oil and Gas Producers
PC	Petrochemical Company
PORT	Petrochemical Organisation Risk Triangle
QF	Qualitative Factor
RAM	Risk Assessment Matrix
RET	Reactive Equilibrium Threshold
RMP	Risk Management Programme/Process
RWDC	Restricted Work Day Case
S	Staff members
SCM	Swiss Cheese Model
TDB	Total Direct Benefit
TDC	Total Direct Cost
TOC	Total Operating Costs
TQF	Total Qualitative Factor
TRIR	Total Recordable Injury Rate
W	Workforce

Roman symbols

1	Player 1 in game models, i.e., W
2	Player 2 in game models, i.e., M
a	Intermediate parameter in comparative statics analysis
a_{ij}	Payoff parameters for W
b	Y-intercept / intermediate parameter in comparative statics analysis
b_{ij}	Payoff parameters for M
A_1	Intermediate parameter in equilibrium calculation for W
A_2	Intermediate parameter in equilibrium calculation for M
B_1	Intermediate parameter in equilibrium calculation for W
B_1	Intermediate parameter in equilibrium calculation for M

B_j	Benefit parameters
B_C	Benefits of clean safety record for W
B_D	Benefits of documented clean safety record for W
B_E	Benefits of enforcing safety procedures for M
B_G	Benefits of good safety performance for M
B_S	Benefits of safety commitment for M
B_V	Benefits of violation for W
c	Intermediate parameter in comparative statics analysis
C_1	Intermediate parameter in equilibrium calculation for W
C_2	Intermediate parameter in equilibrium calculation for M
C_E	Costs of enforcement for M
C_H	Costs for handling of rule violations for M
C_i	Cost parameters
C_{I1}	Incident costs for W
C_{I2}	Incident costs for M
C_P	Costs of punishment for W
D_1	Intermediate parameter in equilibrium calculation for W
D_2	Intermediate parameter in equilibrium calculation for M
e	Enforce
E_1	Intermediate parameter in equilibrium calculation for W
E_2	Intermediate parameter in equilibrium calculation for M
F_1	Intermediate parameter in equilibrium calculation for W
F_2	Intermediate parameter in equilibrium calculation for M
I	Incident
L_2	Intermediate parameter in equilibrium calculation for M
m	Slope
M_2	Intermediate parameter in equilibrium calculation for M

ne	Not enforce
N_2	Intermediate parameter in equilibrium calculation for M
NI	No incident
nv	Not violate
p(I)	A priori probability that an incident occurs
p(NI)	A priori probability that no incident occurs
$p(v \mid I)$	Probability of violation in case an incident has occurred
$p(v \mid NI)$	Probability of violation in case an incident has not occurred
$p(nv \mid I)$	Probability of compliance in case an incident has occurred
$p(nv \mid NI)$	Probability of compliance in case an incident has not occurred
P_i	Points in graphical representation of PORT
Q_2	Intermediate parameter in equilibrium calculation for M
r_v	Incident probability in case of violation
r_{nv}	Incident probability in case of no violation
R_2	Intermediate parameter in equilibrium calculation for M
v	Violate
X	Reactive equilibrium threshold
Y	Generative equilibrium threshold

Greek symbols

α	Violation probability for W
α^*	Equilibrium violation probability for W
β	Enforcement probability in case of an incident for M
β^*	Equilibrium enforcement probability in case of an incident for M
γ	Enforcement probability in case of no incident for M
γ^*	Equilibrium enforcement probability in case of no incident for M
Γ_1	Simultaneous game model

$\hat{\Gamma}_1$	Simultaneous game model with increased punishment
$\tilde{\Gamma}_1$	Simultaneous game model with increased management commitment
$\breve{\Gamma}_1$	Simultaneous game model with contractor safety
Γ_2	Sequential game model
$\hat{\Gamma}_2$	Sequential game model with increased punishment
$\tilde{\Gamma}_2$	Sequential game model with increased management commitment
$\breve{\Gamma}_2$	Sequential game model with contractor safety
$\widehat{\Gamma}_2$	Sequential game model with improved safety standard
π_1^*	Equilibrium payoff for W
π_2^*	Equilibrium payoff for M

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1 Introduction

> *"But the problems he (the physicist) is studying are simple compared to those of the risk manager, because the clouds do not react to what the weatherman or physicist says about them."* (Adams, 2007, p. 10)

The above citation describes the key problem of modern risk management within the petrochemical industry. Despite how sophisticated technical solutions and risk mitigation measures have become, the "human factor" remains as unpredictable as ever.[1] Recognising this irrevocable truth is therefore the first step in creating successful risk management strategies,[2] especially if one considers that the term "human factor" is not limited to the shortcomings of "misguided" individuals; it includes entire organisations and, in particular, the managers in charge.[3]

With this consideration in mind, it is obvious why risk management in the petrochemical industry has been widely criticised in recent years. Several major accidents, such as the "Deepwater Horizon" oil spill in 2010 and the "Texas City" refinery explosion in 2005, have caused severe consequences for people and the environment. In the case of the "Deepwater Horizon" explosion and its subsequent oil spill, eleven offshore workers lost their lives, and cleaning the coastal areas in the Gulf of Mexico will take decades and require billions of dollars. Furthermore, independent accident investigations have identified and disclosed various organisational shortcomings as the root causes of these accidents.[4]

Although the public debate about petrochemical risk management often lacks a sense of objectivity and disregards the industry's considerable safety achievements over the past

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1. See Hudson, van der Graaf, and Bryden (1998, p. 1) or Smith & Zijker (2005, p. 6).
2. See Flin, O'Connor, and Bryden (2000, p. 177).
3. See Celati (2004, p. xi), Hudson (1992, p. 52), Knegtering & Pasman (2009, p. 164) or Sneddon et al. (2005, p. 2).
4. See, for example, Baker III et al. (2007, p. xii) or National Commission on the BP Deepwater Horizon (2011, pp. 223–224).

few decades,[5] it must be acknowledged that petrochemical risk management offers room for improvement, especially in the incorporation of human interactions into decision-making processes. Only the risk manager who is capable of understanding these complex interactions will be able to lead an organisation towards a safer and more profitable future.

> *"Modern safety research has shown that the interaction between 'human', 'technical' and 'organisational' factors determine the performance of a company, not only in terms of quality, cost, and delivery time, but also in terms of safety … ."* (Sonnemans & Körvers, 2006, p. 2)

It is exactly in this area, the incorporation of human interactions into management decision-making processes, that this thesis breaks new ground. For the first time, the complex human interactions within the petrochemical industry were studied using game theoretic methods. This approach allowed a considerable reduction of complexity and led to the development of an easily understandable graphical management decision-making tool, the "Petrochemical Organisation Risk Triangle" (PORT). The thesis draws its uniqueness from the strong conceptual approach behind the PORT. The human interactions in a petrochemical operation are defined in an easily understandable manner, and, even more importantly, working mechanisms and improvement potential can be identified in an analytical way.

In contrast to similar management tools, such as the "Balanced Scorecard",[6] the PORT is based on a solid mathematical foundation, i.e., a game theoretic model. This model was developed from a close observation of reality and specifically describes the interaction between management and the workforce in an archetypal petrochemical operation. In this sense, the thesis differs from many other game theoretic studies that emphasise model mathematics rather than model applicability.[7] Hereafter, the journey towards development of the PORT will be outlined.[8]

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5 Accident rates decreased by almost 90% from 1985 to 1999; see Hudson (2001).

6 See Kaplan & Norton (1992).

7 See, for example, Berentsen, Brügger, and Lörtscher (2008), Morris & Shin (2003) or Ting (2008).

8 To facilitate quick reading of this thesis, every chapter closes with concluding remarks.

In the first chapter, the prevailing definitions, objectives and challenges of risk management, both generally and within the petrochemical industry, will be presented. Modern risk management within the petrochemical industry is mostly concerned with Health, Safety and Environmental (HSE) risks. Furthermore, the petrochemical risk management approach already involves a strong focus on human factors and behavioural risks based on the key findings of accident research. The culminating point of this research, and therefore one of the fundamental principles of petrochemical risk management, is the "safety culture" concept. This concept assumes that there are several stages of organisational maturity in terms of safety and that an organisation evolves over time, i.e., climbs the "safety ladder", if it is properly managed.[9] This assumption is strongly motivated by the field of behavioural economics.[10] Although the safety culture concept itself will not be questioned in the course of this thesis, it will be shown that the concept is not exempt from certain challenges and criticism. It is argued that the underlying behavioural economics are currently a "black box" providing no clear analytical guidelines for petrochemical managers on how to improve their risk management practices and organisational safety culture.

This obvious gap will be closed in the following chapter, which can be considered the essential contribution of the thesis to petrochemical risk management research. The black box of behavioural economics will be structured by means of an analytical mathematical language, i.e., game theory. This approach is unique in the petrochemical industry. It is motivated by game theory's ability to reduce the complexity of interactive behavioural situations and to visualise them in an easily understandable manner.

First, based on the interactions in case of rule violations between management and the workforce in a petrochemical operation, a payoff structure will be derived from the author's experience.[11] This structure reduces the complex interaction between both "players" to simple costs and benefits. Based on the developed payoff structure, an initial game theoretic model Γ_1 is created. The model assumes that the interaction takes place

9 Briefly, an organisation with a weak safety culture will experience many accidents, whereas an organisation with a strong safety culture will experience few accidents. An excellent summary of the safety culture concept is provided by Baram & Schoebel (2007). Also see Hudson (2001) or Wiegmann, Zhang, von Thaden, Sharma, and Mitchell Gibbons (2004). The idea of a safety culture was first introduced by Reason (1990).

10 See Battmann & Klumb (1993).

11 The author has spent more than five years working as an engineer in various roles in a petrochemical refinery of a multinational oil company.

as a single-stage simultaneous game.[12] It will be demonstrated that, interestingly, precise recommendations for the improvement of risk management practices and, therefore, the organisation's safety culture can be derived from the analysis of this very simple game model Γ_1. Nevertheless, the model is not exempt from criticism; several realistic effects have been neglected. For example, neither accident risks nor the sequential nature of the interaction between management and the workforce is incorporated.

Hence, a new and more sophisticated game model Γ_2 is developed. This model includes accident risks and, due to its sequential game structure, reflects the fact that management reacts to the workforce's behaviour and adapts its risk management practices accordingly.[13] The most innovative aspect of game model Γ_2 is that the underlying equations can be transformed into an easily understandable graphical model of an organisation's safety culture, the above-mentioned PORT decision-making tool. Based on PORT, detailed recommendations for the improvement of an organisation's safety culture can be made. Furthermore, different risk management practices can be evaluated in terms of their effectiveness. In summary, the assumption that a higher-level safety culture results in various organisational benefits is largely supported. Risk management costs can not only be reduced, but increased benefits will also be experienced by management and the workforce.

In the last chapter, the road towards industrial application of the PORT will be presented. Thus far, the PORT and its underlying game theoretic model have exclusively relied on a theoretic payoff structure. It is only logical that bringing the tool closer to industrial application requires using "real-life" data. Consequently, various petrochemical data sources were investigated, and, by means of a simple yet tangible cost-benefit analysis, a payoff structure was developed that represents an archetypal petrochemical operation. Together with the required human reliability data, the PORT is capable of evaluating different risk management strategies in terms of their monetary outcomes. It will be demonstrated that the practical results obtained from entering industrial data into the PORT support the theoretical findings from the previous chapter.

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[12] In this game, both players (management and workforce) choose their strategies simultaneously without knowing which strategy their "opponent" has chosen. For more information on the various game theoretic models, see Aliprantis & Chakrabarti (2000), Fudenberg & Tirole (2005), Holler & Illing (2009) or Rieck (2006).

[13] In a sequential game, one player moves first, and the other can observe this move and then choose his strategy. Examples of sequential games can be found in Aliprantis and Chakrabarti (2000), Fudenberg and Tirole (2005), Holler and Illing (2009) or Rieck (2006).

Despite this considerable achievement, it must be noted that both game models Γ_1 and Γ_2 (and thus the PORT) are only an approximation of reality and offer room for future research. For example, more sophisticated game theoretic methods such as repeated interaction,[14] inspector leadership[15] and experimental methods[16] have not been included in the two game models. Furthermore, the game model's cost and benefit structure is still very basic and requires additional economic expertise for its future development.

Nevertheless, the PORT and its underlying game model Γ_2 can be considered the cornerstones of future game theoretic research on the subject of petrochemical risk management. To the best of the author's knowledge, this thesis is the first of its type within the petrochemical industry. Therefore, a strong conceptual approach has been taken. In the author's opinion, it was legitimate to apply only two basic game theoretic models. The analysis focussed on the concept rather than its technical finesse.

At the moment, only the PORT is capable of presenting an integrated view of human interaction and the associated behavioural risks in the petrochemical industry in an easily understandable manner while providing precise guidelines for managers on how to improve their risk management practices.

The key finding of this research is that petrochemical managers should not be deceived by declining accident numbers. The "Deepwater Horizon" incident has demonstrated once again that, without a proper safety culture, disasters will occur. As a consequence, there is a simple advice for petrochemical managers: "Know your organisation's accident numbers, know its safety culture, and use the PORT to improve your risk management practices." Only such an integrated approach will lead to a safer and more profitable future.

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14 See, for example, Andreozzi (2010), Franckx (2001b) or Rothenstein & Zamir (2002).

15 See, for example, Andreozzi (2004), Avenhaus, Okada, and Zamir (1991), Brams & Kilgour (1992) or Rinderle (1996). A similar model can be found in Franckx (2001a).

16 See, for example, Potters & van Winden (1996) or Rauhut (2009).

2 Risk management

2.1 Definition, objectives and challenges

> *"This decision-making process, and nothing else, is the truest form of risk management. In fact, the strict meaning of the word management involves a decision."* (Celati, 2004, p. 165)

In the passage above, Celati provides an excellent starting point for the analysis of risk management within the petrochemical industry. Although his argument that risk management is merely a decision-making process might seem to be oversimplifying at first, it is in fact this stunning simplicity that allows for valuable insights into the various challenges of modern risk management.

It will be pointed out in this thesis that every decision-making process across all industries involves human interaction. Thus, only the risk manager who understands this interaction and the associated risks will be able to make an informed decision when choosing the appropriate risk management strategy.

Before further defining the concept of risk management in this context, it is essential to first develop a common understanding of the term "risk" itself. Developing this common understanding is essential because the definition of risk compromises multiple facets and strongly depends on the individual perspective.[17] Furthermore, it is widely acknowledged that risk can be conceptualised from many different perspectives, including technical, economic and psychological points of view.[18] The resulting risk categories in each of these disciplines are thus extraordinarily versatile, and interference be-

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17 See, for example, Bieta, Kirchhoff, Milde, Siebe, and Walter (2004, p. 32) or Rejda (1998, p. 5).

18 An extensive overview of the various concepts is provided by Glendon, Clarke, and McKenna (2006, pp. 15–66). A short but very comprehensive summary can be found in Aven & Vinnem (2007, pp. 20–23).

tween the different categories is not uncommon.[19] The image of a "galaxy of risks" is therefore often used to refer to this high degree of complexity.[20]

Leaving these sophisticated risk definitions aside, an intuitive understanding of risk can be demonstrated by means of a simple example:

Would you run a red light? If you decide to run a red light, it is uncertain whether an accident will occur. An accident is therefore an event of coincidence. If an accident occurs, the possible consequences are manifold, ranging from a simple "fender bender" to multiple fatalities. However, if no accident occurs, you will reach your destination faster and will benefit from the choice not to stop. With this information in mind, would you now take the risk of running a red light?

In the author's opinion, the example reveals the two decisive elements of risk. On one hand, risk refers to the combination of the *probability* and *consequence* of an uncertain future event.[21] On the other hand, risk is equally associated with potential *negative* and *positive* outcomes.

By including both downside and upside risks, the author adopts a broad risk definition that differs from the prevailing public opinion and contrasts with the exclusive association of risk with negative consequences.[22] This broad definition of risk has gained increasing interest in recent years across a broad range of industries and has been employed in several industry documents.[23]

The nature of risk in the petrochemical industry and the fact that upside and downside risks are intrinsically tied to each other can be seen from the following practical example:

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19 For risk categorisations in economics and finance, see, for example, Crouhy, Galai, and Mark (2001, p. 35), Das (2006, p. 5) or Jorion (2007, p. 516). For risk categorisations in an industrial and technical context, see, for example, Brühwiler (2003, p. 44), Reason (1997, pp. 226–227) or Tweeddale (2003, pp. 9–10). An extensive checklist for uncovering risks in an industrial organisation is provided by Hessian & Rubin (1991, pp. 33–46).

20 See Jorion (2007, p. 516).

21 It must be mentioned that the author adopts the point of view of Aven and Vinnem (2007, p. 21) and acknowledges that, in this context, the term "probability" is considered not only in a purely statistical sense but also as a measure of uncertainty.

22 According to Milde (1992, p. 314), the public exclusively associates the term "risk" with loss, while profits are neglected. In economics and finance, the predominance of loss in the context of risk is stated, for example, in Einhaus (2002, p. 489) or Oehler & Unser (2002, p. 21). In the technical field, the predominance becomes visible in Brühwiler (2003, p. 30) or Sutton (2007, p. 10).

23 See International Organization for Standardization (2009b, p. 1-2) or AIRMIC, ALARM, and IRM (2002, p. 2).

Assume that a pipe work flange within a process unit is leaking. The substance leaking from a flange, e.g., liquefied petroleum gas, is highly flammable, and the unit manager has two options: he could either shut down the unit and safely repair the flange after the unit has been cleared of the flammable substance, or he could perform an online repair while the unit remains in operation and the substance continues to leak. A possible downside risk in both cases is that, after having shut down the unit or while performing an online repair, the presence of an ignition source could cause the vapour cloud to explode and thus lead to severe damage, injuries and even death or the complete destruction of the unit. The upside risk, however, is that the leak could stop by itself in both cases (e.g., due to ice formation on the leak when the liquefied petroleum gas is depressurised).

This example illustrates the typical dilemma of petrochemical risk management. Serious downside and upside risks must be balanced, and the conflict between safety and production must be resolved.[24] The main constraints for achieving profitable and competitive production are risks to health, safety and the environment (HSE).[25] Furthermore, these HSE risks do not only need to be managed; to be competitive, sometimes calculated risks have to be taken. This idea is highlighted by the statement, "*Risks do not simply exist, they are taken, run, or imposed … .*"[26]

Due to the hazardousness and complexity of petrochemical production processes,[27] a conscious risk management approach is required. Although there are numerous definitions of risk management,[28] (Aven & Vinnem, 2007) provide a very comprehensive definition that is specifically tailored to the petrochemical industry:

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24 For information on the conflict of safety and production in the petrochemical industry, see Battmann and Klumb (1993, p. 39), Lawton (1998, p. 89) or Hudson (1992, p. 55).

25 See Duijm, Fiévez, Gerbec, Hauptmanns, and Konstandinidou (2008, p. 909).

26 Glendon, et al. (2006, p. 19).

27 See Sneddon, et al. (2005, p. 2) or Wolf (2002, p. 103). The extraction of gasoline and other chemical products (ethylene, benzene etc.) from crude oil is only made possible by high temperatures, high pressures and chemical reactions. In addition, the production processes create dangerous by-products (e.g., H_2S - hydrogen sulphide). For more information on the production processes of a typical petroleum refinery, see Favennec & Baker (2001, pp. 117–133), Mineralölwirtschaftsverband e.V. (2003, pp. 21–35) or United States Environmental Protection Agency (1996, pp. 5–8). For a detailed risk analysis of chemical substances, see Martel (2004).

28 See, for example, Brühwiler (2003, p. 31), International Organization for Standardization (2009a, p. 7-8), Rejda (1998, p. 40) or Thome & Pauli (2006, p. 1).

> *"The purpose of risk management is to ensure that adequate measures are taken to protect people, the environment and assets from harmful consequences of the activities being undertaken, as well as balancing different concerns, in particular HES (Health, Environment and Safety) and costs. Risk management includes measures both to avoid occurrence of hazards and reduce their potential harms."* (Aven & Vinnem, 2007, p. 1)

Besides its emphasis on risk prevention, this definition also introduces costs and benefits to the risk management equation. However, risk management must not be designed to prevent every imaginable risk. Rather, a balanced approach that allows for safe and profitable operations should be taken. Such a risk management approach can best be summarised by the acronym "ALARP", which stands for "As Low As Reasonably Practicable".[29] It implies that the risks should be compared with their corresponding mitigation costs and that, following this analysis, they should be reduced to a reasonably low level.

In line with this concept, risk management must be a structured, continuous process of managing risks.[30] It should create value, be an integral part of the organisation, be a management responsibility[31] and take into account human factors.[32] Its main objective is *"... to add maximum sustainable value to all the activities of the organisation."*[33]

The suggested core steps of such a structured, continuous risk management process (RMP) are depicted in Figure 2.1. They consist of risk identification, risk analysis, risk evaluation, risk treatment and risk monitoring.[34]

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29 For more information on ALARP, see Health and Safety Executive (2010), Kletz (2003, p. 63) or Sutton (2007, pp. 34–36).

30 Also see Thome and Pauli (2006, p. 1).

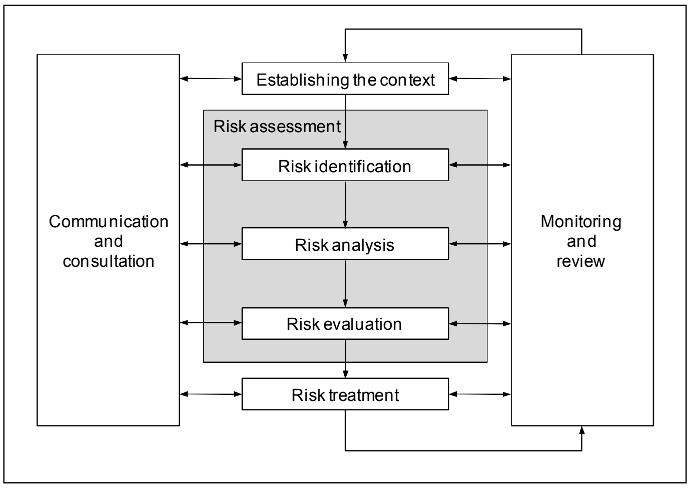
31 See, for example, Brühwiler (2003, p. 19) or AIRMIC, et al. (2002, p. 2).

32 An integration of human factors into RMPs is, for example, postulated in Glendon, et al. (2006, p. 356).

33 AIRMIC, et al. (2002, p. 2).

34 Also see Andersen (2007, p. 37), Brühwiler (2003, p. 159) or AIRMIC, et al. (2002, p. 4).

Figure 2.1: Risk Management Process (RMP)



Adapted from (International Organization for Standardization, 2009a, p. 14)

These steps are essential to every modern RMP and have largely been implemented in the petrochemical industry on an industry-wide basis.[35] Although the RMP might appear to be a straightforward exercise, it is often tested by the people working in the organisation. They react to their environment, constantly adapt their decisions and are influenced by the human factor.[36] Behavioural risks are thus present at all times,[37] and they are very difficult to assess, manage and foresee.[38] They pose a considerable challenge to petrochemical risk management.

Compared to other disciplines such as economics or finance,[39] the petrochemical industry recognised much earlier the pivotal importance of the human factor due to hard lessons learned from several major accidents in the past fifty years.[40] Risk management in the petrochemical industry has thus been strongly influenced by the findings of accident research and has continually evolved over the past fifty years.

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35 For similar RMPs within the petrochemical/process industry, see, for example, Myers, Cramer, and Hessian (1991, pp. 1–6), Sutton (2007, p. 42) or Tweeddale (2003, p. 12). In Aven and Vinnem (2007, pp. 77–89), a detailed risk framework for decision support in the petrochemical industry is described. The risk management approach of a large multinational oil company is described in Hudson (2001, p. 7).

36 See Adams (2007, p. 10), Celati (2004, p. 5) or Morris & Shin (1999, p. 64).

37 See Bieta, Broll, and Siebe (2006, p. 16), Celati (2004, p. 34) or Milde (2004, p. 671).

38 See Andersen (2007, p. 36), Bernard & Bieta (2007, p. 48) or Sutton (2007, p. 221).

39 In economics and finance, most RMPs are characterised by a strong preoccupation with event risks; see, for example, Brealey, Myers, and Allen (2006, p. 180), Brühwiler (2003, p. 75) or Otto (2003). Behavioural risks have long been neglected, and this neglect has been heavily criticised by authors such as Bieta & Milde (2005), Erben (2004), Spremann (2002) and Stulz (1996). Due to the events of the 2008-2010 world financial crises, the concept of behavioural risks now seems to have gained increasing importance in the world of economics and finance.

40 The importance of the human factor in the petrochemical industry is emphasised, for example, in Hudson (1992, p. 55) and Smith and Zijker (2005, p. 6).

2.2 Accident research

In the previous section, risks and risk management were discussed on a rather abstract level, including upside and downside risks. It was pointed out that risk management in the petrochemical industry has been influenced mainly by accident research over the past fifty years. An accident is the materialisation of a downside risk.[41] It is defined as a "*... short, sudden, and unexpected event or occurrence that results in an unwanted and undesirable outcome. The short, sudden and unexpected event must directly or indirectly be the result of human activity ... .*"[42] The following chapter will focus on the impact that accident research has had on the RMP in the petrochemical industry.

Due to the complex nature of manufacturing processes in the petrochemical industry, in most cases, accidents have led to serious, and sometimes even catastrophic, consequences. Such consequences were observed recently during the 2010 "Deepwater Horizon" explosion and the subsequent oil spill. The defining accidents that have occurred in the petrochemical industry over the past fifty years, including "Deepwater Horizon", will be highlighted in this section. Furthermore, the central findings of accident research on the main reasons for accidents and the critical role that the human factor usually plays in the course of events will be presented. In particular, it will be demonstrated that a systemic approach must be applied to create more robust risk management systems in the petrochemical industry.

2.2.1 Historical perspective

It is widely acknowledged that several "ages" of petrochemical risk management can be distinguished.[43] The timeline in Figure 2.2 illustrates the three ages of petrochemical risk management: "Technology and standards" from the late 1950s until the early 1980s; "HSE management systems" from the mid-1980s until the mid-1990s; and "improved culture" from the late 1990s to the present. A continuous improvement in risk

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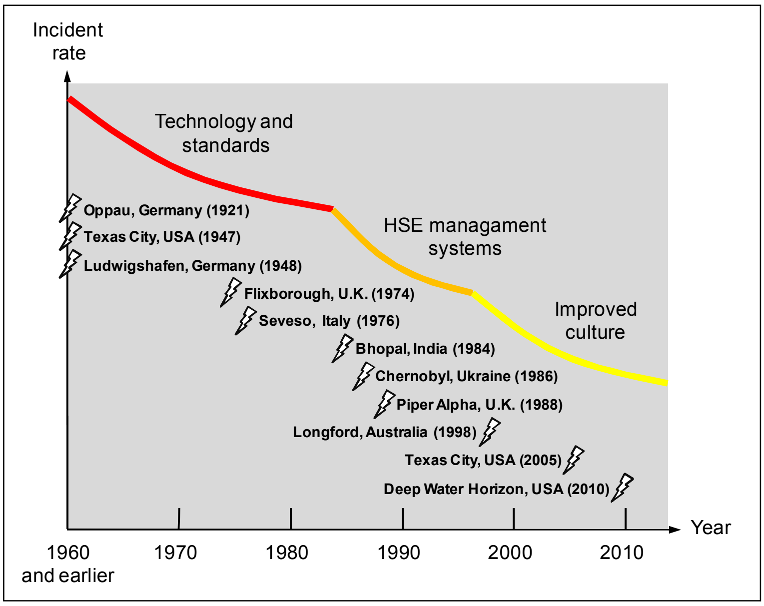
41 See Kletz (2003, p. xii).

42 Hollnagel (2004, p. 5).

43 For an excellent historical overview, see Hollnagel (2004, pp. 29–34). The three-step model and the road towards safety improvement are also described in Bryden, Hudson, van der Graaf, and Vuijk (2004, p. 1) and Hudson (2007, p. 700). Knegtering and Pasman (2009, p. 165) uses a similar terminology but distinguishes five "ages" of risk management.

management processes has led to a significant reduction in incident rates over the past five decades.[44]

Figure 2.2: The industry's defining accidents



Adapted from (Zijker, 2004, p. 1). Similar graphical representations are provided by (Hollnagel, 2004, p. 46), (Hudson, 2001, p. 15) and (Knegtering & Pasman, 2009, p. 165)

In the early days of the petrochemical industry at the beginning of the 20th century, the available technologies were not yet adapted to the specific needs of the industry, and equipment design was often inadequate. Consequently, many accidents were caused by failing equipment such as pressure vessels or rotating machinery.[45] Numerous standards were introduced to provide the industry with common design regulations that allowed for the creation of interchangeable and safe equipment.[46] The most widely accepted petrochemical industry standards were developed by the American Petroleum Institute (API), which has so far issued more than five hundred industry standards.[47]

In addition to the constant drive for standardisation, the era of "technology and standards" was shaped by a number of accidents that contributed to the development of in-

44 Note that the term "incident" refers to both accidents and near misses; see Organisation for Economic Cooperation and Development (2005, p. 26). The reduction of incident rates is documented, for example, in Schouwenaars (2008, p. 6).

45 One serious accident from this era was the BASF tank wagon explosion in 1948; see Landesarchivverwaltung Rheinland-Pfalz (2011).

46 For a brief history of the development of a common industrial standard for pressure vessels, see, for example, American Society of Mechanical Engineers (2011).

47 Although the first standards were introduced in the mid-1920s, the real emergence of standardisation began in the late 1950s with one of the most important standards, the API 610 for centrifugal pumps. See Jones (2008).

herently safer process design, including key events such as “Flixborough”[48] in 1974, “Seveso”[49] in 1976 and “Bhopal”[50] in 1984. The “Seveso” accident led to a series of directives issued by the European Commission to improve the handling and storage of hazardous materials.[51]

As technology progressed and standards improved, incident rates continuously dropped from the 1960s until the 1980s. However, from the mid-1980s onwards, different types of accidents began to occur that led to a rethinking of risk management practices and, subsequently, to the age of “HSE management systems”.

Accidents such as “Chernobyl”[52] in 1986, “Herald of the Free Enterprise”[53] in 1987 and especially “Piper Alpha”[54] in 1988 raised serious questions about the significance attributed to safety within the petrochemical industry. Although standards and technologies were already widely available, they were not always applied consistently, and safety did not receive the priority it deserved. Hence, the next logical step of risk management’s evolution was a more thorough and structured application of safety standards, hazard identification and risk management processes. It was realised that this step could only be taken by implementing integrated HSE management systems (HSE MS).[55] Furthermore, forced by increasing regulatory requirements,[56] the first integrated HSE MS were established in the early 1990s by the large multinational oil companies. Among the first to introduce an integrated HSE MS was the Royal Dutch Shell Group with its “Hazards and Effects Management Process”.[57]

The purposes of such an HSE MS are manifold. Policies and standards describing the handling of HSE risks are defined, and the commitment to safety is established as one of the key goals of the organisation. As depicted in Figure 2.1, this HSE risk management process is embedded in an organisational control loop to facilitate the continuous

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48 For the official report, see Health and Safety Executive (1975). For a condensed summary, see Kletz (1994, p. 83).

49 See Marshall (1992) or Kletz (1994, p. 103).

50 See Institution of Chemical Engineers (1985) or Kletz (1994, p. 110).

51 See European Commission (2011).

52 See International Nuclear Safety Advisory Group (1992) or Kletz (1994, p. 135).

53 See Kletz (1994, p. 226).

54 For the official report, see Cullen (1990). For a condensed summary, see Kletz (1994, p. 196).

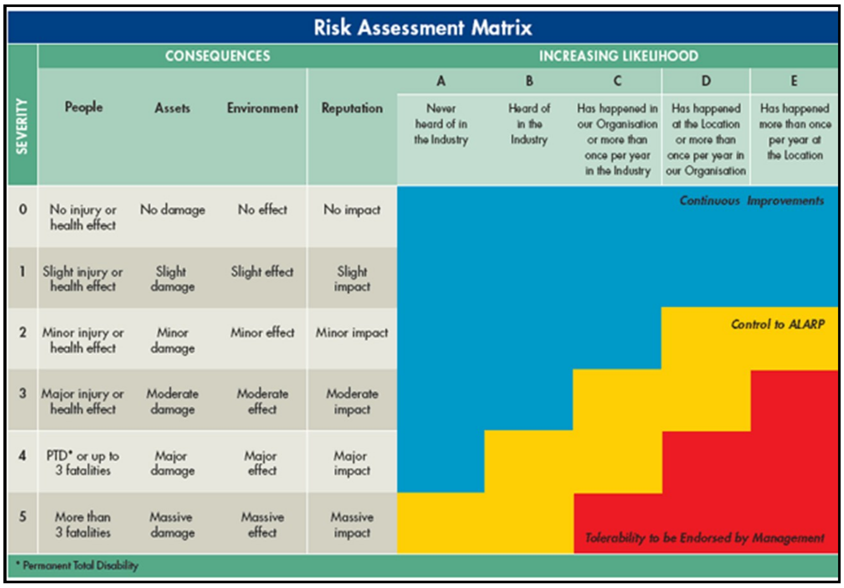
55 See Hudson (2001, pp. 5–6).

56 For example, United Kingdom (1992).

57 See Hudson (2001, pp. 7–11).

improvement of safety performance. Roles and responsibilities are defined to assure that both higher-level risks as well as the risks on the "shop floor" are thoroughly managed by competent people.[58]

Figure 2.3: Risk Assessment Matrix (RAM)



Source: (Energy Institute, 2011b)

There was another significant development within the petrochemical industry during this era. Several tools supporting the different steps of the RMP were introduced in the early 1990s. Methods such as Tripod BETA,[59] BowTie[60] and the Risk Assessment Matrix (RAM)[61] provided strong support for the decision-making process. In combination with an integrated HSE MS, this support led to another significant reduction of incident rates throughout the 1990s. As performance improvement levelled out in the late 1990s, especially as regards more serious incidents,[62] the current stage of petrochemical risk management began: the age of "improved culture".

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58 Management is responsible for controlling and managing the higher-level organisational risks by attributing the right amount of resources in terms of people and money. Staff members are responsible for creating and implementing their own procedures to manage the risks of their daily work.

59 Tripod BETA is a reactive tool for accident investigation. The software is available online via http://www.advisafe.com/software. For more information, see Gower-Jones, van der Graaf, and Doran (1998).

60 BowTie is a proactive tool for hazard identification and risk mitigation. The software is available online at http://www.bowtiepro.com. For more information, see Gower-Jones, et al. (1998) or Hudson (2001, p. 11).

61 The RAM is one of the most important tools of petrochemical risk management. Risks are identified and managed based on the combination of consequences and probability of occurrence; see Energy Institute (2011b), Hudson (2001, p. 9) or Sutton (2007, p. 41).

62 See Hudson (2001, p. 13) or International Association of Oil & Gas Producers (2006, p. 3).

Although HSE standards, risk management systems and tools were in place, they were not always employed in practice. Accidents such as “Longford”[63] in 1998, “Texas City”[64] in 2005 and “Deepwater Horizon”[65] in 2010 dramatically demonstrated that behavioural risks are part of a bigger picture and that compliant behaviour is not guaranteed simply by having an HSE MS in place. Consequently, since the beginning of the 21st century, research efforts in the petrochemical industry have been directed towards the development of methods that foster an intrinsic motivation for safe behaviour.

These efforts acknowledge that bringing an HSE MS to life requires more than written procedures; it requires a systemic approach – a “safety culture”. However, to provide an environment in which employees behave safely and apply the available risk management techniques, an organisation first has to understand the fundamentals of human behaviour. One of the most important developments in this respect is Royal Dutch Shell’s “Hearts&Minds” programme, which is publicly available via the Energy Institute’s website.[66] It offers a variety of tools to improve the safety culture within a petrochemical operation by approaching behavioural risks from various angles, such as supervision, risk assessment and management of non-compliance.

2.2.2 Multiple Causes

Accidents are never caused by a single event, but rather by a multitude of factors.[67] On average, seven unsafe acts occur in the petrochemical industry before an accident happens.[68] When examined individually, these unsafe acts might each appear to be relatively trivial events.[69] However, when they occur in a combined way, they can form a chain of events leading to a catastrophe.

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63 See Hopkins (2000) or Kletz (1994, p. 267).

64 See Baker III, et al. (2007) or U.S. Chemical Safety and Hazard Investigation Board (2007).

65 It has to be noted that the company’s report, British Petroleum (2010), reveals little about the behavioural aspects of the accident. In contrast, the transcripts of the hearings before the joint investigation board reveal serious deficiencies in the existing safety culture on “Deepwater Horizon”, especially in connection with the platform’s gas detection system. For further information, see Deepwater Horizon Joint Investigation Team (2010) or National Commission on the BP Deepwater Horizon (2011).

66 See http://www.eimicrosites.org/heartsandminds.

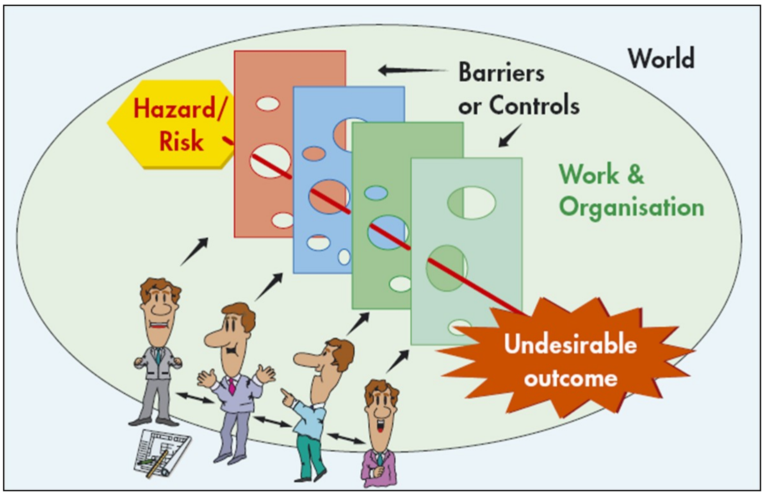
67 See Hudson, et al. (1998, p. 1) or Knegtering and Pasman (2009, p. 164).

68 See Sneddon, et al. (2005, p. 6).

69 See Hudson, et al. (1998, p. 1).

This correlation is best demonstrated by Reason's "Swiss Cheese Model" (SCM).[70] Figure 2.4 shows that a risk materialises or, in other words, an accident happens when several barriers of control are breached successively.[71]

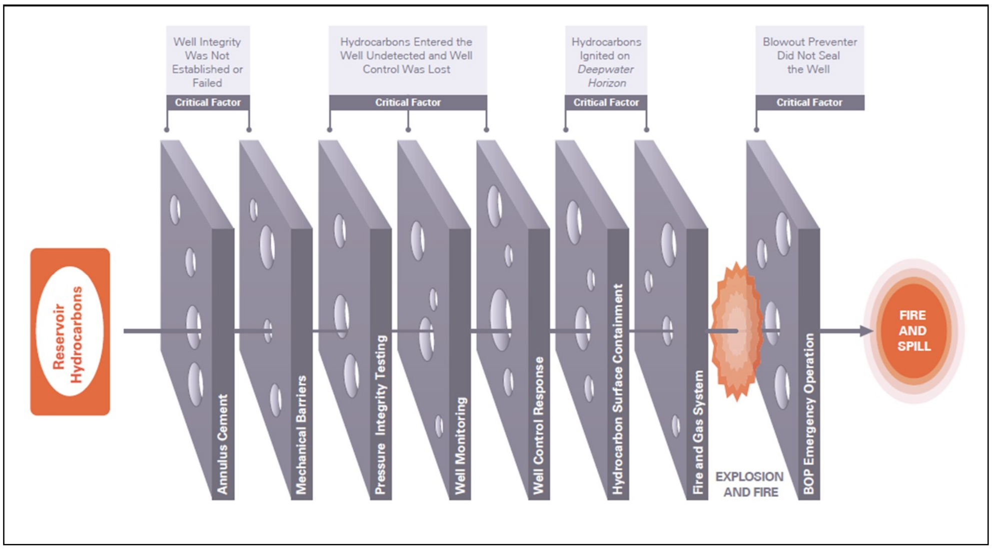
Figure 2.4: Swiss Cheese Model (SCM) of accident causation



Source: (Bryden, Hudson, van der Graaf, & Vuijk, 2004, p. 2)

The barriers compromise all available safety measures derived from the HSE MS, including process and equipment design and operating procedures. The holes in the figure above represent deficiencies within these barriers. In very rare cases, these holes align to form an accident trajectory as shown in Figure 2.5, which is based on the example of the "Deepwater Horizon" accident.

Figure 2.5: "Deepwater Horizon" accident



Source: (British Petroleum, 2010, p. 181)

70 See Reason (1997, p. 12).

71 An excellent source of information on barriers in accident prevention is Hollnagel (2004).

It is argued that the holes within these barriers can stem from either active interventions or latent conditions.[72] An active intervention might consist of an operator disabling a safety defence (such as the reactor minimum load override during the Chernobyl disaster) or committing an error (for example, not inserting a spade into the plant's main pipe work before starting the water flushing procedure at Bhopal). Latent conditions, in contrast, are more difficult to detect because, for the most part, they are hidden deeply within the organisation or equipment design (such as the defective sprinkler system at the Piper Alpha or the poor design of the car deck of the Herald of the Free Enterprise). The connection between active failures and latent conditions is best described as follows: *"The active failures are important in defining the exact form of the accident, but the underlying causes determine whether an accident will happen at all."*[73]

Although the employees on the "shop floor" are often responsible for the active failures, management is usually responsible for the latent conditions in an organisation.

2.2.3 Human factor

As the SCM has clearly demonstrated, the human factor is a key element in the prevention and causation of accidents[74] because the people working in an organisation, including employees and managers, are the weakest element in the HSE MS. While the petrochemical industry has obtained very good control of technical accident causes, unfortunately, the same does not hold true for behavioural risks: *"In the last decades, it has been cleared that human actions constitute a major source of vulnerability to the integrity of interactive systems, complex as well as simple ones."*[75]

Researchers estimate that 80-90% of all accidents are caused by human factors.[76] However, this very high percentage is also quite misleading, and it can even be argued that it represents one of the main obstacles to understanding the true underlying causes of ac-

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[72] See Reason (1997, pp. 233–237).

[73] Hudson (1992, p. 21).

[74] See Reason (1997, p. 61). For an excellent comparison of positive as well as negative human interventions, see Reason (2008). A detailed document on the role of the human factor in system reliability is provided by Research and Technology Organization (2001). The complex interactions of human factors and safety management systems are also well described in Health and Safety Executive (2007).

[75] Nivolianitou, Konstandinidou, and Michalis (2006, p. 7).

[76] The first researcher to issue this statement was Hoyos (1995, p. 234). Lawton (1998, p. 79) and Sneddon, et al. (2005, p. 2) build upon these results, while Konstandinidou, Nivolianitou, Markatos, and Kiranoudis (2006, p. 8) and Bevilacqua, Ciarapica, and Giacchetta (2008) provide empirical proof with current accident data, although with slightly reduced percentages.

cidents.[77] Focussing solely on individual failures[78] most definitely will not lead to a reduction of accident rates.[79] Instead, to improve safety performance, a systemic approach is required that takes both the individual and the latent conditions in an organisation into account.[80]

2.2.4 Systemic approach

Today, the systemic approach is widely accepted within the petrochemical industry.[81] Most petrochemical risk managers are well aware that the root causes of faulty human behaviour are often to be found outside the individual, i.e., within the latent conditions of an organisation.

> *"In this, the present age, we recognise that the major residual safety problems do not belong exclusively to either the technical or the human domains. Rather, they emerge from as yet little understood interactions between the technical and social aspects of the system."* (Reason, 1990, p. 2)

This statement is especially supported by the "Longford" and "Texas City" accident investigation reports. Both reports clearly state that managerial and leadership failures contributed greatly to the disasters.[82] Furthermore, the preoccupation with lagging safety indicators such as the Lost Time Injury Frequency (LTIF), which were commonly used in these cases and in the petrochemical industry in general until several years ago, has also been criticised. It is argued that such lagging indicators neither reflect the real safety climate within an organisation nor predict the probability of the next major accident.[83] This preoccupation with lagging indicators has been largely replaced by a sys-

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77 See Glendon, et al. (2006, p. 153) or Kletz (2001, p. 2).

78 The argument in favour of individual failures was also fostered by studies such as Bird & Germain (1996).

79 See Reason (1997, p. 223).

80 See Hoyos (1995, p. 248) and Reason (1997, p. 230).

81 See Lawton (1998, p. 93), Rauterberg (1998, p. 14) or Reason (1997, p. 239).

82 See, for example, Hopkins (2000, p. 75) or Baker III, et al. (2007, p. viii).

83 See Hopkins (2011, p. 9), Knegtering and Pasman (2009, p. 165), Reason (1997, p. 232) or Sonnemans & Körvers (2006, p. 8).

temic point of view that also takes into account leading indicators. There are even research efforts towards the development of accident forecasting methods.[84]

> *"In recent years there has been a movement away from safety measures purely based on retrospective data or 'lagging indicators' such as fatalities, lost time accident rates and incidents, towards so called 'leading indicators' such as safety audits or measurements of safety climate. ... The shift of focus has been driven by the awareness that organisational, managerial and human factors rather than purely technical failures are prime causes of accidents in high reliability industries ... ."* (Flin, O'Connor, & Bryden, 2000, pp. 177–178)

The key to achieving sustainable safety performance is to bring the HSE MS to life within an organisation. This requires that management, supervisors and staff members are equally responsible for creating a safe working environment.[85]

However, the systemic approach also has its limits. Many systemic factors and latent conditions (e.g., cultural background) are outside the control of management and the individual.[86] Consequently, modern accident research demands a concentration on the core systemic and individual factors[87] so that risk management does not become too abstract and too complex.

2.3 Human factor research

The previous section demonstrated that the fields of accident and human factor research have influenced each other greatly over the past two decades. Each accident provided

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84 See, for example, Maroño, Peña, and Santamaría (2006), Petroleum Safety Authority Norway (2009) or Sonnemans and Körvers (2006). The idea behind these methods is to identify certain accident precursors, which are derived from historical data and can later be used in the form of a forecasting tool. Although research has just begun and first results cannot be expected for a long time, these endeavours could also help organisations within the petrochemical industry to better learn from past accidents.

85 See Hoyos (1995, p. 236) and Hoyos (1995, p. 248).

86 See Hudson, et al. (1998, p. 3).

87 See Reason (2006, p. 26).

vital information on human behaviour in hazardous situations and contributed to the development of sophisticated behavioural models.

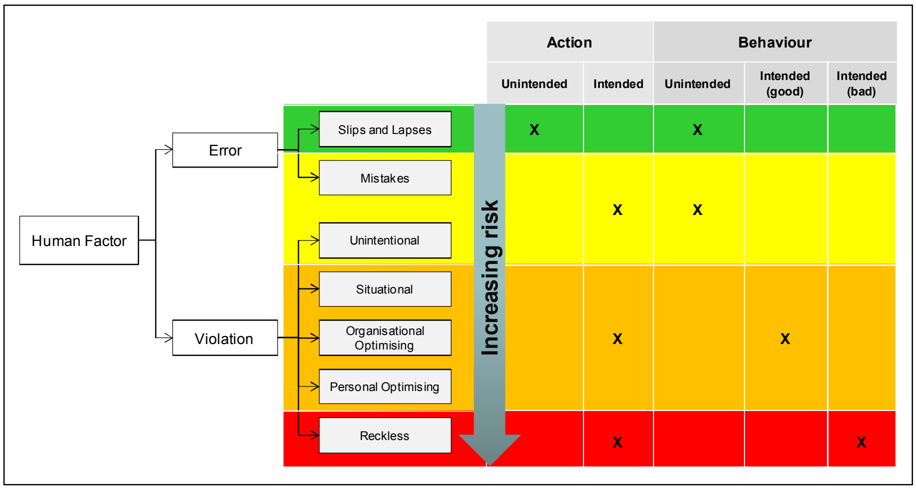
In this section, the current understanding of the human factor within the petrochemical industry will be further investigated. First, a detailed overview of the most common human factors, errors and violations, will be given. It will be followed by a presentation of a commonly used behavioural model, namely, the concept of behavioural economics.

2.3.1 Error and violation

In principle, human factors can be divided into two major categories: *errors* and *violations*. As depicted in Figure 2.6, this categorisation follows a simple distinction between action and behaviour.[88]

The combination of both aspects determines the specific subcategory of the human factor. The colours in Figure 2.6 indicate the areas of increasing risk: while slips and lapses are usually benign, mistakes are more dangerous, and violations are most dangerous of all.[89] A number of practical examples will serve to highlight these implications for each of the described human factor subcategories.[90]

Figure 2.6: Categories of human factor



Adapted from (Glendon, Clarke, & McKenna, 2006, p. 115)

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88 There is extensive literature on the different types of human error. Recommended further reading includes Glendon, et al. (2006, pp. 113–127), Hudson, Verschuur, Parker, Lawton, and van der Graaf (1998, p. 3), Kletz (2001), Salvendy (2006, pp. 708–710), Reason (1990), Reason & Hobbs (2004), Redmill & Rajan (1997) and Wiegmann & Shappell (2001). The author's categorisation of errors and violations builds upon Energy Institute (2011a). Although it should be noted that there is a fine line between errors and violations, the author follows the prevailing opinion that errors and violations are distinct from each other. See hereto Lawton (1998, p. 78).

89 The author follows Hudson, et al. (1998) and their definition of increasing risk.

90 For more practical examples of the types of human error, see Kletz (2001).

- *Errors*: Per definition, an *"... error is the failure of planned actions to achieve their desired goal, where this occurs without some foreseeable or chance intervention."*[91] Errors can take the form of *slips*, *lapses* or *mistakes*.

  Slips are unintended actions that lead to an unintended behaviour. A simple example is an operator pushing the wrong button on a control panel, resulting in the unintended shutdown of a machine. *Lapses* are very similar, but in this case, there is an unintended inaction leading to an unintended behaviour. For example, an operator sees a high vibration alarm of a machine on the control screen. Because there are many other alarms sounding at the same time, he forgets to shut down the machine, and as a consequence, the machine breaks down.

  Mistakes are different. Although the action might be intended and an operator thinks that he is doing the right thing, the behaviour is unintended. A typical example is that an operator sees a machine's high vibration alarm on the control screen. To decrease the vibration level, he decides to decrease the machine's product flow. Unfortunately, this results in the unintended behaviour of increased vibrations.

- *Violations*: Per definition, violations are *"... deliberate departures from rules that describe the safe or approved method of performing a particular task or job."*[92]

  The definition also reveals a very interesting aspect of violations: in theory, there could be no violations in the absence of rules or procedures. This theory leads to the paradoxical situation in which, especially in organisations characterised by a high degree of regulation, such as the military, the airline industry or the petrochemical industry, the possibilities of committing violations are manifold.[93] Hence, the less individual freedom the pilot or the operator is given, the more he is prone to violating procedures. According to the classification of action and behaviour that is already used to describe errors, the following types of violations can be distinguished: *unintended, situational, optimising* and *reckless violations*.

  An *unintended violation* is very similar to a mistake. The action is intended, but the behaviour is not. However, in contrast to a mistake, an unintended violation is not in accordance with a certain rule or procedure. For example, consider the operator

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91 Reason and Hobbs (2004, p. 39).

92 Lawton (1998, p. 78).

93 See Reason (1997, p. 61).

seeing a machine's high vibration alarm on the control screen. There is a procedure requiring the operator to increase the product flow in case of a high vibration alarm. If the operator is not aware of this procedure, then he may decrease the product flow, thinking that he acted correctly.

Situational violations arise when there is a gap between the rule or procedure and the real situation on site, which means that the job cannot be performed without committing a violation. In this case, both action and behaviour are intended. For example, consider lifting a heavy piece of equipment. The lifting procedure clearly states that equipment is only to be lifted in the vertical direction and that any simultaneous horizontal movement is prohibited. On site, the mechanics find that the crane does not reach far enough to correctly lift the equipment - it can only be lifted by simultaneously moving it in horizontal direction. If the mechanics lift the equipment nevertheless, then they commit a situational violation, which can lead to disastrous consequences.

Optimising violations also occur when an intended action is followed by an intended behaviour. They are characterised by the intention to seize opportunities to perform a task more efficiently. The optimisation can happen on either an organisational or a personal level. *Organisational optimising violations* are committed as a result of outside pressure, e.g., to keep the production running or to reduce downtime. Consider a unit that had to be shut down due to a leaking product line. The production unit manager clearly communicates to his staff that the repair of the line must be performed as quickly as possible to get the production up and running again. If, in a situation like this one, staff members consciously did not implement parts of the safety procedures because their implementation was considered too time consuming, they would commit violations with the goal of benefitting the organisation. In contrast, *personal optimising violations* occur for reasons of personal convenience. For example, a procedure requires an operator to check a certain pressure reading once per hour. In the last hour before the shift change, the operator had many other things to do, so he did not perform the check. Checking the pressure reading now would result in being late for the shift change. Consequently, he decides not to check the pressure reading in order to get home on time.

Finally, there are *reckless violations*. These violations are the worst type because they imply that an individual performed an intended action in combination with an intended malevolent behaviour. An important characterisation of this type is that people do not care about the consequences of their actions. For example, smoking inside a production unit is prohibited. Nevertheless, a contractor walks by the unit and recklessly throws away a burning cigarette.

Now that the different types of errors and violations have been defined, it is of great importance to put both phenomena into perspective. The current focus of petrochemical risk management and of this thesis is on the handling of violations, not of errors. Although there have been several efforts to reduce human error (for example, in the aircraft maintenance business),[94] the petrochemical industry regards violations as the more critical human factor and has thus focussed on the human factor for several reasons.

Errors can never be fully eliminated because they are an integral part of human nature.[95] Hence, the prevention of human error requires considerable effort with rather uncertain chances of success. In contrast, violations are a part of human behaviour that can be influenced more easily by applying adequate techniques. In short, working on the reduction of violations offers more chances for success than working on the reduction of human error, at least in terms of the efforts required.

This is especially the case because the safety barriers of the HSE MS were designed with human error in mind. Hence, the system consists of several redundant technical and organisational barriers. Committing an error (i.e., breaching a safety barrier) will therefore almost never lead to an undesirable event because other control barriers will take over (see also Chapter 2.2.2). Consider an operator who wants to start a pump. As it is critical for a pump to be started only after it has been fully filled with liquid, a technical barrier in the form of a level switch is implemented. This level switch monitors the liquid level inside the pump. By means of a functional logic, the pump can only be started when the level indicator shows a "good condition". Now, even if the operator committed an error (for example, did not fill the pump and tried to start the pump), it would not start. The technical barrier would "intercept" the human error.

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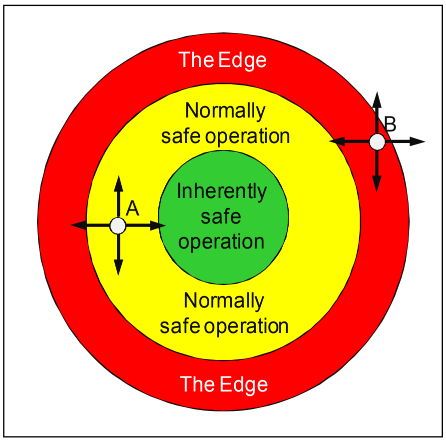
94 See Reason and Hobbs (2004), Shappell et al. (2007) or Wiegmann and Shappell (2001).

95 See Kletz (2001, p. 2) .

Figure 2.7: Dangerous effects of violation



Adapted from (Hudson, Verschuur, Parker, Lawton, & van der Graaf, 1998, p. 10)

In contrast, the HSE MS is not designed with human violation in mind. Because most systems rely to a great extent on procedural controls, there is an implicit assumption that people will follow the rules.[96] However, what happens if people do not follow the rules? In that case, the violation of a procedure takes the system from a safe state (see Figure 2.7, point A) to a state outside of the safe boundaries (see Figure 2.7, point B). If one considers that procedures are often the last line of defence when all other technical measures have been exhausted, then it becomes clear that the system will be pushed to the edge in such a scenario.

On the edge, the probability of an accident rapidly increases[97] because people are confronted with unusual or unpractised situations, leading to an increased error probability. In addition, one line of defence has been deliberately circumvented, and the system itself becomes less forgiving of errors. In this context, consider the red light example from the beginning of the thesis. The violation of "running a red light" puts the system on the edge, and the accident risk increases dramatically.[98]

Finally, if violations and errors collide, the result is usually catastrophic. Human factor research within the petrochemical industry has therefore developed a simple, yet powerful equation: "error + violation = disaster".[99]

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96 See Hudson, et al. (1998, p. 1).

97 See Lawton (1998, p. 79).

98 In this context, the study by Elliott, Baughan, and Sexton (2007) provides additional information on errors and violations in motorcycle accidents. A similar study by Massaiu & Kaarstad (2006) investigated the reasons for non-compliance in road traffic centres.

99 See Glendon, et al. (2006, p. 122) or Hudson, et al. (1998, p. 5).

The significance of this equation becomes even more obvious when one takes into account that challenging working environments, such as those in the petrochemical industry, usually foster violations.[100] To provide a practical example of the equation, a pump-starting scenario is presented. The level indicator on the pump is broken, and, as a consequence of the functional logic, the pump cannot be started. The operators urgently need the pump to be able to start the production process, and a replacement of the indicator would take at least one additional shift. Because the operators assume that the pump was correctly filled by the workers on the previous shift, they decide to disable the functional logic and start the pump (violation). Unfortunately, the previous shift filled the wrong pump, and the pump that is to be started is still empty (error). Once the empty pump is started up with gas inside, the bearings immediately fail, the gas ignites on the hot surface of the bearings and a large fire occurs (disaster).

In addition to this extensive overview of the most common human factors present in the petrochemical industry, three other interesting aspects of violations should not be left unaddressed. The quality of procedures usually has no influence on the violation probability – even good procedures will be violated.[101] Furthermore, not all violations lead to bad outcomes, and some even have positive effects.[102] The most widely known example of a violation that led to success is that of the survivors of the Piper Alpha accident. In contrast to their colleagues who followed the safety procedure, went to the assembly point inside the platform's mess and died as a consequence, the survivors did not go the assembly point and jumped directly into the water.[103] Finally, violations are also very closely connected to the existing safety culture and management commitment in an organisation.[104] This aspect will be further explored in Chapter 2.4.

The following section will elaborate on the underlying causes of violations based on the theory of behavioural economics.

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[100] See Lawton (1998, p. 87).

[101] See Lawton (1998, p. 79).

[102] See Reason (1997, p. 81).

[103] See Reason (1997, p. 206).

[104] This finding by Lawton (1998, p. 78) was proven in several empirical studies; see Fogarty & Worth (2003) or Fogarty & Shaw (2010).

2.3.2 Behavioural economics

Over the past two decades, risk management research within the petrochemical industry has extended and adapted several psychological models to explain human behaviour and to investigate the reasons for violations.[105] One of the core concepts of most modern RMPs is that of behavioural economics.[106]

> *"The main assumption of behavioural economics is that human beings try to optimize their behavioural efficiency within the limits defined by internal and external constraints ... ."* (Battmann & Klumb, 1993, p. 37)

Hence, it is argued[107] that the choice to violate a procedure is determined not by moral considerations but rather by a simple comparison of the perceived *benefits* and *costs* that are connected to a certain action. According to the model, people thus strive to optimise their behaviour by spending as little as possible of their limited human resources while trying to achieve a maximum gain. These resources represent the "money" of behavioural economics and *"... can be either internal resources (knowledge, skills, ability, time, energy) or external ones (tools, fellow workers, plant, etc.)."*[108] Furthermore, it is assumed that all human actions are bound to certain internal (e.g., psychological) or external limitations (e.g., rules and procedures) and that a conflict can easily arise between the individual optimising behaviour and these limitations.

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105 For example, the Theory of Planned Behaviour, which was originally developed by Ajzen (1991), can be considered as a key element of Royal Dutch Shell's "Hearts&Minds"; see Energy Institute (2008). Another behavioural model that was used in the same context is the Safe Behaviour Model; see Sneddon, et al. (2005).

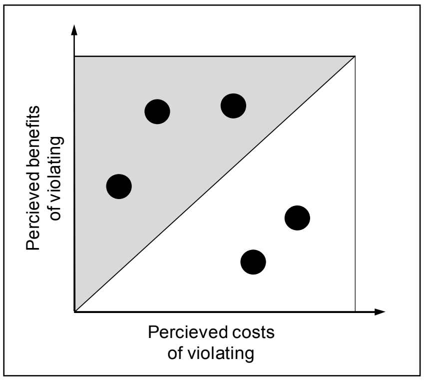
106 The concept was first brought into the safety context by Battmann and Klumb (1993). However, it must be noted that the scientific community has not yet reached a commonly accepted definition of behavioural economics. An excellent literature review of the current state of research is provided in Health and Safety Executive (2009). According to this review, behavioural economics consists of various theories that offer explanations for why people deviate from rationally expected behaviour when faced with decisions under risk. Bounded rationality, strategic behaviour and learning effects are identified as key themes. In this thesis, the author adopts the definition of behavioural economics according to Battmann and Klumb (1993), which is further described in the following pages. The author does not understand behavioural economics in the sense of bounded rationality that is caused by a framing of decisions according to Kahneman & Tversky (1979) and Kahneman & Tversky (1986).

107 The presentation of the main assumptions of behavioural economics is based on Battmann and Klumb (1993, pp. 37–39) and Reason, Parker, and Free (1994, pp. 12–15). Hence, there will be no further quotes of these two authors on the following three pages except for graphical illustrations and direct citations.

108 Reason, et al. (1994, p. 12).

In this context, the model of behavioural economics has contributed significantly to understanding the various mechanisms of violation. Violations usually emerge for one of the following reasons: individual misperceptions of the risk involved with an action, the conflict between individual optimising behaviour and organisational goals and, finally, missing feedback or commitment in an organisation.

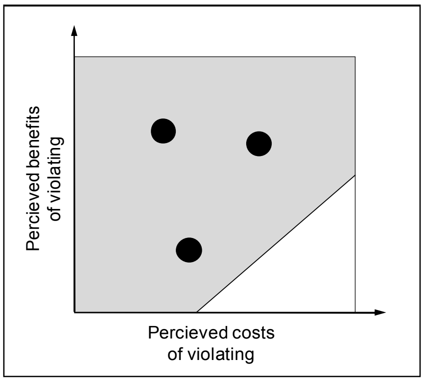
Figure 2.8: Behavioural economics



Source: (Reason, Parker, & Free, 1994, p. 13)

According to the model, whenever the perceived benefits of a violation outweigh its costs, the rule will be violated (see Figure 2.8). All actions in the grey area of Figure 2.8 are likely to be executed, whereas the ones in the white area will most likely be rejected.

Figure 2.9: Behavioural economics and "skewed" perception of risk



Source: (Reason et al., 1994, p. 14)

However, especially in high-reliability industries such as the petrochemical industry, the individual perceptions of the costs and benefits of a violation are often misleading. Because accidents happen very rarely, employees attribute a very low perceived probability to the occurrence of an accident and consequently underestimate the underlying (objective) risk (see Figure 2.9).[109] This "skewed" perception of risk[110] thus represents one

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109 See Kletz (2003, p. xii), Lawton (1998, p. 83) or Sneddon, et al. (2005, p. 9).

110 See Health and Safety Executive (2009, p. 21).

of the key factors in the emergence of violations and is a driver behind the erosion of compliance in high-reliability industries.[111]

A typical example illustrating the conflict between individual optimising behaviour and organisational goals has already been presented in the previous section. If a production unit must be put back into operation as quickly as possible, then staff members might be inclined not to implement parts of safety procedures that they consider too time-consuming. There is a clear conflict between safety and production,[112] which is best described by the following citation: *"... Safety and productivity constrain each other. There is no productivity without safety, but safety can become so expensive that productivity decreases below acceptable standards."*[113]

When examining this example, it is clear that this conflict cannot be resolved by an individual. On the contrary, it is an imperative for the organisation and, more precisely, its management to communicate clear priorities on safety and production to prevent conflicts.

The last factor contributing to the emergence of rule violations is also closely connected with the organisation. Violations usually occur if the actions taken do not result in unwanted costs for the individual. Hence, as long as there are no consequences for the violation of a safety procedure, people will continue to violate it. This circle can only be broken if the organisation demonstrates a strong commitment to safety and provides instant feedback to its employees (e.g., in the form of fines).[114]

In this respect, management plays a key role in both the prevention and emergence of rule violations.[115] It is responsible for creating a cultural mindset in which safety is highly valued and rule violations are not tolerated.[116] The characteristics of such a "safety culture" will be described in the following section.

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111 See hereto Gonzalez & Sawicka (2003).

112 This conflict has been discussed extensively in several publications, such as Celati (2004, p. 236), Lawton (1998, p. 89), Petroleum Safety Authority Norway (2006, p. 13) and Reason, et al. (1994, p. 12).

113 Battmann and Klumb (1993, p. 39).

114 See Battmann and Klumb (1993, p. 40).

115 The coherence between management commitment and violations has also been proven empirically in Fogarty and Shaw (2010, p. 1457).

116 See Reason (1997, p. 212).

2.4 Safety culture

It has been demonstrated in the previous sections that in order for risk management to be effective, a systemic approach is required, and simply having HSE MS in place will not be sufficient.

Bringing HSE risk management to life is the biggest challenge that the petrochemical industry faces today. All efforts to create integrated HSE risk management programmes that are capable of reducing behavioural risks can be summarised under the term "safety culture". However, why does one need such a "safety culture", what does it stand for and how can it be created? These questions will be answered in the following section.[117]

2.4.1 Why safety culture?

> *"The possession of a management system, no matter how thorough and systematic it may be, is not, however, sufficient to guarantee sustained performance. What is also needed is an organisational culture that supports the management system and allows it to flourish."* (Hudson, 2001, p. 3)

The above citation provides a strong argument for the "safety culture" concept. Although accident numbers within the petrochemical industry have continuously dropped over the past decades and HSE MS have matured, today's accidents are often connected to aspects of the broader organisation.[118] The "Texas City" explosion in 2005 and the "Deepwater Horizon" oil spill are only two recent examples where the *"... corporate safety culture ... may have tolerated serious and longstanding deviations from good safety practice."*[119]

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[117] Note that there are several excellent publications on the subject of safety culture, and only a short overview will be presented in this thesis. For further detail, see, for example, Baram and Schoebel (2007), Health and Safety Executive (2005), Hudson (2001), Hudson (2007), Rauterberg (1998), Reason (1997, pp. 191–220) and Reason and Hobbs (2004, pp. 145–157). The most exhaustive overview of the different aspects of safety culture reflecting the current state of research is provided by Glendon, et al. (2006, pp. 363–406). The safety culture concept has even travelled to other industry segments. See, for example, Vredenburgh (2002), who studied safety culture in hospitals.

[118] See Knegtering and Pasman (2009, p. 168).

[119] Baker III, et al. (2007, p. viii).

Furthermore, researchers argue that safety in itself is non-motivating.[120] This idea means that, on one hand, when safety performance is good, there is rarely positive feedback from management to the employees working in the organisation. On the other hand, when the safety performance is bad, serious pressure is often placed on employees to "behave more safely".

Thus, to prevent these organisational accidents, it is necessary to make safety more motivating and to resolve the conflict between safety and production.[121] To achieve this goal, the culture within the organisation must be shaped in such a way that safety is recognised as a positive aspect and as a key element in achieving operational excellence. Several researchers have argued that organisations with a strong safety culture are not only safer places[122] but also are much more effective organisations that deliver better results.[123] Frequently cited examples of such highly effective organisations are the chemical company DuPont[124] and the U.S. Navy aircraft carrier fleet.[125] The main characteristics of such effective organisations are also at the root of the definition of a safety culture.

2.4.2 Definition and characteristics

First, it must be noted that there is no definition of the term "safety culture" that would be applicable universally.[126] Nevertheless, there is a common understanding among most researchers that the term "safety culture" refers to the following two aspects: the behaviour of people within an organisation and the attitude and values towards safety that are incorporated by the organisation.[127] (Hudson, 2001, p. 16) opts for an even simpler definition by saying that *"a safety culture is ... one in which safety has a special place in the concerns of those who work for the organisation."*

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[120] See Mearns & Reader (2008, pp. 388–389).

[121] In his study of several chemical companies, Zimolong (1992, p. 86) argues that coordinated safety management can resolve the conflict between safety and production.

[122] See Baker III, et al. (2007, p. xii).

[123] See, for example, Baram and Schoebel (2007, p. 632) or Hudson (2001, p. 28).

[124] DuPont is known as the industry leader in terms of safety. It has consistently worked on its safety culture for over 200 years; see hereto Leinweber (2009). Today, DuPont even provides its safety solutions to many other companies; see hereto DuPont (2007).

[125] See Reason (1997, pp. 214–215).

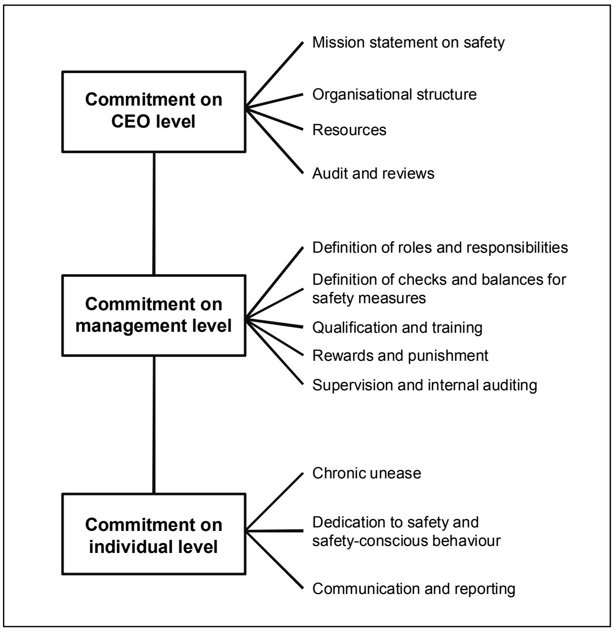
[126] See hereto Baram and Schoebel (2007, p. 633), Hudson (2007), Reason (1997, p. 192) or Reason and Hobbs (2004, p. 145).

[127] See hereto Glendon, et al. (2006, pp. 364–369); Health and Safety Executive (2005, p. iv) or Reason and Hobbs (2004, p. 145).

In this understanding, the safety culture concept is far more than an explanation method in accident analysis;[128] it is a holistic approach to dealing with behavioural risks in an organisation and achieving a safer working environment.[129] Thus, instead of striving for an overarching definition, several researchers define a safety culture as a combination of certain key characteristics.[130]

A safety culture is characterised by strong leadership and managerial commitment to safety,[131] staff involvement and empowerment (especially in the reporting of safety concerns), a high level of knowledge about the current safety state, a high degree of justice (especially when dealing with safety infractions)[132] and a strong desire to learn from mistakes.

Figure 2.10: Elements of a safety culture



Adapted from (Rauterberg, 1998)

The graphical representation in Figure 2.10 further details these characteristics and illustrates that the elements of a safety culture are closely tied to each other. Hence, if

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128 The term "safety culture" was first used in an accident investigation by the International Atomic Energy Agency (IAEA) in connection with the 1986 Chernobyl disaster; see hereto International Nuclear Safety Advisory Group (1992, pp. 21–22).

129 See Díaz-Cabrera D., Hernández-Fernaud, and Isla-Díaz (2007, p. 1202) or Rauterberg (1998, p. 19).

130 See Health and Safety Executive (2005, pp. iv–v), Hudson (2001, pp. 17–19), Reason (1997, pp. 193–194) or Reason and Hobbs (2004, pp. 145–146).

131 See hereto Reason (2008, p. 277) or Wiegmann, et al. (2004, p. 126). It is even argued that a safety culture must be "CEO-proof"; see Reason (2008, p. 274).

132 In contrast to a blame culture, a just culture fairly balances reward and punishment; see Bond (2008).

there is a consistent commitment to safety on all company levels, from the Chief Executive Officer (CEO) to the local management and down to the shop floor employees, the effort will succeed, and behavioural risks can be managed. In contrast, if even one element is missing, operational excellence and good safety performance cannot be expected.

> *"Summarizing it can be noted that a holistic approach of leadership, empowerment and participation, with continual alertness of top management, a dedicated reliability and safety attitude trickling down through the organisation, with metrics and a potential 'precursor' analysis team in place are essential requisites to enhance safety and with that profitability."* (Knegtering & Pasman, 2009, p. 165)

It must be noted that the above characteristics draw a picture of an ideal safety culture. If one or more characteristics of a safety culture are missing within a company, the culture will further depart from this ideal picture.[133] It has therefore become very common in the petrochemical industry to think of safety culture in an evolutionary way.

2.4.3 Evolutionary model

Safety cultures cannot simply be created overnight; they evolve over the course of years, decades or, as the example of DuPont demonstrates, over centuries.[134] To describe this evolution, the petrochemical industry adopts a five-stage model, which was derived from the original three-stage model by (Westrum, 1993).

The corresponding "HSE culture ladder", which is depicted in Figure 2.11, is at the heart of Royal Dutch Shell's "Hearts&Minds" programme[135] and has been the focus of several empirical studies.[136] The ladder shows the path towards world-class safety per-

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133 An excellent assembly of examples of positive as well as negative safety cultures is provided by Tweeddale (2003, pp. 351–368).

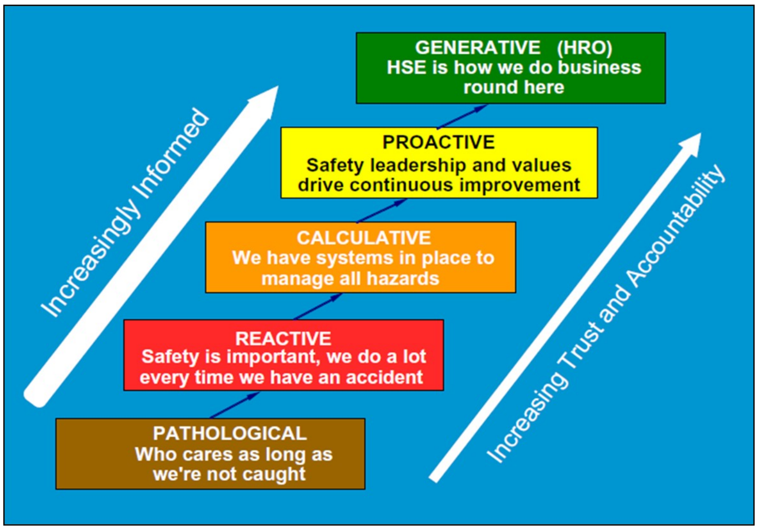
134 See, for example, Hudson (1992, p. 46). The "long and winding road" towards safety is very well described in Hudson (2001).

135 See Hudson (2007).

136 See Lawrie, Parker, and Hudson (2006) or Parker, Lawrie, and Hudson (2006).

formance and describes the different stages an organisation must pass through to reach the summit.[137]

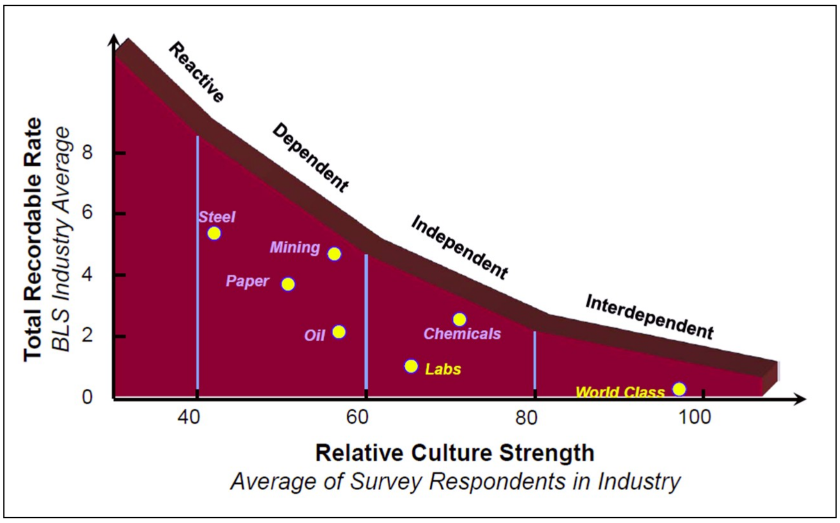
Figure 2.11: Safety culture ladder



Source: (Hudson, 2007, p. 704)

The *generative stage* can be described as the ideal state of a safety culture, which possesses all of the attributes defined in Chapter 2.4.2. At this stage, people are intrinsically motivated to behave safely, and safety is deeply embedded in the organisation. Unfortunately, there are very few of these generative organisations. As previously mentioned, the most popular examples of generative organisations include DuPont and the U.S. Navy aircraft carrier fleet.

Figure 2.12: Safety culture of the petrochemical industry



Source: (Leinweber, 2009)

137 According to Hudson (2001, p. 21), an organisation cannot leap between the different cultural stages. It can only progress stage by stage. A detailed description of the different stages can be found in International Association of Oil & Gas Producers (2010b).

Most petrochemical companies find themselves in either a *calculative* or a *proactive* stage or are currently in the transition process between the two stages. Hence, they have HSE MS in place and are in the process of bringing them to life, as depicted in Figure 2.12. This figure shows the results of an annual survey that is part of DuPont's global benchmarking initiative. The petrochemical industry (oil and chemical) still has a considerable way to go before achieving world-class safety performance.[138] The events of the Deepwater Horizon crisis have clearly demonstrated that there are still operations within the industry with safety cultures that can be rated reactive at best.

Fortunately, there are only very few organisations still caught in the *reactive* or, even worse, the *pathological* stage, where safety is either only important in case of accidents or is recklessly neglected. Of course, this progression towards a stronger safety culture was also fostered by ever-stricter risk management regulations[139] and external auditing.

The remaining question is how can a company's safety culture be improved? A short, yet very comprehensive, answer to this question is provided by Hudson:

> *"What has to be done for an organisation to develop along the line towards the generative or true safety cultures is a managed change process. The next culture defines where we want to go to, the change model determines how we get there."* (Hudson, 2001, p. 22)

Hence, an organisation first has to assess its current culture. Following this assessment, a plan must be set up for reaching the next cultural step that incorporates the characteristics described in Chapter 2.4.2. This plan must then be implemented and constantly monitored (see Figure 2.13).[140]

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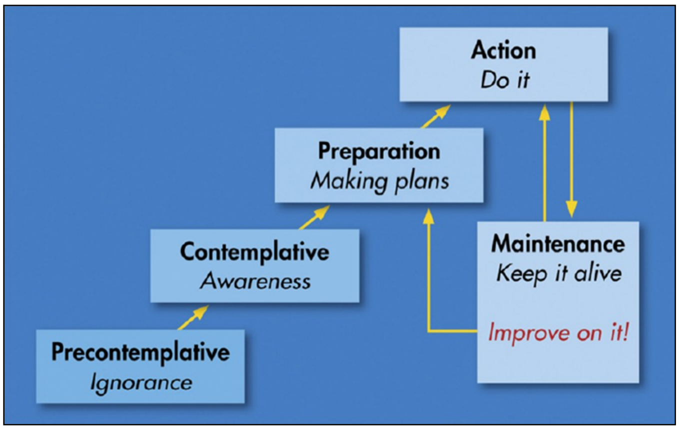
138 Note that DuPont uses a slightly different four-stage safety culture model. When comparing the two models, the term "dependent" can be put on a level with "calculative", "independent" with "proactive" and "interdependent" with "generative".

139 Such as the ISO standards or European Directives, which have been translated into national laws. See, for example, International Organization for Standardization (2009a) or Bundesministerium für Arbeit und Soziales (2002).

140 Please note that this is only a very short outline of the cultural change process. A much more detailed description can be found in either Hudson (2001, p. 22) or Hudson (2007).

Figure 2.13: Culture change model



Source: (Hudson, 2007, p. 704)

During this process, a large set of tools developed in the petrochemical industry over the last decade can be used.[141] The recent developments in the petrochemical industry reflect the current cultural transition.

2.4.4 Recent developments

Along with the findings of petrochemical risk management research that were just described, an industry-wide change process has taken place in recent years. This change process was heavily influenced by the "Texas City" refinery explosion in 2005. After this event, several petrochemical companies adopted an even more thorough approach to the handling of HSE and behavioural risks.

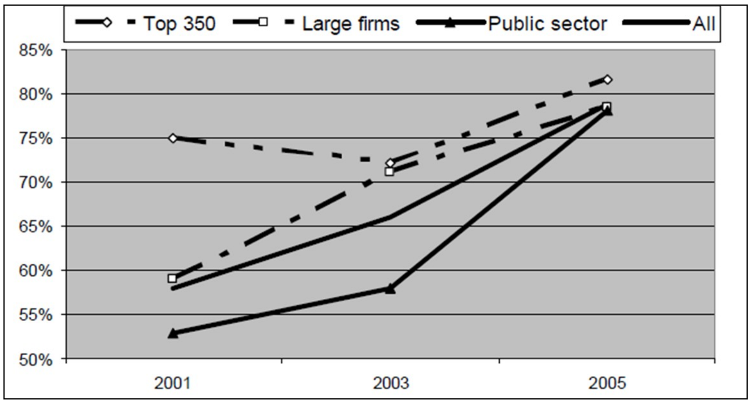
The main developments were a strong increase in *management commitment* towards safety, an increased focus on *process safety*, an increased importance of *contractor safety,* increased *punishment* for rule violations and a call for *industry-wide data collection and forecasting* methods.

- *Management commitment*: Major petrochemical companies define safety as their "number one" business goal, and the message of "safety first" is communicated on a company-wide level. Specific safety campaigns relying on a strong top-down approach were introduced to reach a broad audience of staff members and to achieve the required credibility. From the CEO down to the local employees, the message is constantly communicated. Examples of these campaigns include BP's "Six-Point

[141] These tools are available via the website http://www.eimicrosites.org/heartsandminds/tools.php and include, for example, a questionnaire to assess the current state of the safety culture, "Understanding Your Culture", or a matrix defining appropriate measures in case of violation of safety rules, "Managing Rule Breaking". A detailed guide for selecting the appropriate tools for achieving a culture improvement can also be found in International Association of Oil & Gas Producers (2010b).

Plan",[142] ExxonMobil's "Nobody gets hurt" initiative[143] and Royal Dutch Shell's "Goal Zero" initiative.[144] The increasing commitment towards safety at the highest level of these companies is also demonstrated by a survey of company CEOs that was conducted by the U.K. Health and Safety Executive. As shown in Figure 2.14, there was a strong increase in the percentage of companies that direct HSE issues at the board level between 2001 and 2005.[145]

Figure 2.14: Percentage of companies that direct HSE issues at the board level



Source: (Health and Safety Executive, 2006b, p. vi)

- *Process safety*: The "Texas City" accident also resulted in an increased focus on process safety. Specific programmes and workshops were set up in the different petrochemical companies to review the safety standards of process plants and implement industry best practices. This development was long overdue because companies had overemphasised personal safety in the past, a decision that was criticised by the Baker report:

> *"While BP has an aspirational goal of 'no accidents, no harm to people,' BP has not provided effective leadership in making certain its management and U.S. refining workforce understand what is expected of them regarding process safety performance."* (Baker III et al., 2007, p. xii)

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142 See British Petroleum (2006) or Warner (2006).

143 See Smith (2003b).

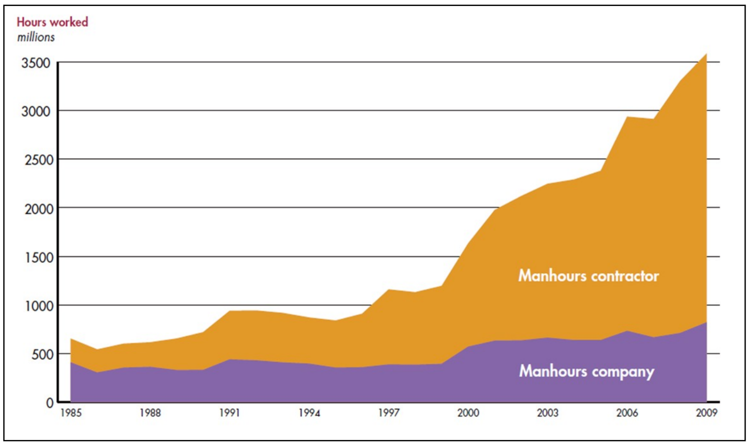
144 See Royal Dutch Shell Group (2010, p. 16).

145 Unfortunately, more recent numbers were not available. Nevertheless, the author strongly believes that recent figures would also underline this trend.

The investigation following the 1998 "Longford" accident was the first to reveal certain weaknesses in the personal injury prevention approach.[146] These weaknesses are highlighted by several more recent studies.[147]

- *Contractor safety*: Over the past decade, the number of contract personnel within the petrochemical industry has increased steadily (see Figure 2.15).

Figure 2.15: Contractor personnel in the petrochemical industry



Source: (International Association of Oil & Gas Producers, 2010a, pp. A-1)

Furthermore, safety-critical activities in petrochemical operations (e.g., maintenance activities) are almost exclusively conducted by contractor personnel. This development provides a difficult challenge for the petrochemical industry in terms of safety because contractors usually do not have rigorous HSE programmes, and they suffer the majority of fatal accidents.[148] As a result, petrochemical companies have increased their efforts to achieve a sustainable safety culture among their contract companies:[149]

> *"The final lesson learned for an Oil Major was that their contractors also have to have Safety Management Systems and that it is in the interests of both parties to have them. ... It may seem surprising that a large*

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146 It is demonstrated by Hopkins (2000, p. 68) and Hopkins (2011, p. 9) that a pure focus on lagging personal safety indicators such as Lost Time Injuries (LTI) will not prevent such accidents from happening.

147 See Anderson (2005) and Knegtering and Pasman (2009, p. 164).

148 See International Association of Oil & Gas Producers (2010a, pp. 1-1).

149 The first indications of the crucial importance of an integrated contractor and company HSE programme were provided by, for example, Rebitzer (1995).

company may even help pay for the development of its contractors, but the experience has shown that it pays off." (Hudson, 2001, p. 13)

Contractors are also audited more rigorously in terms of safety performance and safety management systems. The HSE competence of contractor staff is fostered, and regular on-site safety workshops with company and contractor personnel are conducted.

- *Punishment*: After years of fostering blame-free cultures with only moderate punishment for violation of safety regulations, several major petrochemical companies started to drastically increase punishment for violations. Royal Dutch Shell, for example, has set up a catalogue of so-called "Life-Saving Rules" (LSR).[150] Because a violation of a LSR could have lethal consequences, the punishment for the "offender" ranges from formal discipline to instant dismissal.
- *Industry-wide data collection and forecasting*: Another important challenge that the petrochemical industry faces is the availability and quality of the accident data that serve as the basis for HSE risk assessment. Hence, there are currently increased efforts to compile company- and even industry-wide near-miss and accident databases.[151] The purposes of these databases are to improve quantitative risk assessments through better probability and consequence estimation, to serve as a starting point for the development of accident forecasting methods[152] and to act as a source of continuous learning.

These developments indicate that the idea of a safety culture (and with it, the concept of behavioural economics) is much more deeply embedded in petrochemical organisations today than it was at the beginning of the 21st century. Nevertheless, recent accidents such as the "Deepwater Horizon" oil spill demonstrate that many companies remain far from having generative safety cultures.

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150 See Royal Dutch Shell Group (2010, p. 16).

151 Industry-wide databases include, for example, the Failure and Accidents Technical Information System (FACTS), available at http://www.factsonline.nl, or the Major Accident Reporting System (MARS), available at http://emars.jrc.ec.europa.eu. An example of a company-wide database is Royal Dutch Shell's Fountain Incident Management System, which is based on the Syntex IMPACTEnterprise® software; see Syntex Management Systems (2008).

152 See, for example, Maroño, et al. (2006), Meel et al. (2007), Petroleum Safety Authority Norway (2009) or Sonnemans and Körvers (2006).

In general, the author considers the behavioural approach to safety to be one of the most important developments in the history of petrochemical risk management. However, this approach is not exempt from criticism and faces several strong challenges.

2.4.5 Challenges and criticism

An excellent starting point for the discussion of the safety culture's key challenges is provided by the following passage:

> *"In conclusion, behavioural safety approaches have their place in the management of health and safety on major accident hazard installations and so they are not merely a 'shot in the dark'. However, there are no 'magic bullets' in health and safety."* (Anderson, 2005, p. 115)

Although the idea of an evolutionary, company-wide safety culture has been widely adopted within the petrochemical industry, it is argued that several important aspects of the concept have neither been sufficiently explained in terms of theoretical foundations nor proven empirically.[153] Thus, one of the key challenges for new research in this area will be to address these weaknesses and to provide further theoretical and empirical foundations for the concept.

Furthermore, the road towards a change in safety culture (and, with it, the change of human behaviour in the organisation) often remains unclear. Although the literature provides several tools and guidelines for a managed change process, these tend to be very generic and complicated.[154] For the managers of a petrochemical operation, it is therefore very difficult to determine how the behavioural change process can best be tackled and which influencing factors are within or outside their control. Thus, the concept of behavioural economics in its current state only represents a "black box"; it might be able to predict human behaviour with sufficient accuracy, but it does not reveal any specifics about the working mechanisms of human interactions in a petrochemical operation.

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[153] See Baram and Schoebel (2007, p. 634). The argument of lacking empirical support is seen very differently in Hudson (2007, p. 703).

[154] There is even an implementation guideline for the different HSE culture tools; see International Association of Oil & Gas Producers (2010b).

It is in this field where this thesis breaks new ground. The call for further research on the subject of safety culture[155] and the incorporation of human interactions into risk management decisions is answered by means of an innovative game theoretic approach.

2.5 Concluding remarks

In the second chapter of this thesis, the prevailing definitions, objectives and challenges in the field of petrochemical risk management have been presented. It has been demonstrated that petrochemical risk management is mainly focussed on HSE risks. Furthermore, the human factor and the corresponding behavioural risks play important roles. These facts can be explained by the industry's long history of accident investigation and research, which has shown that, in the majority of cases, human factors (on both the individual and organisational levels) have been the root cause of serious disasters. In this context, deliberate deviations from safe working practices, i.e., violations, pose a considerable challenge for petrochemical risk management and often push the safety system to the edge.

The reasons for the emergence of violations have been investigated extensively, and the concept of behavioural economics provides the most comprehensive explanatory framework. In contrast to common belief, people do not commit violations out of moral considerations but rather by simply balancing the perceived costs and benefits of the action.

To address such behavioural risks, the petrochemical industry has widely acknowledged that simply having an HSE MS in place is not sufficient. These systems or programs must be brought to life by creating a positive organisational safety culture. The concept of a safety culture has been developed within the industry over the past two decades. It is at the core of most petrochemical companies' risk management programmes today. The concept assumes that a safety culture evolves over time and that five stages of organisational maturity need to be distinguished: the *pathological*, *reactive*, *calculative*, *proactive* and *generative* stages. The ideal state is a generative culture, where people are intrinsically motivated to behave safely and safety is deeply embedded in the organisation. Unfortunately, there are only very few organisations today that have attained a generative culture.

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155 See Baram and Schoebel (2007, p. 634).

Hence, most petrochemical companies still strive to improve their safety culture, to reduce their accident numbers and, as a consequence, to increase their profitability. Although there are guidelines on how organisations should undertake this change process, these tools tend to be very generic and complicated. Furthermore, there is a strong call among researchers for further theoretical and empirical foundations of the safety culture concept.

In this thesis, a game theoretic model will be developed that is based on a dedicated mathematical language and that captures the interaction between management and the workforce in a petrochemical operation. This model will not only provide further theoretical foundations for safety culture concepts but also reduce the complexity of such concepts. The complex human interactions will be reduced to their core behavioural economic aspects and will be presented in an easily understandable manner. In addition, a graphical management tool, called the Petrochemical Organisation Risk Triangle (PORT), will be created, which will facilitate the evaluation of different risk management practices, such as increased management commitment, increased severity of punishment and an increased focus on contractor safety. Furthermore, specific recommendations for the improvement of an organisation's safety culture will be provided (e.g., where to attribute resources or which punishment is appropriate). The following chapter describes why a game theoretic approach was chosen and how it can be implemented.

3 Game theoretic approach

3.1 Why game theory?

At first sight, introducing game theory[156] to the context of petrochemical risk management might seem unusual. However, it will be demonstrated in this section that petrochemical risk management indeed offers an ideal "playground" for the application of game theoretic methods.[157]

Simply speaking, game theory studies the interaction between several, i.e., at least two, decision makers.[158] These interactions are modelled in the form of *games* in which the decision makers take the roles of *players*.[159] In a game, each player chooses his respective *strategy,*[160] and at the end of each round, the game results are revealed in the form of *payoffs*. In the course of the interaction, the players' behaviour and the interdependence of their decisions become visible.

By offering a standardised mathematical language, the complexity of human interactions can thus be reduced to only a few constituent parts. Based on these parts, the behavioural risks associated with the interaction can be quantified, and, even more importantly, adequate risk mitigation strategies can be developed. Considering that behav-

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156 John von Neumann and Oscar Morgenstern are considered the founding fathers of modern game theory; see hereto von Neumann & Morgenstern (1953). Important extensions to the game theoretic framework were later provided by the works of John F. Nash, Jr., John C. Harsanyi and Reinhard Selten, who were all honoured with the Nobel Prize in Economics in 1994. See, for example, Nash (1951), Harsanyi & Selten (1988) or Selten (1975).

157 In this section, only a very brief outline of game theory will be provided. For further detail, see, for example, Aliprantis and Chakrabarti (2000), Gibbons (1992), Holler and Illing (2009) or Rieck (2006). In terms of mathematical sophistication, Fudenberg and Tirole (2005) is considered the benchmark of game theory literature.

158 Note that decision makers need not necessarily be individuals. They can also be institutions or even countries; see, for example, Avenhaus (2004) or Tsebelis (1990a).

159 An often-cited example of a simple interaction between two players is the "prisoner's dilemma"; see Aliprantis and Chakrabarti (2000, p. 42) or Gibbons (1992, p. 3).

160 In a game theoretic sense, a "strategy" is a complete plan of actions for every situation the player could confront in the course of the game. See hereto Aliprantis and Chakrabarti (2000, p. 99), Bieta, et al. (2004, p. 234) or Rieck (2006, p. 113).

ioural risks are present at all times and in all forms of human interactions,[161] it is obvious why game theory is such a powerful and almost universal tool.

> *"Many situations in society, from everyday life to high-level politics, are characterized by what economists call strategic interactions. When there is strategic interaction, the outcome for one agent depends not only on what that agent does, but also very largely on how other agents act or react."* (Mäler, 1994)

Especially when revisiting Celati's statement that risk management equals decision-making (see Chapter 2.1), one has to wonder why game theory, as a tool specifically designed for the study of decision making processes, was not introduced to the petrochemical industry much earlier. Although several researchers have long demanded an extension of game theoretic methods to practical applications outside of economics,[162] it has only very recently been recognised that game theory could also provide useful insights to the field of HSE risk management.[163] Therefore, the pioneering work of this thesis is considerably ahead of its time.

Although game theory does not provide a "magic formula", it offers undisputed advantages when dealing with practical applications.[164] Due to its rigorous mathematical standardisation, a practitioner will be guided through the game theoretic labyrinth by means of a strong "thread".[165] When setting up a game model, he will immediately be confronted with the underlying assumptions, facilitating the conceptualisation of a practical problem. Furthermore, game results need to satisfy several well-known solution concepts, such as the Nash equilibrium,[166] and thus offer further assistance in the course of the investigation.

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[161] The interactivity of decisions is often missing in the psychological models also used in petrochemical risk management; see, for example, Cooper & Kagel (2008, p. 433).

[162] See, for example, Avenhaus, von Stengel, and Zamir (2002, p. 1984).

[163] See Health and Safety Executive (2009, p. 8).

[164] See hereto Bagwell & Wolinsky (2002), Bieta, et al. (2004) or Morris and Shin (1999).

[165] This analogy is borrowed from Greek mythology and the saga of Theseus and Ariadne.

[166] For further details on the Nash equilibrium, see, for example, Aliprantis and Chakrabarti (2000, p. 47).

The largest advantage of using game theory in the context of petrochemical risk management is that the concept of behavioural economics is already embedded in the game structure. As has previously been mentioned, the players receive certain payoffs after each round of play. The striking aspect of this seemingly trivial statement is that these payoffs represent the *costs* and *benefits* of their *actions*. Thus, game theory is capable of providing a mathematical structure to the "black box" of behavioural economics. By identifying the key influencing factors of the interaction, game theory is capable of leading the way towards an improved safety culture in *quantitative* terms. The psychological models that are currently used as the basis of safety culture research are not capable of providing specific recommendations to the decision makers, such as how many resources should be attributed to certain HSE issues.

The following sections outline how an adequate game theoretic framework for the petrochemical industry can be developed and integrated into current risk management practices.

First, a practical scenario taken from the daily operation of an archetypal petrochemical refinery will be described. This scenario centres around the current practices on the handling of rule *violations*. The issue of violations was chosen for investigation because this form of human factor poses the most difficult challenge to petrochemical risk management (see Chapter 2.3.1). Furthermore, several recent developments in the context of organisational safety culture will be investigated by means of this practical scenario: the industry-wide introduction of increased *punishment* for the violation of safety procedures, increased *management commitment* towards safety and the increased focus on *contractor safety*.[167]

In an initial step, the interaction between the management and workforce of a petrochemical refinery in the case of rule violations will be analysed by means of a simultaneous inspection game with single interaction, game Γ_1. Special reference will be made to the extensive game theoretic literature on "law enforcement," which serves as a guideline for the investigation. The game model is based on (Pradiptyo, 2007) and does not include accident risks. Nevertheless, the model will provide sound explanations for the emergence of rule violations and will highlight several key influencing factors. A

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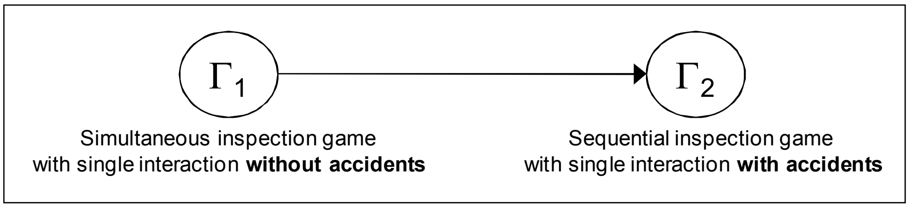
[167] Note that other recent developments, such as the increased focus on process safety as well as the industry-wide data collection and forecasting methods, are also considered important but are not part of this investigation because they are not connected to the issue of behavioural risks.

comparative statics analysis will replicate the effects of increased punishment, increased management commitment and contractor safety.

Because the initial model is not exempt from criticism, it will be extended to incorporate accident risks in a sequential-form inspection game with a single interaction, game Γ_2. The relation between the two game models is depicted in Figure 3.1.

Figure 3.1: Relation between game models Γ_1 and Γ_2



By including both accident risks and a sequential structure in the new model Γ_2, the game theoretic analysis will be brought much closer to reality. Model Γ_2, which is motivated by research results from (Hipel, Kilgour, & Yin, 1995), acknowledges that a violation could lead to an accident and that management only enforces safety procedures after it has witnessed the workforce's actions. Furthermore, the PORT graphical risk management tool will be developed based on Γ_2.

Finally, game Γ_2 will be subjected to the same comparative statics analysis as Γ_1, although it should be kept in mind that the evaluation of different risk management practices is facilitated by the PORT's graphical nature. The chapter will conclude with a presentation of the game theoretic investigation's findings and its impact on petrochemical risk management.

3.2 Violation without accidents

> *"There is a fine line between showing initiative and breaking the rules."*
> (Kletz, 2001, p. 98)

In hazardous environments, which are constantly present in the petrochemical industry (see Chapter 2.2), it is critical that safety procedures are followed. Violations therefore represent the most critical challenge to petrochemical risk management given the unpredictability of human behaviour (see Chapter 2.3.1). The game theoretic analysis of petrochemical risk management thus begins with a practical scenario illustrating the interaction between management and the workforce in case of a violation of safety procedures.

Strong commitment to safe working behaviour and a reduction of accident numbers within company operations are the top business goals of a *Petrochemical Company (PC)*. The essential goal of "no accidents and no harm to people"[168] is transmitted down from the head of the organisation to local operations, e.g., a refinery.[169] Thus, local *Management (M)* is not only in charge of operating its refinery profitably, but it must also generate and enforce the required safety performance among its *Workforce (W)*. The PC finances the enforcement and sets out the guidelines for the punishment of safety rule violations. Given this background, M can choose between *enforcing* and *not enforcing* safety procedures, while W can either *violate* or *not violate* those procedures. If W is "caught" during a violation, it will suffer a punishment. Hence, if W expects M to enforce safety procedures, W will prefer not to violate. However, enforcement will also be costly for M. Hence, if M expects W not to violate, then M will prefer not to enforce and not to spend any unnecessary effort on the enforcement. Similarly, if W knows that M is not going to enforce the safety procedures, W will violate and profit from the associated benefits.

Because this interaction is considered strategic, i.e., both players know about their opponent's possible choices and try to play the "best responses", it can best be analysed by means of a game theoretic model.

3.2.1 Model

The above scenario will be modelled as a standard two-player[170] simultaneous inspection game Γ_1 according to (Pradiptyo, 2007), featuring W as *Player 1* and M as *Player 2*. This game, which represents a revised version of the original inspection game described in (Tsebelis, 1990), was chosen for several reasons.

The strategic enforcement situation between two players, an *inspector* and an *inspectee*,

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168 See, for example, British Petroleum (2008).

169 In a refinery, petroleum products such as gasoline or fuel oil are produced by means of chemical processes. For further information, see Favennec and Baker (2001, p. 134).

170 The PC is not incorporated into the game model because it does not participate directly in the interaction. Instead, it issues the guidelines for punishment and reward of both players, i.e., it defines the rules of the game. Based on these rules, M and W interact on a regular basis in the local petrochemical operation. As a consequence, it seems reasonable to assume that a two-player game model captures the main ingredients of the risk management problem.

exactly fits the scenario of safety procedure violations, i.e., that M, as the inspector, wants the inspectee W to comply. Furthermore, inspection games have been successfully implemented in a large array of different applications, ranging from arms control to law enforcement and the enforcement of environmental regulations. These applications are very well documented and show many similarities to the enforcement of safety procedures in the petrochemical industry.[171] This thesis argues that, in principle, enforcing a law is no different from enforcing a safety procedure and it is therefore considered worthwhile to extend the application of inspection games to the field of petrochemical risk management.[172]

In the "language" of game theory, the initial scenario can be "translated" into a simple 2x2 matrix, as shown in Table 3.1, or an identical game tree, as shown in Figure 3.2.[173] In both cases, the strategic interaction between M and W is defined by the following assumptions and corresponding algebraic inequalities:

1. $a_{21} > a_{11}$: W prefers not to violate if M enforces. More specifically, W's payoff for not violating in case of enforcement is considered to be positive, whereas its payoff from a detected violation is negative, i.e., $a_{21} > 0 > a_{11}$.
2. $a_{12} > a_{22}$: W prefers to violate if M does not enforce. Furthermore, W's payoff for not violating in case of no enforcement is considered to be positive, i.e., $a_{12} > a_{22} > 0$.
3. $b_{11} > b_{12}$: M prefers to enforce if W violates. In addition, M's payoff of not enforcing in case of violation is considered to be neutral at best but is most likely negative, i.e., $b_{11} > 0 \geq b_{12}$.

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171 For a short overview of typical applications, see Avenhaus, et al. (2002) or Avenhaus (2004). For specific applications in law enforcement, see, for example, Andreozzi (2004), Friehe (2008), Kirstein (2005), Pradiptyo (2007), Tsebelis (1990a), Tsebelis (1990b) or Rauhut (2009). For environmental enforcement applications, see, for example, Brams and Kilgour (1992), Fang, Hipel, and Kilgour (1997), Franckx (2001a), Franckx (2002) or Hipel, Kilgour, and Yin (1995).

172 The proximity between law enforcement and the enforcement of safety procedures is also underlined by the literature on behavioural economics; see Battmann and Klumb (1993, p. 38). The search for new practical applications is postulated by Avenhaus, et al. (2002, p. 1984).

173 For further information on "matrix" and "game tree" representations, see Aliprantis and Chakrabarti (2000, pp. 42–49) and Aliprantis and Chakrabarti (2000, pp. 74–79). These representations are identical with regard to content. For reasons of conceptual completeness, both are presented.

4. $b_{22} > b_{21}$: M prefers not to enforce if W does not violate. Furthermore, M's payoff for not enforcing in case of no violation is considered to be positive, i.e., $b_{22} > 0$.

Table 3.1: Matrix representation of game Γ_1

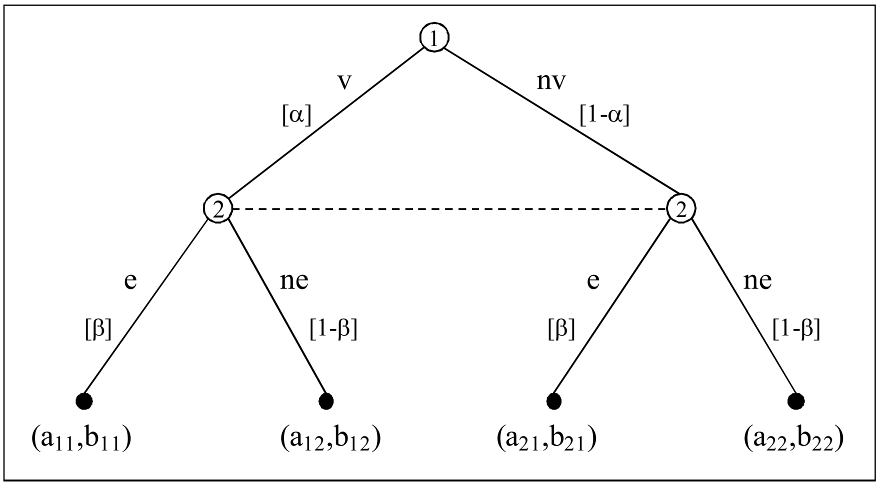
Workforce (1)	Management (2)	
	enforce (β)	not enforce (1- β)
violate (α)	a_{11}, b_{11}	a_{12}, b_{12}
not violate (1- α)	a_{21}, b_{21}	a_{22}, b_{22}

Note. $a_{21} > 0 > a_{11}$, $a_{12} > a_{22} > 0$, $b_{11} > 0 \geq b_{12}$ and $b_{22} > b_{21}$

α: W's violation probability a_{ij}: W's payoff parameters

β: M's enforcement probability b_{ij}: M's payoff parameters

Figure 3.2: Game tree representation of game Γ_1



By offering a standardised conceptual approach and compact representation formats, the use of game theory immediately leads to a drastic reduction of complexity. However, because there is always a trade-off between complexity, i.e., the "real-life" practical application, and simplicity, i.e., the game theoretic model, a careful identification of the model's underlying assumptions is required:

1. The game is only played once by M and W, i.e., a *single interaction*.
2. M and W are both considered a *homogeneous mass*, i.e., there will be no distinction between individual members of each group.
3. Both players choose their strategies *simultaneously*.

4. The game is characterised by *imperfect information*,[174] i.e., the players do not possess any knowledge about their opponent's strategy until both have made their choices and game results are revealed.[175] The dotted line in Figure 3.2 indicates the simultaneous choice at the corresponding information set.[176]
5. If a violation takes place when M enforces, it will be detected with certainty, i.e., the game is characterised by *perfect detection*.[177]
6. A violation will not necessarily lead to an accident. Accident risks are thus not incorporated, i.e., there are *no accidents*.
7. Enforcement of safety procedures will induce costs for M, i.e., the game is characterised by *costly inspections*.

It is crucial that these assumptions and the corresponding model limitations are kept in mind during the investigation. The simple structure of game Γ_1 was chosen primarily because it allows easy access to the field of game theory. Painting an accurate picture of the practical application was a secondary consideration. However, the model will later be extended, and several of the initial assumptions, i.e., model limitations, will be relaxed.

As the game model has now been sufficiently defined, the analysis will proceed to further investigate the players' behaviour and, more specifically, the key influencing factors regarding violations and enforcement. Unfortunately, the current payoff structure with a single unified parameter a_{ij} or b_{ij} at each of the game tree's end nodes (see Figure 3.2) does not allow any specific conclusions to be drawn in that respect.

At this point, this thesis breaks new ground for petrochemical risk management research by creating a direct link between game theory and behavioural economics. To perform a more detailed behavioural analysis, specific identities for the players' payoff parameters a_{ij} and b_{ij} will be developed and expressed as *costs* and *benefits*.

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174 For more details on the different types of information, see Fudenberg and Tirole (2005) or Holler and Illing (2009, pp. 42–52). An excellent summary is provided by Rieck (2006, pp. 142–143).

175 However, according to Tsebelis (1990a, p. 11), this assumption might be irrelevant because different states of information do not alter the inspection game's results.

176 For more details on the significance of information sets, see, for example, Aliprantis and Chakrabarti (2000, pp. 96–99) or Sieg (2005, pp. 34–37).

177 For games with imperfect detection, see, for example, Brams and Kilgour (1992) or Rothenstein and Zamir (2002). Imperfect detection is defined as a second-order statistical error; see Rinderle (1996, p. 53).

Although the theory of behavioural economics has been known for almost two decades and it has been widely acknowledged that people weigh the perceived costs and benefits of their actions before committing a violation (see Chapter 2.3.2), research has so far only provided a very limited idea of the actual structure of these costs and benefits.[178] Game theory provides an excellent tool to fill this research gap and to shed some light on the "black box" of behavioural economics because the underlying "mental economics" can be structured in a very simple and analytical way.

In a first step, the influencing factors of W's strategic behaviour will be highlighted and the corresponding payoff parameters will be labelled. The second step consists of performing an identical analysis of M's payoff parameters. During the analysis, both *direct* and *indirect* effects on the payoff parameters will be considered.[179]

- *Workforce's payoff parameters:* If W has so far not been caught violating a safety procedure, i.e., W has a clean safety record, W receives a benefit B_C. This benefit includes indirect components in the form of positive reputational effects, e.g., more respect from supervisors as well as less work pressure and better chances on the job market. Furthermore, having a clean safety record also results in a direct monetary benefit due to a good performance appraisal.

  This positive reputational effect and monetary benefit are increased even more if W has demonstrated safe working behaviour on specific occasions. In this case, the documented clean safety record results in a benefit B_D with $B_D > B_C$.

  If W has been caught violating a safety procedure, such positive effects can obviously not be expected. In case of violation, W will receive a punishment and will suffer the corresponding cost C_P. Besides a direct negative effect in the form of a bad performance appraisal, fine, reprimand, demotion or even job loss, the detection will also result in significant indirect reputational losses as well as increased work pressure and limited chances on the job market. Consider, for example, the

178 For example, Reason (2008, p. 58) shows a very good overview of the mental mechanisms of violation but does not elaborate on the hierarchy or correlation of the corresponding costs and benefits.

179 "Direct effects" are defined as having an immediate influence on the players' "earnings", e.g., a fine or bonus. In contrast, "indirect effects" cannot be easily expressed in "monetary terms" but still influence the players' payoff parameters, e.g., gain or loss of reputation. Although the author acknowledges this important distinction, these influences will not be treated separately for reasons of model simplicity and are instead combined in a single payoff parameter. For a detailed analysis of the direct and indirect effects of punishment treated as separate payoff parameters, see, for example, Pradiptyo (2007, p. 209).

violation of a LSR as described in Chapter 2.4.4. The question arises of whether and which other petrochemical company would employ a known safety offender.

Nevertheless, committing a violation will also result in certain benefits B_V. These benefits range from various direct factors such as time savings or extra premiums to indirect effects such as increased respect and less work pressure. A simple example will illustrate these seemingly paradox benefits: consider a supervisor who puts production issues before safety and expects his subordinates to perform quick troubleshooting in the production unit. If the workforce manages to restart production by committing a violation that does not result in an accident, it might be admired for being very effective at troubleshooting. Hence, as long as this violation goes undetected, there will be no negative consequences.

In summary, W's behavioural economics can be characterised by the following parameters:[180]

- B_C: Benefits of a clean safety record
- B_D: Benefits of a documented clean safety record
- B_V: Benefits of a violation
- C_P: Costs of a punishment

By applying the same logic, M's payoff parameters can also be structured in the form of costs and benefits.

- *Management's payoff parameters:* As mentioned in the underlying assumptions, enforcing safety procedures will be costly. Enforcement costs are represented by the parameter C_E. They include direct costs of a safety department that is in charge of implementing and designing safety procedures as well as the costs of safety inspections and meetings. Furthermore, there is an indirect cost component, which refers to the inefficiencies in daily operation caused by the enforcement. Consider, for example, that all employees need to perform regular safety inspections. There will not only be costs caused by the actual loss of productivity and the time required when performing the inspection, but certain inefficiencies will arise because employees are distracted from their regular job activities.

  Furthermore, if a violation has been detected, then M must deliver the punishment

180 The parameters are assumed to be strictly positive. Hence, a negative sign will be applied to indicate a negative value.

and handle the violation. The handling results in costs C_H. On one hand, there will be direct costs such as the time lost while attending safety council meetings, a possible indemnity after instant dismissal of an employee or legal expenses due to a labour court trial. On the other hand, there will also be indirect effects, such as a deteriorating relationship with the local work council or trade unions. Consider the instant dismissal of an employee after violation of a LSR. One can imagine that such a dismissal could easily lead to a controversy between M and the local work council.

Enforcement will nevertheless also result in certain benefits. If M enforces safety procedures in case of a violation, then it will receive an enforcement benefit B_E. This parameter once again includes both direct and indirect effects. In terms of indirect effects, the delivered "sentence" results in deterrence. If M sends the message that "violations are not tolerated", it will gain credibility and respect among W and PC as well as among external regulators. This credibility will lead to an overall reduction of the corporate risk. Direct benefits from the enforcement include a reduction in the number of production upsets and lower insurance premiums due to the decreased number of violations.

With respect to the overall picture, PC's main business goal is to achieve "no accidents and no harm to people" in its local operations. Thus, M also has to meet these objectives in its petrochemical refinery according to the rules of the game that are defined by PC. If the objectives are met, which is generally the case if W complies, then M receives a benefit B_G for having good safety performance. Indirectly, M will be respected and recognised for its effort by W, PC and external regulators. Directly, M will profit from PC's willingness to invest in a safe and thus profitable refinery. Finally, there will also be a positive effect on M's performance appraisals.

If M does not enforce a punishment in case of a violation, it will lose its safety commitment benefits B_S. The negative indirect effects from the message that "violations are tolerated" range from a deteriorating organisational safety culture to deteriorating relations with PC and external regulators. Furthermore, the increased number of violations will lead to more accidents, i.e., direct negative effects. It is argued in this thesis that B_S is contingent on the current state of the organisational safety culture. Hence, if M has established a strong safety culture, then costs for not enforcing a punishment will be high. In contrast, if the safety culture is weak, reputational losses will be small or even non-existent. In summary, M's behavioural economics can be characterised by the following parameters:

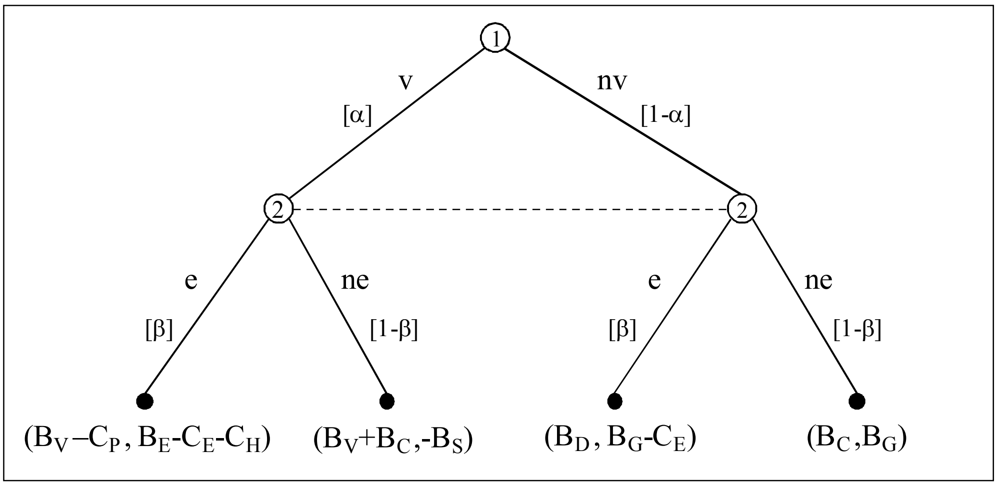
- B_E: Benefits of enforcing safety procedures
- B_G: Benefits of a good safety performance
- B_S: Benefits of a safety commitment
- C_E: Costs of enforcement
- C_H: Costs for handling of a rule violation

Finally, W and M's payoff parameters can be integrated into a new and more detailed representation of game Γ_1, as depicted in Table 3.2 or Figure 3.3, which will serve as the baseline for all further game theoretic analysis.

Table 3.2: Matrix representation of game Γ_1 with explicit payoff parameters

Workforce (1)	Management (2)	
	enforce (β)	not enforce (1- β)
violate (α)	B_V-C_P , B_E-C_E-C_H	B_V+B_C , -B_S
not violate (1- α)	B_D , B_G-C_E	B_C , B_G

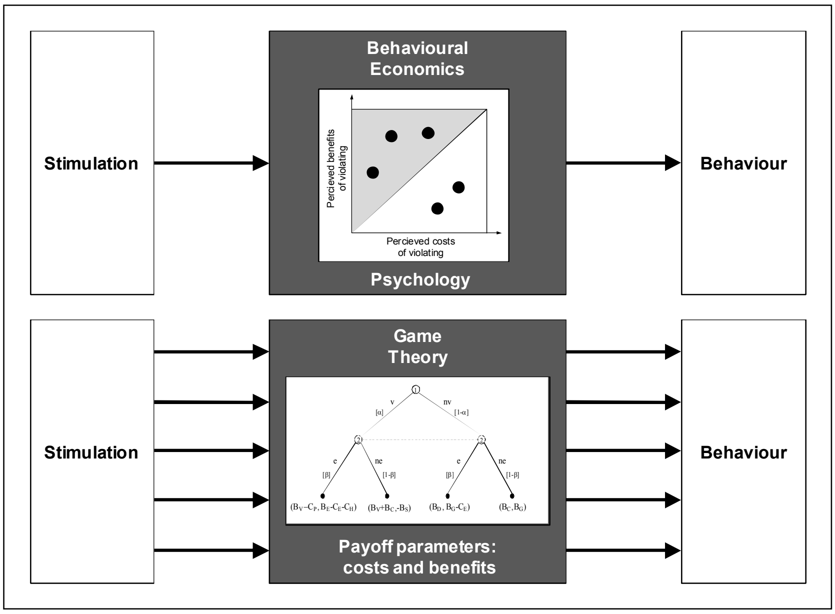
Figure 3.3: Game tree representation of game Γ_1 with explicit payoff parameters



It should be noted that the author does not fully follow (Pradiptyo, 2007) in the identification of payoff parameters. A slightly different notion is used in accordance with (Brams & Kilgour, 1992), i.e., that not enforcing in case of a violation will send a "wrong signal" to W, which is that "violations are tolerated". Hence, instead of setting b_{12} to 0, it is set to a negative value -B_S.

As shown in Figure 3.4, the "black box" of behavioural economics has been structured by means of game theory. Multiple influencing factors in the strategic interaction between W and M have been identified. In contrast to the psychological model, game theory offers specific costs and benefits that will facilitate a quantitative analysis of the associated behavioural risks.

Figure 3.4: Black box of behavioural economics



3.2.2 Solution

It can easily be demonstrated that the game's solution is a single *mixed strategy Nash equilibrium*[181] with the players' optimum strategies denoted by α^* and β^* (see Appendix A.1):

$$\alpha^* = \frac{C_E}{B_E + B_S - C_H} \qquad \text{with} \qquad \alpha^* \in (0,1), \tag{3.1}$$

$$\beta^* = \frac{B_V}{C_P + B_D} \qquad \text{with} \qquad \beta^* \in (0,1). \tag{3.2}$$

The corresponding equilibrium payoffs for both players are given by

$$\pi_1^* = B_C + B_V \frac{B_D - B_C}{B_D + C_P}, \tag{3.3}$$

$$\pi_2^* = B_G - C_E \frac{B_G + B_S}{B_E - C_H + B_S}. \tag{3.4}$$

---

[181] For more information on "mixed strategy" Nash equilibria, see, for example, Aliprantis and Chakrabarti (2000, pp. 69–70) or Rieck (2006, pp. 72–80).

Because $\alpha^*, \beta^* \in (0,1)$, the following payoff parameter conditions[182] can be deduced:

$$C_E > 0 \quad (3.5)$$

$$B_V > 0 \quad (3.6)$$

$$B_E + B_S > C_E + C_H \quad (3.7)$$

$$C_P + B_D > B_V. \quad (3.8)$$

The players' equilibrium strategies[183] (3.1) and (3.2) can be transferred into a proposition that reveals the behavioural economics of the interaction between M and W.

Proposition 1: In the simultaneous inspection game Γ_1, as specified in Table 3.2 or Figure 3.3, among equilibrium conditions:

1. M can never achieve *perfect deterrence,* and W will always violate to some extent. Equally, M will always enforce safety procedures to some extent, i.e., $\alpha^*, \beta^* \in (0,1)$.
2. W's violation probability α^* is determined by the ratio of M's enforcement costs to enforcement benefits plus safety commitment benefits minus handling costs. Interestingly, the violation probability is not influenced by any of W's own payoff parameters, but exclusively by M's costs and benefits of the enforcement; see equation (3.1).
3. M's enforcement probability β^* is positively correlated with W's violation benefits and negatively correlated with W's costs of punishment as well as benefits from a documented clean safety record. M's enforcement probability is also not influenced by any of its own payoff parame-

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182 Note that these parameter conditions are a result of the algebraic inequalities that were defined at the beginning of Chapter 3.2.1 and the resulting mixed-strategy Nash equilibrium. If the game's payoff parameters do not satisfy these conditions, different equilibrium results will be obtained. However, because different results would also signify a complete alteration of the game's strategic interaction, these cases will not be discussed further in this thesis.

183 Not all authors fully agree with this equilibrium selection. Andreozzi (2004) argues that an alternative equilibrium defined by the players' "maximin" strategies could also be imagined. However, this point of view, which is adapted from Holler (1993), does not reflect the prevailing opinion of game theoretic research on the inspection game; see Rieck (2006, pp. 290–293). This path is therefore not pursued further in this thesis. For the interested reader, the author recommends a very compelling article on mixed-strategy equilibrium selection based on the example of penalty kicks in soccer by Chiappori, Levitt, and Groseclose (2002).

ters, but exclusively by W's costs and benefits of violation; see equation (3.2).

In summary, the game theoretic model provides explanations for the emergence of rule violations, in direct contrast to the findings of behavioural economics. The violation of a safety procedure is thus not determined by the violator's (W) own perceived costs and benefits, but by the costs and benefits of its opponent, i.e., the enforcer (M). The same holds true for the enforcement of safety procedures, which is determined exclusively by the violator's (W) and not the enforcer's (M) costs and benefits.

Although these results seem counterintuitive at first, they acknowledge that game theory treats the problem of violations as an interaction between two rational players and not just as a simple single-player decision problem.[184] Game theory thus takes the opponent's reaction into account and delivers new insights on human interaction and the underlying behavioural risks. Therefore, in equilibrium, the reasons for violation are found outside the individual. Whether a rule will be violated is exclusively determined by organisational factors, i.e., management.

It is worthwhile to illustrate the above proposition using a short numerical example. Based on conditions (3.5), (3.6), (3.7) and (3.8), each payoff parameter will be assigned a numerical value.

Table 3.3: Numerical parameter values of game Γ_1

Workforce (1)			Management (2)		
Parameter	Range	Value	Parameter	Range	Value
B_C	[1..5]	2	B_E	[1..20]	14
B_D	[1..5]	3	B_G	[1..10]	5
B_V	[1..10]	5	B_S	[1..10]	6
C_P	[1..20]	10	C_E	[1..5]	3
			C_H	[1..5]	2

Assuming that parameter values and parameter ranges[185] apply according to Table 3.3, the payoff matrix in Table 3.4 can be developed. The corresponding game tree is depicted in Figure 3.5.

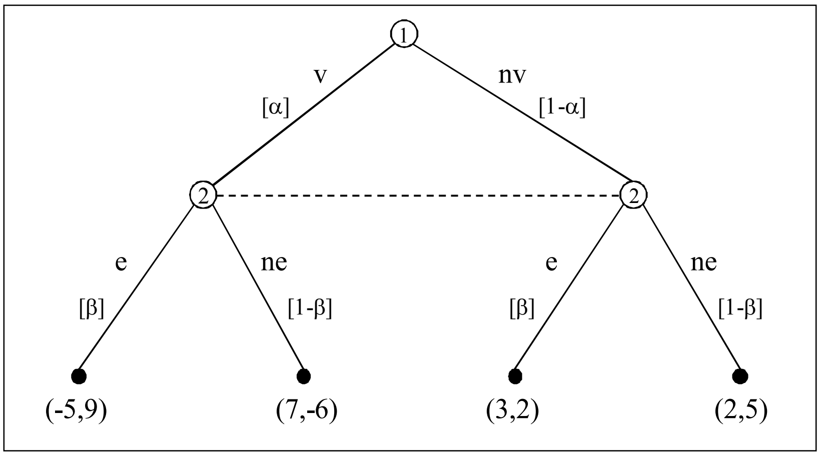
184 It is demonstrated in Tsebelis (1990a, pp. 12–13) that the above propositions are justified despite their counterintuitive nature. The phenomenon that Tsebelis termed the "Robinson Crusoe Fallacy" is detailed in Tsebelis (1989).

185 Parameter ranges have been assigned arbitrarily.

Table 3.4: Matrix representation of game Γ_1 with numerical payoffs

Workforce (1)	Management (2)	
	enforce (β)	not enforce (1- β)
violate (α)	-5 , 9	7 , -6
not violate (1- α)	3 , 2	2 , 5

Figure 3.5: Game tree representation of game Γ_1 with numerical payoffs



By inserting the above payoff parameters into equations (3.1), (3.2), (3.3) and (3.4), the corresponding Nash equilibrium can be calculated. These calculations result in a violation probability $\alpha^* = 0.167$, a payoff $\pi_1^* = 2.385$, an enforcement probability $\beta^* = 0.385$ and a payoff $\pi_2^* = 3.167$.

Among equilibrium conditions, W will thus violate in one out of six cases and will receive a positive expected payoff. M, however, will enforce with a higher probability in approximately four out of ten cases and will receive a slightly higher positive expected payoff. One can easily imagine that M does not consider W's behavioural strategy, i.e., high violation probability, to be very attractive, especially in view of the hazardous environment of a petrochemical refinery. It will therefore be very interesting to investigate which risk management strategies M can apply to reduce W's violation probability and thus the associated behavioural risks.

The investigation will be guided by the recent developments in petrochemical risk management. Comparative statics analyses will provide additional insights into the equilibrium conditions, the underlying rule violations and the enforcement mechanisms.

3.2.3 Increased punishment

Until recently, the common belief within petrochemical risk management was that punishment is not the first best solution to reduce or prevent violations.[186] In accordance with these research results, a systemic approach was favoured in dealing with behavioural risks (see Chapter 2.2.4). Creating a strong organisational safety culture and thus eliminating the root causes for violations were the predominant ideas within the industry. However, as has been described in Chapter 2.4.4, this preoccupation with systemic influencing factors also led to a certain negligence of individual responsibility and almost "blame-free" safety cultures with light to moderate punishment. This outcome must be considered a surprise because risk management research stated long ago that sanctioning violations and rewarding compliance are of key importance[187] and that "*a 'no-blame' culture is neither feasible nor desirable.*"[188] Of course, a punishment must be wisely chosen and contingent on the severity of the infraction.[189]

The recent developments in petrochemical risk management underline that the industry has reconsidered the importance of individual responsibility and direct consequences. One of the most controversial recent developments in that respect is the introduction of severe punishment for certain rule violations such as the LSR. Even though HSE tools had acknowledged that formal discipline is an appropriate means of dealing with violators, HSE tools had never gone as far as instant dismissal of an employee until the LSR and similar regulations were introduced. Consequently, it seems very compelling to investigate the effects of increased punishment on W's violation behaviour from a game theoretic point of view. The key question is whether M will be able to achieve a sustainable improvement of safety performance by employing such a risk management strategy.

During the investigation of increased punishment, one of the central assumptions of (Pradiptyo, 2007) will be upheld. Hence, there is a positive correlation between the severity of a punishment C_P and the handling costs of a violation C_H. If C_P increases, C_H

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186 Hudson, et al. (1998) argue that incentives, i.e., punishment and bonus payments, only fall into the category of less effective remedies against violations.

187 See Reason (1997, p. 73).

188 Reason (1997, p. 195).

189 See Lawton (1998, p. 91). Reason (1997, pp. 205–209) developed the first guidelines for delivering "staged punishments", which were also integrated into modern HSE tools; see, for example, Energy Institute (2011a).

also increases. For example, a severe punishment in the form of an instant dismissal requires careful consideration by M. For M to avoid the impression of a “blame culture”, the punishment must be just and must be backed up by PC. Only then can the punishment be communicated and “fought through” with the local work council.[190] Furthermore, as punishment increases, several effects also lead to an increase of the benefits of enforcement B_E. If M underlines a rigorous safety management with increased punishment, it will gain credibility and reputation among PC as well as among external regulators. In addition, positive deterrence effects will result from this increased credibility.

In game theoretic terms, the introduction of increased punishment is reduced to affecting C_P, C_H and B_E with $\hat{C}_P > C_P$, $\hat{C}_H > C_H$ and $\hat{B}_E > B_E$. Therefore, it is assumed that the level of safety commitment B_S, the benefit from violation B_V, the costs of enforcement C_E and the benefits from good safety performance B_G remain unchanged. These assumptions can be explained as follows.

Increased punishment does not necessarily decrease or increase the amount of incidents, and as a consequence, the level of safety commitment benefits, B_S, will not be altered. Because W’s violation mechanism is defined by two separate components, the benefits of violation, B_V, and the costs of punishment, C_P, only the latter will be influenced. Due to the fact that M still applies the same amount of enforcement, i.e., the same number of inspections and safety department employees, the costs of enforcement, C_E, remain constant. Although the demonstration of a more rigorous safety management increases M’s reputation among PC, in the end, only the resulting safety performance matters. As a consequence, an increased benefit for a good safety performance, B_G, cannot be expected a priori. These assumptions yield a revised version of the original game model, termed $\hat{\Gamma}_1$, and the new payoff matrix[191] displayed in Table 3.5.

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[190] This point of view is strongly influenced by the author’s insights into the restrictive German laws on dismissal protection. In other countries, laws might be less restrictive. Nevertheless, handling costs will also occur in these countries, so the general assumption still holds.

[191] For reasons of simplicity, only the matrix representation of game Γ_1 will be used in the remaining pages of this section. The game tree representation will not be used as it does not provide additional benefit.

Table 3.5: Matrix of game Γ_1 with increased punishment

Workforce (1)	Management (2)	
	enforce (β)	not enforce (1- β)
violate (α)	$B_V - \hat{C}_P$, $\hat{B}_E - C_E - \hat{C}_H$	$B_V + B_C$, $-B_S$
not violate (1- α)	B_D , $B_G - C_E$	B_C , B_G

The new equilibrium conditions of game $\hat{\Gamma}_1$ are denoted by $\hat{\alpha}^*$ and $\hat{\beta}^*$:

$$\hat{\alpha}^* = \frac{C_E}{\hat{B}_E + B_S - \hat{C}_H} \qquad \text{with} \qquad \hat{\alpha}^* \in (0,1), \tag{3.9}$$

$$\hat{\beta}^* = \frac{B_V}{\hat{C}_P + B_D} \qquad \text{with} \qquad \hat{\beta}^* \in (0,1). \tag{3.10}$$

According to common belief, an introduction of increased punishment should result in fewer rule violations by W.[192] Surprisingly, the comparative statics analysis demonstrates that this cannot be guaranteed; see equations (3.11) and (3.12). It is not obvious whether the net benefit of an increased punishment $\hat{B}_E - \hat{C}_H$ will be higher, lower or equal to the initial benefit $B_E - C_H$. Hence, as long as the cost/benefit ratio of the new and more severe punishment remains undetermined, three cases need to be distinguished:

$$\hat{\alpha}^* < \alpha^* \qquad \text{if} \qquad (\hat{B}_E - \hat{C}_H) > (B_E - C_H), \tag{3.11}$$

$$\hat{\alpha}^* \geq \alpha^* \qquad \text{if} \qquad (\hat{B}_E - \hat{C}_H) \leq (B_E - C_H). \tag{3.12}$$

On the other hand, the introduction of a more severe punishment reduces M's enforcement probability with certainty (i.e., over the entire range of parameters), as demonstrated by equation (3.13):

$$\hat{\beta}^* < \beta^* \qquad \text{since} \qquad \hat{C}_P > C_P. \tag{3.13}$$

These results can be summarised by the following proposition:

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192 The effects of punishment on violation behaviour have long been debated in the game theoretic literature. Despite the conventional wisdom that punishment affects violation, the initial research by Tsebelis (1989), Tsebelis (1990a) and Tsebelis (1990b) indicated that punishment has no effect on violation. Since then, the "Payoff Irrelevance Proposition" (PIP) has been challenged by several authors, such as Andreozzi (2004), Fang, et al. (1997) and Hirshleifer & Rasmusen (1992). Their works and the findings on correlated payoffs by Friehe (2008) and Pradiptyo (2007) indicate that punishment can indeed have considerable effects on violation behaviour.

Proposition 2: In equilibrium, an increased punishment reduces M's enforcement with certainty and W's violation probability as long as the net benefits of the new type of punishment dominate those of the initial punishment.

Hence, if a risk management strategy of increased punishment is adopted, it is imperative that the punishment is effective and that the handling costs are kept under control. In practice, this can be achieved, for example, if a severe punishment with strong deterrence effects is applied according to a fair procedure and if it is introduced in close connection with the local work council. In such a case, it is realistic to assume that handling costs rise only marginally and that the new strategy will be successful. The following numerical example highlights the effects of a risk management strategy where punishment and deterrence effects rise drastically and where handling costs only rise marginally. It is assumed that the dominant parameter change among the new strategy is an increased punishment $\hat{C}_P$. Accordingly, $\hat{C}_P$ is set at the maximum of its range. The correlated payoff parameters are represented in Table 3.6.

Table 3.6: Numerical parameter values of game Γ_1 with increased punishment

Workforce (1)		Management (2)	
Parameter	Value	Parameter	Value
B_C	2	$\hat{B}_E$	**18**
B_D	3	B_G	5
B_V	5	B_S	6
$\hat{C}_P$	**20**	C_E	3
		$\hat{C}_H$	**4**

This resulting game matrix of $\hat{\Gamma}_1$ is depicted in Table 3.7.

Table 3.7: Matrix of game Γ_1 with increased punishment and numerical payoffs

Workforce (1)	Management (2)	
	enforce (β)	not enforce (1- β)
violate (α)	**-15 , 11**	7 , -6
not violate (1- α)	3 , 2	2 , 5

The calculation delivers the following equilibrium results: a violation probability $\hat{\alpha}^* = 0.150$, an enforcement probability $\hat{\beta}^* = 0.217$ and the corresponding payoffs $\hat{\pi}_1^* = 2.217$ and $\hat{\pi}_2^* = 3.350$.

Faced with an increased (double) punishment, W will violate less, but compared with the original violation probability, this only means a reduction by 1.7%. On the other hand, M inspects significantly less, i.e., a reduction by 16.8%. In terms of payoffs, there has been a "trade-off" between the players. Whereas M profits from this strategy and receives a slightly increased payoff, W receives a slightly decreased payoff.

Briefly, the results of game $\hat{\Gamma}_1$ indicate that one has to remain sceptical towards increasing the severity of punishment. In addition, when deciding on new risk management strategies, it is advisable to apply proven "best practices" and focus more on providing the positive incentives:[193]

> *"The challenge here is not so much to increase the costs of violating (by stiffer penalties and the like) but to increase the perceived benefits of compliance."* (Reason, 2008, p. 57)

3.2.4 Increased management commitment

As discussed in Chapter 2.4.4, another recent development in petrochemical risk management is that companies nowadays define safety as their top business priority and urge their local management to continuously improve the existing safety culture. This change of mindset has long been demanded,[194] and it is a clear result of numerous research activities that uniformly state that the conflict between safety and production as well as the missing management commitment towards safety are key factors in the emergence of rule violations; see Chapter 2.3.2.

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193 On the doubtful effects of punishment, see Reason (1997, p. 212). Recent experimental game theoretic research also indicates that although punishment might be able to deter violation, it will not always deliver effective results. See hereto Rauhut (2009) and Rauhut & Junker (2009).

194 See hereto Hudson (1992, p. 52). Some positive results of this new mindset have been documented, for example, in Petroleum Safety Authority Norway (2006, p. 13).

"... workers do see managers as exerting control over the quality of their work through the relative emphasis managers place on such things as quality versus production, working safe versus working quickly (the old saying: 'Safety works until we are busy'), and the attitude of management to errors and violations." (Fogarty & Shaw, 2010, p. 1458)

Considering this argument, it is worthwhile to further investigate the risk management strategy of increased management commitment. In game theoretic terms, increased management commitment affects a multitude of parameters: B_C, B_D, B_E, B_G, B_S and B_V, with $\tilde{B}_C > B_C$, $\tilde{B}_D > B_D$, $\tilde{B}_E > B_E$, $\tilde{B}_G > B_G$, $\tilde{B}_S > B_S$ and $\tilde{B}_V < B_V$. At first sight, this strong influence might seem unusual, but there is sufficient empirical and theoretical evidence to underline the subject's pivotal importance.[195] If M is truly committed to safety, then it will increase W's benefits for not violating safety procedures, for example, by receiving higher safety bonus payments, i.e., $\tilde{B}_C > B_C$ and $\tilde{B}_D > B_D$. Furthermore, W's violation benefits will decrease because rule breaking to continue production will not be tolerated, i.e., $\tilde{B}_V < B_V$. By employing a credible commitment, M can also increase the safety performance of its refinery. This will not only lead to fewer production upsets, i.e., $\tilde{B}_E > B_E$, but it will also lead to increased reputational benefits with PC, i.e., $\tilde{B}_G > B_G$. Finally, in such an environment, M would be harshly criticised for tolerance of rule violations and would suffer a considerable loss of reputation, i.e., $\tilde{B}_S > B_S$. Assuming that enforcement costs C_E, handling costs C_H and punishment levels C_P remain unchanged, the corresponding matrix in Table 3.8 can be developed.

Table 3.8: Matrix of game Γ_1 with increased management commitment

Workforce (1)	Management (2)	
	enforce (β)	not enforce (1- β)
violate (α)	$\tilde{B}_V - C_P$, $\tilde{B}_E - C_E - C_H$	$\tilde{B}_V + \tilde{B}_C$, $-\tilde{B}_S$
not violate (1- α)	$\tilde{B}_D$, $\tilde{B}_G - C_E$	$\tilde{B}_C$, $\tilde{B}_G$

195 See Fogarty (2003, p. 4), Mearns and Reader (2008, p. 389), Knegtering and Pasman (2009, p. 168), Organisation for Economic Cooperation and Development (2008, p. 41) or Veltri, Pagell, Behm, and Das (2007, pp. 16–17).

The new equilibrium conditions $\tilde{\alpha}^*$ and $\tilde{\beta}^*$ of the revised game $\tilde{\Gamma}_1$ can easily be deduced:

$$\tilde{\alpha}^* = \frac{C_E}{\tilde{B}_E + \tilde{B}_S - C_H} \qquad \text{with} \qquad \tilde{\alpha}^* \in (0,1), \tag{3.14}$$

$$\tilde{\beta}^* = \frac{\tilde{B}_V}{C_P + \tilde{B}_D} \qquad \text{with} \qquad \tilde{\beta}^* \in (0,1). \tag{3.15}$$

It follows that

$$\tilde{\alpha}^* < \alpha^* \qquad \text{because} \qquad (\tilde{B}_E + \tilde{B}_S) > (B_E + B_S), \tag{3.16}$$

$$\tilde{\beta}^* < \beta^* \qquad \text{because} \qquad (\tilde{B}_V - \tilde{B}_D) < (B_V - B_D). \tag{3.17}$$

These results can be summarised by the following proposition:

> *Proposition 3:* In equilibrium, increased management commitment reduces both W's violation and M's enforcement probability.

The comparative statics analysis shows that increased management commitment has very positive effects: W will violate safety procedures less frequently if it observes that M is truly committed to safety and that compliant behaviour will be rewarded. At the same time, M's enforcement probability also decreases because, in a strong safety culture such as a generative safety culture, W is intrinsically motivated to comply and work safely. Accordingly, once M observes that it has reached a high-level safety culture, it will reduce its enforcement efforts.

A numerical example will illustrate the positive effects of increased management commitment. The dominating parameter changes in this case are a reduced benefit from violation $\tilde{B}_V = 4$ and an increased safety commitment benefit $\tilde{B}_S = 8$.

Table 3.9: Numerical parameter values of game Γ_1 with increased management commitment

Workforce (1)		Management (2)	
Parameter	Value	Parameter	Value
$\tilde{B}_C$	**3**	$\tilde{B}_E$	**20**
$\tilde{B}_D$	**4**	$\tilde{B}_G$	**6**
$\tilde{B}_V$	**4**	$\tilde{B}_S$	**8**
C_P	10	C_E	3
		C_H	2

Together with the parameters in Table 3.9, the matrix representation of game $\tilde{\Gamma}_1$ depicted in Table 3.10 can be deduced.

Table 3.10: Matrix of game Γ_1 with increased management commitment and numerical payoffs

Workforce (1)	Management (2)	
	enforce (β)	not enforce (1- β)
violate (α)	**-6 , 15**	**7 , -8**
not violate (1- α)	**4 , 3**	**3 , 6**

Calculating the new equilibrium results delivers a violation probability $\tilde{\alpha}^* = 0.115$, an enforcement probability $\tilde{\beta}^* = 0.286$ and the corresponding payoffs $\tilde{\pi}_1^* = 3.286$ and $\tilde{\pi}_2^* = 4.385$.

Obviously, increased management commitment causes W to violate less, i.e., a reduction of 5.2% compared with the original game. M's enforcement probability also decreases by 9.9%, but the most striking result is that both players receive a considerably higher expected payoff.

It thus seems that increased management commitment is an appropriate risk management strategy that is even more effective than increased punishment. Nevertheless, achieving a higher-level safety culture does not occur overnight. It is a continuous and time-consuming process that has limits.[196]

3.2.5 Contractor safety

Thus far, W has only been considered as a "homogenous mass", which is rather unrealistic. As pointed out in Chapter 2.4.4, safety-critical activities (e.g., maintenance tasks) within M's petrochemical complex are almost exclusively performed by *Contractors (C),* while *Staff members (S)* mainly execute supervisory tasks.[197] Because the ratio of C to S in daily operations is at least two to one, it is of key importance to find out whether M's enforcement strategy can effectively cope with C's violation behaviour. Several researchers argue that the extensive use of contractors within the petrochemical industry may result in negative changes in safety performance.[198]

196 See Mearns and Reader (2008, p. 396).

197 See Hudson (1992, p. 43).

198 See, for example, Mayhew, Quinlan, and Ferris (1997) and Rebitzer (1995).

"*The use of contractors has, in some cases, increased the risk of chemical incidents. This may be due to the fact that the contractors do not have sufficient knowledge or training in the enterprise's safety policy and procedures, or there is not sufficient co-ordination with regular staff.*" (Organisation for Economic Cooperation and Development, 2008, p. 65)

To determine whether the above statement holds true, the game theoretic analysis provided by Γ_1 will be extended to incorporate C. The introduction of C results in the following parameter changes: $\breve{B}_C < B_C$, $\breve{B}_D < B_D$, $\breve{B}_E < B_E$, $\breve{C}_H < C_H$ and $\breve{C}_P < C_P$. Hence, C faces a less severe punishment $\breve{C}_P$ in case of a violation compared to S. After committing a serious violation, C would simply not be allowed to work in M's petrochemical complex anymore but could still work at different locations for its contractor company. Accordingly, there will most likely not be an immediate loss of earnings. Although C might also face serious reputational losses when caught committing a violation, these would not be as severe as the losses faced by S. Furthermore, C are in general more mobile, provide cheap labour and their safety record does not affect their chances on the job market as strongly as in S's case. As a consequence, $\breve{B}_C$ and $\breve{B}_D$ will be smaller for C than for S. When it comes to M's payoff parameters, its benefits from deterrence $\breve{B}_E$ will be much smaller among C. This difference can be explained by the fact that C often change work locations, i.e., deterrence effects "erode", and M does not have the ability to take direct disciplinary actions. The handling costs $\breve{C}_H$ for delivering a punishment among C are also smaller because, in case of a serious infraction, M simply has to advise the responsible contractor company to remove the violator from its refinery. There will be no lengthy discussion with the local work council. Finally, the benefit from violation B_V remains unchanged because it is irrelevant whether C or S violates, i.e., both will have an immediate benefit in the form of time savings and an improved reputation. Taking all of these effects into account, the corresponding payoff matrix depicted in Table 3.11 can be developed.

Table 3.11: Matrix of game Γ_1 with contractor safety

Contractor (1)	Management (2)	
	enforce (β)	not enforce (1- β)
violate (α)	$B_V - \breve{C}_P$, $\breve{B}_E - C_E - \breve{C}_H$	$B_V + \breve{B}_C$, $-B_S$
not violate (1- α)	$\breve{B}_D$, $B_G - C_E$	$\breve{B}_C$, B_G

The new equilibrium conditions $\breve{\alpha}^*$ and $\breve{\beta}^*$ of the revised game $\breve{\Gamma}_1$ can easily be deduced:

$$\breve{\alpha}^* = \frac{C_E}{\breve{B}_E + B_S - \breve{C}_H} \qquad \text{with} \qquad \breve{\alpha}^* \in (0,1), \tag{3.18}$$

$$\breve{\beta}^* = \frac{B_V}{\breve{C}_P + \breve{B}_D} \qquad \text{with} \qquad \breve{\beta}^* \in (0,1). \tag{3.19}$$

Theoretically, and similar to Chapter 3.2.3, three cases need to be distinguished:

$$\breve{\alpha}^* < \alpha^* \qquad \text{if} \qquad (\breve{B}_E - \breve{C}_H) > (B_E - C_H), \tag{3.20}$$

$$\breve{\alpha}^* \geq \alpha^* \qquad \text{if} \qquad (\breve{B}_E - \breve{C}_H) \leq (B_E - C_H). \tag{3.21}$$

On the other hand, M's enforcement probability increases with certainty:

$$\breve{\beta}^* > \beta^* \qquad \text{because} \qquad (\breve{C}_P + \breve{B}_D) < (C_P + B_D). \tag{3.22}$$

These results can be summarised by the following proposition:

> *Proposition 4:* In equilibrium, increased violation and enforcement probabilities are to be expected as long as the net benefits of the enforcement are smaller with C than they are with S.

The fact that the petrochemical industry has seen a high number of accidents involving contractors is considered an indication that equation (3.21) holds. This assumption is also supported by the statement that *"mercenaries are contractors. ... we cannot expect the same commitment from them."*[199]

A more detailed comparative statics analysis delivers the following interesting insights: inserting $\breve{B}_E = B_E - \Delta B_E$ and $\breve{C}_H = C_H - \Delta C_H$ with ΔB_E, $\Delta C_H \in R^+$ into equation (3.21) delivers $\Delta C_H - \Delta B_E \gtreqless 0$. Considering that M also needs a contractor manage-

199 Kletz (2001, p. 110).

ment programme, which results in non-negligible handling costs, it does not seem far-fetched to assume that $\Delta C_H < \Delta B_E$ and, consequently, $\Delta C_H - \Delta B_E < 0$. This delivers $\breve{\alpha}^* > \alpha^*$, which supports the proposition that C will violate more often than S.

The following numerical example will highlight the difference between contractor and staff member safety.

Table 3.12: Numerical parameter values of game Γ_1 with contractor safety

Contractor (1)		Management (2)	
Parameter	Value	Parameter	Value
$\breve{B}_C$	**1**	$\breve{B}_E$	**10**
$\breve{B}_D$	**2**	B_G	5
B_V	5	B_S	6
$\breve{C}_P$	**6**	C_E	3
		$\breve{C}_H$	**1**

By inserting the numerical parameters from Table 3.12, the matrix representation of game $\breve{\Gamma}_1$ depicted in Table 3.13 is developed.

Table 3.13: Matrix of game Γ_1 with contractor safety and numerical payoffs

Contractor (1)	Management (2)	
	enforce (β)	not enforce (1- β)
violate (α)	**-1** , **6**	**6 ,** -6
not violate (1- α)	**2 ,** 2	**1 ,** 5

Calculating the new equilibrium outcomes delivers a violation probability $\breve{\alpha}^* = 0.200$, an enforcement probability $\breve{\beta}^* = 0.625$ and corresponding expected payoffs $\breve{\pi}_1^* = 1.625$ and $\breve{\pi}_2^* = 2.800$. Thus, C will violate more frequently than S, i.e., an increase of 3.3% compared with the original game. Because enforcement instruments are less effective, M must enforce significantly more often, i.e., an increase of 24%. In terms of payoffs, it can be observed that both players receive a decreased expected payoff. In case of C, this decrease is significant, and it underlines why C cannot produce the same safety performance as S.

In summary, if M wants to improve safety performance in its refinery, it must employ a risk management strategy that offers an adequate incentive structure to contract companies. For example, by setting up long-term contracts that include specific HSE targets and by integrating contractors into the refinery's safety programme, such incentives can be generated. However, as the game model demonstrates, one has to remain sceptical whether a company can ever achieve the same safety performance with contractors as it can with its own staff.

3.3 Violation with accidents

The analysis of the simple game model Γ_1 and the corresponding comparative statics analyses indicate several factors contributing to successful HSE risk management. According to the game model, punishment is less effective than management commitment, and good safety performance among contractors can only be achieved if M offers adequate incentives to the contract companies. Although M could use these insights to optimise its risk management strategy, it also has to be acknowledged that several realistic effects of the interaction between M and W have thus far been neglected. It will be compelling to investigate whether the propositions of game Γ_1 also hold true under more realistic circumstances.

The most important simplifications of game Γ_1 are that accident risks were not incorporated and the interaction was considered simultaneous. To render the analysis more realistic, the interaction between W and M with accident risks will now be studied by means of a new and more sophisticated game model Γ_2. This game model is motivated by the research results provided by (Hipel et al., 1995).

It must be kept in mind that when W commits a violation, it leaves the circle of "normally safe operation", and, as a consequence, accident risks rise dramatically; see Chapter 2.3.1. However, even if W complies with all safety procedures, it cannot be ruled out that an accident might be caused by a "force majeure". Of course, the risk of an accident is much greater in case of violation than in case of compliance.

To proceed with the investigation, the original scenario known from Γ_1 will be revisited. The central parts of the scenario will remain unchanged, i.e., M is still part of a bigger organisation PC, and its main goal is to achieve good safety performance in its petrochemical refinery. However, despite this common starting point, several of Γ_1's initial assumptions will be relaxed on the road towards the new game model Γ_2. The new and more realistic game model Γ_2 will also lead to an intuitive graphical representation of an organisation's safety culture. This representation, called the PORT, is one of the central innovations of this thesis.

3.3.1 Model

The new model Γ_2 differs from the original game in the following important aspects:

1. Both players choose their strategies *sequentially*. At first, W decides whether to *violate* or *not to violate* a safety procedure, knowing that his choice might lead to an *incident* or *no incident*.[200] Following this choice, M observes the result and decides either to *enforce* or *not to enforce*. Despite the model's sequential nature, the game is still characterised by *imperfect information*. Hence, M cannot determine whether W's violation or compliance have led to an incident.
2. A newly introduced player, *Nature (N)*, randomises between *incident* and *no incident* based on *exogenously determined* incident probabilities[201] in case of *violation* r_v or *no violation* r_{nv}.

The remaining assumptions of game model Γ_1 also apply to game Γ_2. By introducing incident risks and eliminating imperfect detection, the environmental monitoring game of (Hipel et al., 1995) is converted into the new game model Γ_2, which is specifically tailored to the requirements of petrochemical risk management.

Following this new set of assumptions, the interaction between M and W in case of violation under incident risks is best captured by the game tree[202] representation of Γ_2 as depicted in Figure 3.6.

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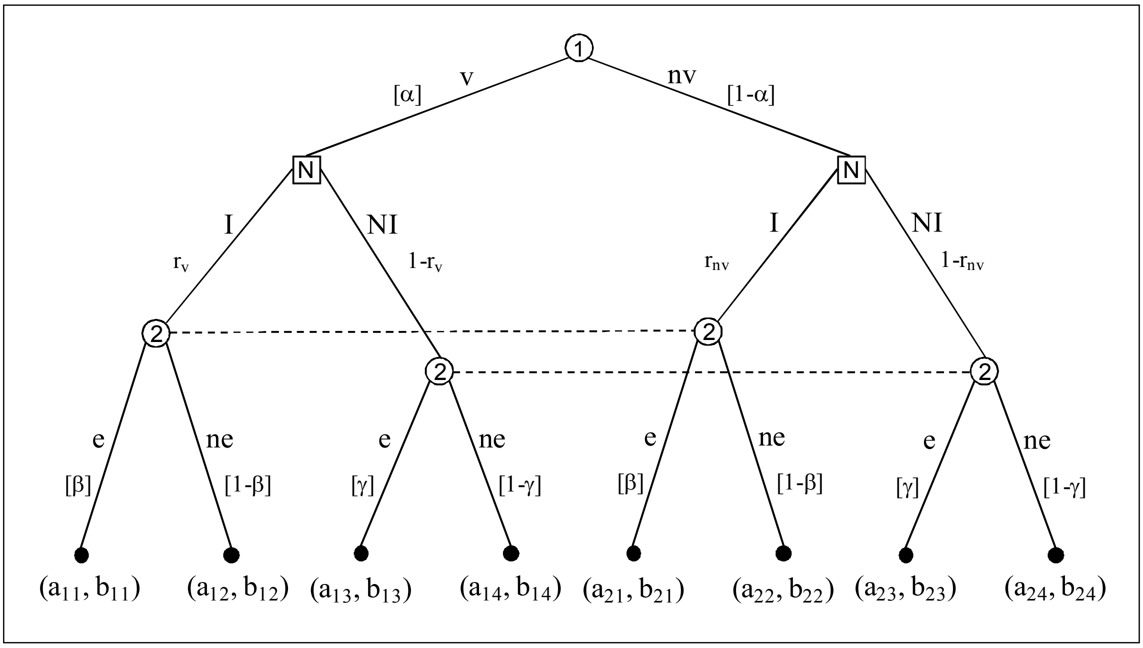
[200] It is important to note that the term "incident" will be used in connection with the new game model Γ_2 instead of the term "accident". This change can be explained by the fact that both near misses and accidents shall be included in the new game model. This is in line with the definition presented in Organisation for Economic Cooperation and Development (2005, p. 26).

[201] The assumption of exogenous incident probabilities is a model simplification. However, it is a standard assumption within a one-shot game. In a repeated game, endogenous incident probabilities can also be generated by applying Bayesian learning; see, for example, Gibbons (1992, pp. 175–244) or Jordan (1995).

[202] In this case, the matrix representation would not provide a good understanding of game model Γ_2's sequential nature. As a consequence, only the game tree will be used in the remainder of this section.

Figure 3.6: Game tree representation of game Γ_2



Note. α: W's violation probability

β: M's enforcement probability in case of an incident

γ: M's enforcement probability in case of no incident

r_v: Incident probability in case of a violation

r_{nv}: Incident probability in case of no violation

a_{ij}: W's payoff parameters

b_{ij}: M's payoff parameters

The strategic interaction between M and W is defined by the following assumptions and corresponding algebraic inequalities:

1. $a_{21} > a_{11}$ and $a_{23} > a_{13}$: W prefers not to violate if M enforces.
2. $a_{12} > a_{22}$ and $a_{14} > a_{24}$: W prefers to violate if M does not enforce.
3. $a_{13} > a_{11}$, $a_{23} > a_{21}$, $a_{14} > a_{12}$ and $a_{24} > a_{22}$: In all cases, suffering an incident is not attractive for W.
4. $a_{12} > a_{11}$ and $a_{14} > a_{13}$: In case of violation, W prefers that M does not enforce.
5. $a_{21} > a_{22}$ and $a_{23} > a_{24}$: In case of no violation, W prefers that M enforces.
6. $b_{11} > b_{21}$ and $b_{13} > b_{23}$: M prefers to enforce if W violates.
7. $b_{22} > b_{12}$ and $b_{24} > b_{14}$: M prefers not to enforce if W does not violate.

8. $b_{13} > b_{11}$, $b_{23} > b_{21}$, $b_{14} > b_{12}$ and $b_{24} > b_{22}$: In all cases, suffering an incident is not attractive for M.

9. $b_{11} > b_{12}$ and $b_{13} > b_{14}$: In case of violation, M prefers to enforce.

10. $b_{22} > b_{21}$ and $b_{24} > b_{23}$: In case of no violation, M prefers not to enforce.

To perform a more detailed behavioural analysis, specific identities for the players' payoff parameters a_{ij} and b_{ij} are developed and are shown in Table 3.14.

Table 3.14: Explicit payoff parameters of game Γ_2

Workforce (1)	**Management (2)**
$a_{11} = B_V - C_{I1} - C_P$	$b_{11} = B_E - C_E - C_H - C_{I2}$
$a_{12} = B_V - C_{I1}$	$b_{12} = -B_S - C_{I2}$
$a_{13} = B_V - C_P$	$b_{13} = B_E - C_E - C_H$
$a_{14} = B_C + B_V$	$b_{14} = -B_S$
$a_{21} = B_D - C_{I1}$	$b_{21} = -C_E - C_{I2}$
$a_{22} = B_C - C_{I1}$	$b_{22} = -C_{I2}$
$a_{23} = B_D$	$b_{23} = B_G - C_E$
$a_{24} = B_C$	$b_{24} = B_G$

Most parameters are already known from Γ_1; only C_{I1} and C_{I2} have been newly introduced. C_{I1} represents W's incident costs, i.e., Player 1, while C_{I2} represents M's incident costs, i.e., Player 2. Once again, these costs can have both *direct* and *indirect* components. In W's case, for example, a direct cost would be suffering an injury, while an indirect cost would be the reputational loss due to having been involved in an incident. M can suffer direct costs due to damaged infrastructure or equipment or indirect costs due to loss of respect from neighbours or external regulatory bodies. By applying the explicit payoff parameters of Table 3.14, one finds the model's essential assumptions shown in Table 3.15. For more detail, a consultation of Appendix A.2 is recommended.

Table 3.15: Essential assumptions of game Γ_2

$B_D - B_V + C_P > 0$	$B_E - C_E - C_H + B_S > 0$
$B_V > B_C > 0$	$B_E - C_H - B_G > 0$
$B_D > B_C$	$B_G + B_S > 0$
$B_C + C_{I1} > 0$	$B_S > 0$
$C_{I1} > 0$	$C_E > 0$
$B_C + C_P > 0$	$B_G + C_{I2} > 0$
$C_P > 0$	$C_{I2} > 0$

In addition, the incident probabilities can be characterised as follows:

$$0 < r_v < 1, \tag{3.23}$$

$$0 < r_{nv} < 1, \tag{3.24}$$

$$r_{nv} < r_v. \tag{3.25}$$

As previously mentioned, both parameters r_{nv} and r_v are determined exogenously. Equations (3.23), (3.24) and (3.25) signify that the probability of suffering an incident can never be fully eliminated and, furthermore, that the incident probability in case of violation is obviously higher than it is in case of non-violation.

3.3.2 Solution

Because all pieces of the new model Γ_2 have now been sufficiently defined, it can be demonstrated that the model possesses three non-transitional Nash equilibria, two in mixed and one in pure strategies. Due to the extensive nature of the equilibrium calculation, only the essential results are presented in the thesis' main text. The complete calculation can be found in Appendix A.3.

The three non-transitional Nash equilibria developed from game Γ_2 all differ in quality. The first equilibrium, which is considered the "worst" of the three, is characterised by "a lot" of enforcement and "a lot" of violation. The second equilibrium is considered "mediocre" because it is characterised by "some" violations and "some" enforcement. Finally, the third equilibrium can be considered an "ideal" state with no violation and no enforcement.

By connecting these game theoretic results with the concept of organisational safety culture, this thesis breaks new ground for petrochemical risk management research.

Hence, in accordance with the evolutionary safety culture ladder described in Chapter 2.4.3, the worst equilibrium is termed *reactive*, the mediocre is termed *calculative/proactive* and the ideal state is termed *generative*.

1. Reactive equilibrium:

$$(\alpha^*,\beta^*,\gamma^*) = (R_2, 1, \frac{E_1 - B_1}{F_1}) \quad (3.26)$$

$$\text{if} \quad 0 < r_v \leq X \qquad \text{with} \qquad X = \frac{B_V - r_{nv}(B_D - B_C - C_{II})}{B_C + C_P + C_{II}}, \quad (3.27)$$

$$R_2 = \frac{(1 - r_{nv})C_E}{(1 - r_{nv})C_E + (1 - r_v)(B_E - C_E - C_H + B_S)} \quad (3.28)$$

$$\frac{E_1 - B_1}{F_1} = \frac{r_v(B_C + C_{II} + C_P) + r_{nv}(B_D - B_C - C_{II}) - B_V}{r_v(B_C + C_P) + r_{nv}(B_D - B_C) - (B_D + C_P)}. \quad (3.29)$$

The parameter X represents the *Reactive Equilibrium Threshold (RET)*, which can be interpreted as a measure of W's willingness to violate. X depends on W's violation benefits, and the expected costs and benefits in case of an incident despite compliant behaviour. This expression is divided by the sum of W's benefits of compliance, its punishment and its incident costs.

As demonstrated by equation (3.27), the reactive equilibrium applies if the incident probability in case of violation r_v is smaller or equal to the RET. In this case, W violates with probability R_2, whereas M always enforces in case of an incident, i.e., probability 1, and to some extent in case of no incident with probability $\frac{E_1 - B_1}{F_1}$; see equation (3.26).

It becomes obvious that R_2 is determined by M's expected net enforcement and safety commitment benefits in case of a violation but no incident. However, $\frac{E_1 - B_1}{F_1}$ is determined by W's violation benefits and a multitude of W's expected benefits and costs.

Considering the different stages of the HSE culture ladder as depicted in Figure 2.11, the players' strategies best correspond with a *reactive* mindset, i.e., *"Safety is important, we do a lot every time we have an accident."*[203]

Although the reactive equilibrium represents the worst equilibrium, it cannot be termed *pathological* because, in a pathological culture, there would be little or no enforcement. This is clearly not the case in this equilibrium, and the term *reactive* is therefore justified.

The expected payoffs for both players are denoted by the following equations:

$$\pi_1^* = A_1 + C_1 + \frac{D_1(E_1 - B_1)}{F_1} \tag{3.30}$$

$$= B_C + r_{nv}(B_D - B_C - C_{I1}) + (1 - r_{nv})(B_D - B_C)\frac{r_v(B_C + C_P + C_{I1}) + r_{nv}(B_D - B_C - C_{I1}) - B_V}{r_v(B_C + C_P) + r_{nv}(B_D - B_C) - (B_D + C_P)}, \tag{3.31}$$

$$\pi_2^* = A_2 - C_2 + R_2(B_2 + E_2) \tag{3.32}$$

$$= B_G - r_{nv}(B_G + C_E + C_{I2}) + (1 - r_{nv})C_E \frac{r_{nv}(B_G + C_E + C_{I2}) + r_v(B_E - C_E - C_H - C_{I2} + B_S) - (B_G + B_S)}{(1 - r_{nv})C_E + (1 - r_v)(B_E - C_E - C_H + B_S)}. \tag{3.33}$$

2. Calculative/proactive equilibrium:

$$(\alpha^*, \beta^*, \gamma^*) = (Q_2, \frac{B_1}{E_1}, 0) \tag{3.34}$$

$$\text{if} \quad X \le r_v \le Y \quad \text{with} \quad Y = \frac{B_V + r_{nv}C_{I1}}{B_C + C_{I1}}, \tag{3.35}$$

$$Q_2 = \frac{r_{nv}C_E}{r_{nv}C_E + r_v(B_E - C_E - C_H + B_S)} \tag{3.36}$$

$$\frac{B_1}{E_1} = \frac{B_V - r_v(B_C + C_{I1}) + r_{nv}C_{I1}}{r_vC_P + r_{nv}(B_D - B_C)}. \tag{3.37}$$

The parameter Y represents the *Generative Equilibrium Threshold (GET)*, which can also be interpreted as a measure of W's willingness to violate. Y depends on

203 Hudson (2007, p. 704).

W's violation benefits and the expected costs in case of an incident, despite compliant behaviour. The main difference between the reactive threshold X and the generative threshold Y is that, in the case of the generative threshold, the expression is only divided by the sum of W's benefits of compliance and its incident costs. The costs of punishment are not included in the equation.

As demonstrated by equation (3.35), the calculative/proactive equilibrium applies if the incident probability in case of violation r_v lies between the RET and GET. In this mediocre equilibrium, W still violates with positive probability Q_2. Furthermore, M enforces with the probability $\frac{B_1}{E_1}$ in case of an incident and it does not enforce at all in case of no incident, i.e., probability of 0; see equation (3.34).

It becomes obvious that Q_2 is determined by M's expected net enforcement and safety commitment benefits in case of violation and incident. However, $\frac{B_1}{E_1}$ is determined by W's violation benefits and by a multitude of W's expected benefits and costs.

Because this equilibrium represents an intermediate region, it was not possible to attribute a single safety culture. It was therefore decided to regard this equilibrium as the missing link between the *reactive* and *generative* safety cultures. Consequently, it was termed *calculative/proactive*. This mindset is characterised by the statements, "*We have systems in place to manage all hazards*" and *"Safety leadership and values drive continuous improvement."*[204]

Although the game model does not allow an exact distinction between the two safety cultures, it can nevertheless be assumed that a stepwise movement from the calculative towards the proactive stage results in a decreasing violation probability.

The corresponding expected payoffs are given by

$$\pi_1^* = A_1 + \frac{C_1 B_1}{E_1} \tag{3.38}$$

$$= B_C + r_{nv}\left[(B_D - B_C)\frac{B_V - r_v(B_C + C_{I1}) + r_{nv}C_{I1}}{r_v C_P + r_{nv}(B_D - B_C)} - C_{I1}\right], \tag{3.39}$$

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204 Hudson (2007, p. 704).

$$\pi_2^* = A_2 + B_2 Q_2 \tag{3.40}$$

$$= B_G + r_{nv}\left[C_E \frac{r_{nv}(B_G + C_{I2}) - r_v C_{I2} - (B_S + B_G)}{r_{nv} C_E + r_v \left(B_E - C_E - C_H + B_S\right)} - (B_G + C_{I2})\right]. \tag{3.41}$$

Finally, in comparison to the reactive equilibrium, violation and enforcement frequencies of the calculative/proactive equilibrium are reduced for all strategic parameters, as can easily be demonstrated by examining equations (3.26) and (3.34):

$$Q_2 < R_2,\ \frac{B_1}{E_1} < 1 \text{ and } 0 < \frac{E_1 - B_1}{F_1}.$$

3. Generative equilibrium:

$$(\alpha^*, \beta^*, \gamma^*) = (0,0,0) \tag{3.42}$$

$$\text{if } \; Y < r_v < 1. \tag{3.43}$$

If the incident probability r_v exceeds the GET, the ideal safety culture is reached; see equation (3.43). This ideal state without violation and enforcement, as shown in equation (3.42), is termed *generative* and is characterised by the statement, "*HSE is how we do business round here*".[205]

The corresponding expected payoffs are given by the following equations:

$$\pi_1^* = A_1 = B_C - r_{nv} C_{I1}, \tag{3.44}$$

$$\pi_2^* = A_2 = B_G - r_{nv}(B_G + C_{I2}). \tag{3.45}$$

In a nutshell, the behavioural economics of the interaction between M and W can be described by the following proposition.

> *Proposition 5:* In a sequential inspection game Γ_2, as specified in Figure 3.6:
>
> 1. In equilibrium, the violation and enforcement mechanisms of M and W depend on the type of organisational safety culture. The better the safety culture, the less violation by W and the less enforcement by M are to be expected. *Reactive*, *calculative/proactive* and *generative* interactions need to be distinguished.

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205 Hudson (2007, p. 704).

2. In a *reactive* equilibrium, W's violation probability α^* is negatively correlated with M's expected net enforcement and safety commitment benefits in case of a violation but no incident. Interestingly, W's violation probability is not influenced by any of its own payoff parameters. Incident costs also have no influence on W's decision to violate; see equation (3.28).
3. In a *reactive* equilibrium, M enforces with certainty in case of an incident with probability β^*; see equation (3.26).
4. In a *reactive* equilibrium, M's enforcement probability γ^* in case of no incident is determined by W's benefits from violation as well as a multitude of W's expected benefits and costs. These expected costs and benefits refer to the cases of violation and incident as well as no violation and incident; see equation (3.29). Interestingly, W's incident costs influence M's enforcement decision.
5. In a *calculative/proactive* equilibrium, W's violation probability α^* is negatively correlated with M's expected net enforcement and safety commitment benefits in case of violation and incident. Interestingly, W's violation probability is not influenced by any of its own payoff parameters. Incident costs also have no influence on W's decision to violate; see equation (3.36).
6. In a *calculative/proactive* equilibrium, M's enforcement probability β^* in case of an incident is determined by W's benefits from a violation as well as by a multitude of W's expected benefits and costs. These expected costs and benefits refer to the cases of violation and incident as well as to the cases of no violation and incident; see equation (3.37). Interestingly, W's incident costs influence M's enforcement decision.
7. In a *calculative/proactive* equilibrium, M does not enforce in case of no incident; see equation (3.35).
8. In a *generative* equilibrium, there is no violation by W and no enforcement by M; see equation (3.42).

The above proposition offers a new perspective on behavioural economics. The findings indicate that, in equilibrium, the reasons for violation are to be found outside of the individual. Hence, whether a rule will be violated is determined exclusively by organisational factors in combination with exogenously determined incident probabilities. Furthermore, there is a fundamental difference in W's risk perception:

In a *reactive* safety culture, incident risks are blinded out, and only the chance that "everything will go well" is considered. In contrast, in a *calculative/proactive* safety culture, risk perception is characterised by a "chronic unease"[206] that something "could go wrong" see equations (3.28) and (3.36).

This connection of the game theoretic framework and petrochemical risk management research offers an unprecedented possibility to further extend the body of knowledge about human interaction in hazardous environments. As will be demonstrated in the following section, the above equilibrium conditions can even be transformed into a graphical risk management decision-making tool.

3.3.3 Petrochemical Organisation Risk Triangle (PORT)

The idea of developing a graphical risk management tool was developed in this thesis because the significance of the equilibrium results of game Γ_2 will not immediately be evident to an observer without game theoretic knowledge. Thus, to render the model more attractive and accessible for the petrochemical industry, an easily understandable graphical tool termed the "Petrochemical Organisation Risk Triangle" (PORT) was developed. The PORT, which is based on the solid mathematical foundation of game Γ_2, joins the long history of graphical petrochemical risk management tools such as the RAM and SCM; see Chapter 2.2.1.

The combination of a game theoretic model, petrochemical risk management and a graphical tool is, to the best of the author's knowledge, unique and is the central innovation provided by this thesis. As will be demonstrated, this graphical tool even allows for an evaluation of different risk management strategies.

The starting point for developing the PORT are Γ_2's equilibrium conditions (3.27), (3.35) and (3.43), which represent simple linear equations of the type $y = mx + b$ with $y = r_{nv}$ and $x = r_v$. Together with the initial assumption (3.25) that defines the *Equilibrium Envelope Threshold (EET),* the following equations can be deduced:

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206 See Reason (1997, p. 214).

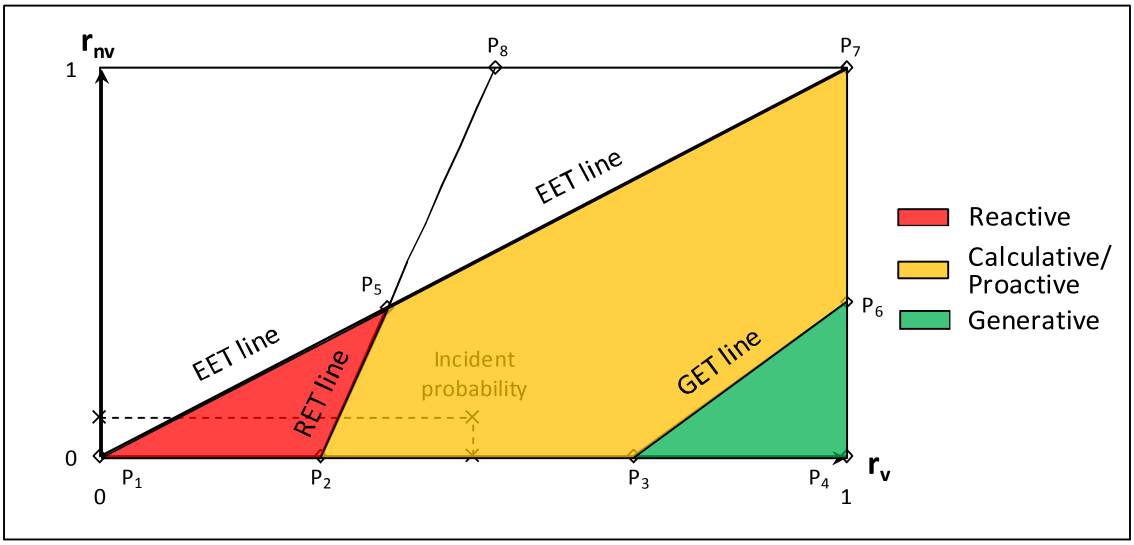
- EET line: $r_{nv} = r_v$. (3.46)

- RET line: $r_{nv} = -\frac{B_C + C_P + C_{II}}{B_D - B_C - C_{II}} \cdot r_v + \frac{B_V}{B_D - B_C - C_{II}}$. (3.47)

- GET line: $r_{nv} = \frac{B_C + C_{II}}{C_{II}} \cdot r_v - \frac{B_V}{C_{II}}$. (3.48)

The striking feature about these three equations is that they represent not only straight lines but also the borders of the equilibrium existence regions. Thus, they allow an immediate visualisation of the safety culture associated with the equilibrium, as depicted in Figure 3.7.

Figure 3.7: Petrochemical Organisation Risk Triangle (PORT)

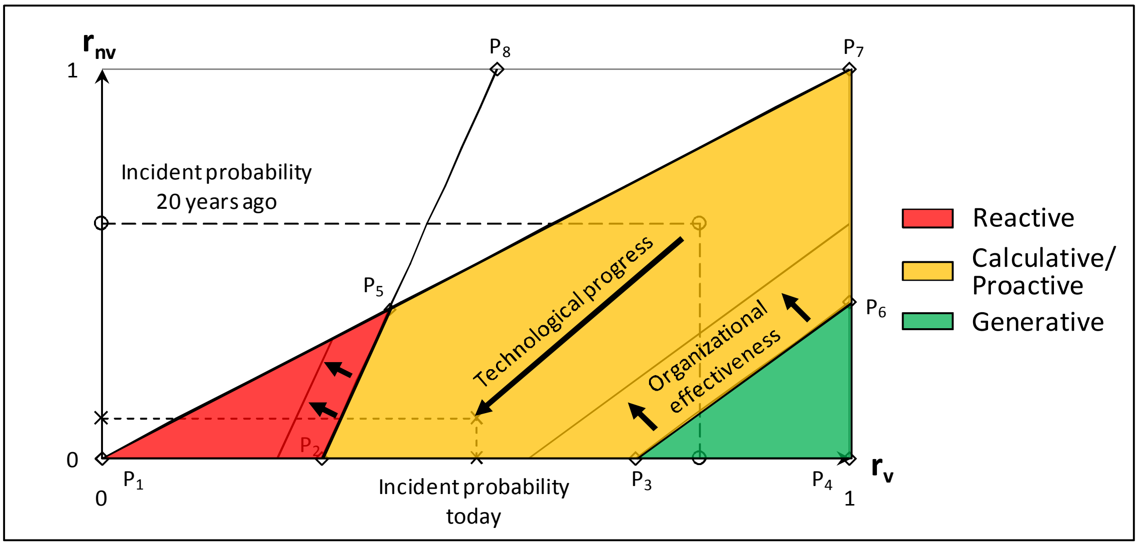


The *reactive* region is determined by the triangle ($P_1P_2P_5$) without line (P_1P_5), the *calculative/proactive* region by the pentagon ($P_2P_3P_6P_7P_5$) without line (P_5P_7) and the *generative* region by the triangle ($P_3P_4P_6$) without line (P_3P_6). The equilibrium thresholds are defined as follows: EET line (P_1P_7), RET line (P_2P_5) and GET line (P_3P_6).

Figure 3.7 reveals that the type of equilibrium and thus the safety culture of a petrochemical organisation depends on the combination of *incident probability* and *attitude towards safety*. The *incident probability*, represented by the exogenous parameters r_v and r_{nv}, determines the x-y coordinates within the PORT. The *attitude towards safety* is represented by the size and shape of the safety culture regions in the PORT. Size and shape depend on the players' payoff parameters and thus on the corresponding equilibrium thresholds.

To understand how the PORT can assist a petrochemical organisation in improving its safety culture by employing adequate risk management strategies, the working mechanisms of the PORT will be explained briefly.

Figure 3.8: PORT with technological progress and organisational effectiveness



In principle, three possible “movements” within the PORT can be imagined: a *change of x-y coordinates*, a *change of safety culture borders* and a *change of both*. These movements can be described in terms of several practical phenomena in the evolution of petrochemical risk management:

1. *Technological progress:* A change of the x-y coordinates in the PORT can only be realised by a variation of the incident probabilities r_v and r_{nv}. Because these parameters are considered exogenous, M and W have no direct influence on them. However, incident probabilities are directly connected to *technological progress*. Consider the following practical example: until twenty years ago, it was not very common in the petrochemical industry for operators to wear flame-retardant clothing. Today, such special clothing is an integral part of the standard personal protective equipment. The introduction of improved personal protective equipment as a part of technological progress thus led to a significant reduction of the incident probability. Therefore, a change in x-y position can be caused by technological process. If M and W had played game Γ_2 twenty years ago, incident probabilities and thus the x-y coordinates would have been different; see Figure 3.8.[207]

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[207] Of course, equilibrium borders would also have been different twenty years ago, but for illustrative reasons this effect was not considered.

2. *Organisational effectiveness*: Changes of the safety culture regions' sizes and shapes can only be realised if the corresponding equilibrium thresholds are "manipulated". According to equations 3.47 and 3.48, this manipulation requires a change in W's incentive structure. Such a change is usually associated with *organisational effectiveness,* which will be demonstrated by the following practical example: Today, safety is regarded as the "number one" business goal. Hence, it is very common that performance appraisals are directly connected to safety performance. A good safety performance will thus lead to a higher bonus payment for W at the end of the year. By implementing such a safety bonus scheme, M improves the organisational effectiveness, which will have a direct impact on the equilibrium borders; i.e., the generative safety culture will move closer. See Figure 3.8.
3. *Safety culture improvement:* A change in x-y coordinates and changes in the shapes and sizes of the equilibrium regions can only be achieved by a combination of the approaches described above. A practical example will be used to illustrate how such a simultaneous movement can occur. Today, all companies within the petrochemical industry have considerably more management commitment towards safety, which leads to increased incentives for W and thus to increased *organisational effectiveness*. In addition, this organisational effectiveness creates room for further *technological progress*. If there is a strong commitment towards safety, improvement will certainly not stop at the individual safety level; process safety, which has a strong technical component, will also be fostered.[208] For example, new technological innovations such as electronic protective functions will be implemented. Consequently, a *safety culture improvement* will cause a decrease in incident risks as well as a shift in safety culture borders; see Figure 3.8.

Because technological progress and organisational effectiveness are slow-moving processes, these improvements take years or even decades. A desirable movement within the PORT can be described as follows:

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208 The point of view that management commitment favours both, personal and process safety, is also supported by Hopkins (2011).

Proposition 6: Assuming that incident probabilities decrease over time and an organisation aims at improving its safety performance, it has to change the safety culture borders within the PORT. The goal is to achieve a movement that allows a generative safety culture to be reached, i.e., the green area.

The following section discusses which risk management practices are appropriate to achieve movement of the safety culture borders. Furthermore, by applying a comparative statics analysis that is identical to the analysis that was used for game Γ_1, additional insights into the violation and enforcement mechanisms of M and W in case of incident risks will be generated.

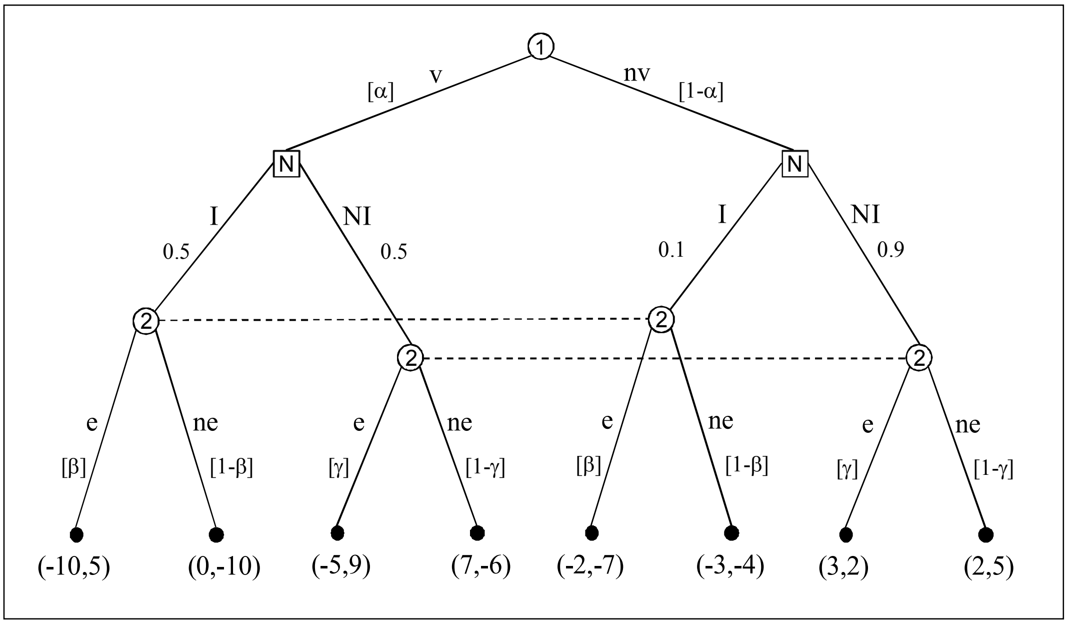
First, to clarify the PORT's working mechanisms, a short numerical example will be provided. Based on the numerical payoff parameters in Table 3.16, a game tree representation of game Γ_2 can be developed, as depicted in Figure 3.9. The corresponding PORT is shown in Figure 3.7.

Table 3.16: Numerical parameter values of game Γ_2

Workforce (1)			Management (2)		
Parameter	Range	Value	Parameter	Range	Value
B_C	[1..5]	2	B_E	[1..20]	14
B_D	[1..5]	3	B_G	[1..10]	5
B_V	[1..10]	5	B_S	[1..10]	6
C_P	[1..20]	10	C_E	[1..5]	3
C_{I1}	[1..10]	5	C_H	[1..5]	2
			C_{I2}	[1..10]	4
Incident probability					
r_v	(0..1)	0.5	r_{nv}	(0..1)	0.1

These numerical values are designed to represent an "average" petrochemical refinery. It is assumed that this refinery has an existing enforcement system with medium punishment, $C_P = 10$, and a safety culture slightly above average, $B_S = 6$. Furthermore, it is assumed that an incident will occur in one out of ten cases if W does not violate, $r_{nv} = 0.1$, and in every second case, if W violates, $r_v = 0.5$.

Figure 3.9: Game tree representation of game Γ_2 with numerical payoffs



It can be demonstrated that, under these conditions, a *calculative/proactive equilibrium* applies because the following values:

$$X = \frac{B_V - r_{nv}(B_D - B_C - C_{I1})}{B_C + C_P + C_{I1}} = 0.318, \; Y = \frac{B_V + r_{nv} C_{I1}}{B_C + C_{I1}} = 0.786 \text{ and } r_v = 0.5$$

satisfy equation (3.35) with $0.318 \leq 0.5 < 0.786$.

A calculation of the corresponding equilibrium parameters from equations (3.34), (3.38) and (3.40) delivers a violation probability $\alpha^* = 0.038$, an expected payoff $\pi_1^* = 1.539$, an enforcement probability in case of an incident $\beta^* = 0.392$, an enforcement probability in case of no incident $\gamma^* = 0$ and an expected payoff $\pi_2^* = 3.635$.

Interestingly, although most of the payoff parameters of game Γ_2 remain unchanged compared with the initial game Γ_1, W violates significantly less, whereas there is almost no change in M's enforcement probability. A possible explanation is that a rather high incident probability in case of violation $r_v = 0.5$ has been chosen. Thus, if W knows that the risk of suffering an incident due to a violation is high, it will be inclined to violate less, in line with the findings of behavioural economics.

3.3.4 Increased punishment

As demonstrated in Chapter 3.2.3, introducing a more severe punishment affects C_P, C_H and B_E with $\hat{C}_P > C_P$, $\hat{C}_H > C_H$ and $\hat{B}_E > B_E$. All other parameters remain unchanged.[209]

It is obvious that the comparative statics analysis for game Γ_2 becomes considerably more complicated in comparison to the original game Γ_1 without incident risks. Different equilibrium cases need to be taken into account; e.g., increasing the severity of punishment in a reactive safety culture will have different effects than implementing the same risk management strategy in a calculative/proactive or generative safety culture.

Table 3.17 summarises the effects of increased punishment on the violation and enforcement probabilities for all equilibrium cases of the revised game $\hat{\Gamma}_2$. A detailed comparative statics analysis can be found in Appendix A.4.

Table 3.17: Effects of increased punishment on equilibrium parameters of game Γ_2

Increased punishment	$C_P \uparrow$, $B_E \uparrow$, $C_H \uparrow$				
Equilibrium parameters	α^*	β^*	γ^*	X	Y
Reactive	$\uparrow=\downarrow$	=	$\downarrow$	$\downarrow$	=
Calculative/proactive	$\uparrow=\downarrow$	$\downarrow$	=	$\downarrow$	=
Generative	=	=	=	$\downarrow$	=

The following proposition summarises the effects of increased punishment.

Proposition 7: In a sequential inspection game $\hat{\Gamma}_2$ with increased punishment:

1. In a *reactive* equilibrium, W's violation probability $\hat{\alpha}^*$ decreases as long as the net benefits of the new type of punishment dominate those of the initial punishment. M's enforcement probability in case of an incident $\hat{\beta}^*$ remains unaffected, and M still enforces with certainty. In case of no incident, M's enforcement probability $\hat{\gamma}^*$ decreases.
2. In a *calculative/proactive* equilibrium, W's violation probability $\hat{\alpha}^*$ decreases as long as the net benefits of the new type of punishment domi-

209 It has to be noted that enforcement costs are assumed to be linear. Exponential costs leading to a prohibitively expensive enforcement as, for example, in air pollution abatement - see Meadows, Randers, and Meadows (2004, p. 18) - have not been considered.

nate those of the initial punishment. M's enforcement probability in case of an incident $\hat{\beta}^*$ decreases. In case of no incident, M's enforcement probability $\hat{\gamma}^*$ remains unaffected, and M still does not enforce.

3. In a *generative* equilibrium, W's violation probability $\hat{\alpha}^*$ remains unaffected, and W still does not violate. Furthermore, M's enforcement probabilities $\hat{\beta}^*$ and $\hat{\gamma}^*$ also remain unaffected, and M still does not enforce.
4. In equilibrium, the RET line moves further to the left and thus shrinks the region in which the reactive equilibrium exists. The GET remains unaffected.

Assuming that harsh punishment of safety violators produces very strong deterrence effects and high reputational losses for the offender and that, at the same time, handling costs only rise marginally, an increase in the severity of punishment will result in fewer rule violations.

Table 3.18: Numerical parameter values of game Γ_2 with increased punishment

Workforce (1)		Management (2)	
Parameter	Value	Parameter	Value
B_C	2	$\hat{B}_E$	**18**
B_D	3	B_G	5
B_V	5	B_S	6
$\hat{C}_P$	**20**	C_E	3
C_{I1}	5	$\hat{C}_H$	**4**
		C_{I2}	4
Incident probability			
r_v	0.5	r_{nv}	0.1

A numerical example with payoff parameters according to Table 3.18 will illustrate the results of this strategy. The results of the numerical calculations are shown in Table 3.19 and are displayed in the PORT in Figure 3.10.

Figure 3.10: PORT with increased punishment

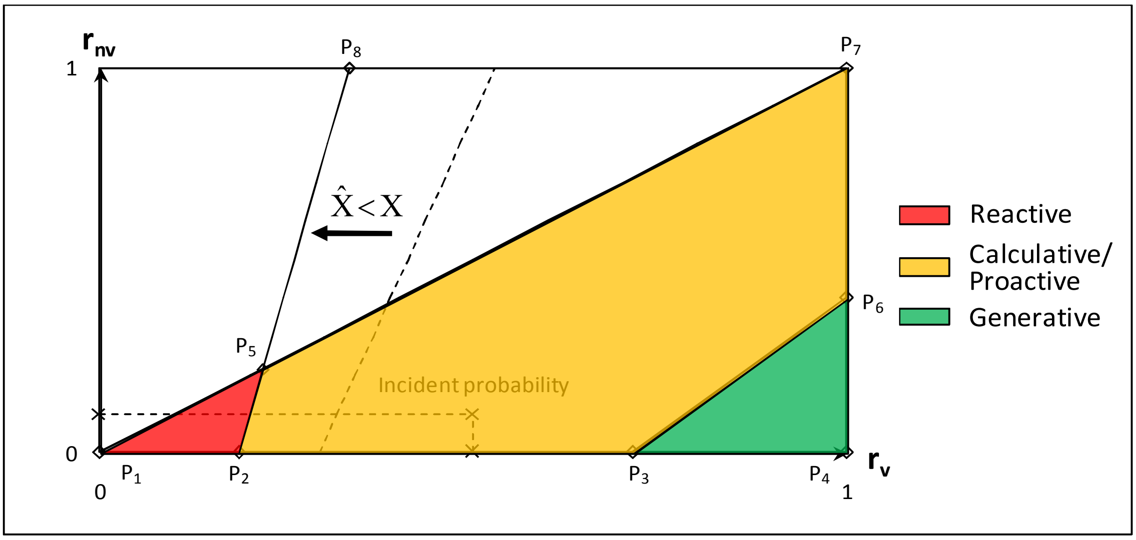


Table 3.19: Numerical effects of increased punishment on game Γ_2

Equilibrium parameters	α^*	β^*	γ^*	π_1^*	π_2^*	X	Y
Original game	0.038	0.392	0	1.539	3.635	0.318	0.786
Increased punishment	**0.034**	**0.198**	**0**	**1.520**	**3.688**	**0.200**	**0.786**

Note that, for reasons of simplicity, this numerical test is only performed for a single incident probability and thus for a calculative/proactive safety culture. An identical analysis could be performed for different safety cultures, but it would not provide any additional benefit to the investigation conducted in this thesis.

Studying the PORT of game $\hat{\Gamma}_2$ depicted in Figure 3.10 reveals that, by increasing punishment, the RET moves further to the left, i.e., $\hat{X} < X$. This corresponds to an increased area of the calculative/proactive region and an improved safety culture because incident probabilities remain unchanged. W will obviously be deterred by M's effective enforcement and will violate less. Equally, M can reduce its enforcement efforts and thereby gain a higher expected payoff. Nevertheless, Table 3.19 also reveals that the improvement of W's violation probability and M's expected payoff are only marginal despite the significant increase in punishment, i.e., the doubling of $\hat{C}_P = 20$.

Finally, the PORT allows the conclusion to be drawn that a risk management strategy of increased punishment, in equilibrium, causes an organisation to move further away from a reactive safety culture (to move closer to a calculative/proactive culture) but does not bring it closer to the generative stage. This statement questions the effectiveness of increased punishment as a successful HSE risk management strategy. Consequently, different risk management strategies will be explored in the following sections.

3.3.5 Increased management commitment

As demonstrated in Chapter 3.2.4, increased management commitment results in the following parameter changes: $\widetilde{B}_C > B_C$, $\widetilde{B}_D > B_D$, $\widetilde{B}_E > B_E$, $\widetilde{B}_G > B_G$, $\widetilde{B}_S > B_S$ and $\widetilde{B}_V < B_V$. However, in comparison to the original game Γ_1, an important simplification is introduced. Increased management commitment increases the benefits of having a clean safety record B_C and of having a documented clean safety record B_D at least equally or slightly in favour of B_D, which results in $\widetilde{B}_D - \widetilde{B}_C \geq B_D - B_C$.

The effects of increased management commitment on all three equilibrium cases of the revised game $\widetilde{\Gamma}_2$ are summarised in Table 3.20. A detailed comparative statics analysis can be found in Appendix A.5.

Table 3.20: Effects of increased management commitment on equilibrium parameters of game Γ_2

Increased management commitment	$B_C \uparrow$, $B_D \uparrow$, $B_E \uparrow$, $B_G \uparrow$, $B_S \uparrow$, $B_V \downarrow$				
Equilibrium parameters	α^*	β^*	γ^*	X	Y
Reactive	↓	=	↑=↓	↓	↓
Calculative/proactive	↓	↓	=	↓	↓
Generative	=	=	=	↓	↓

An increased management commitment has very positive effects on the interaction of M and W, which are summarised by the following proposition.

Proposition 8: In a sequential inspection game $\widetilde{\Gamma}_2$ with increased management commitment:

1. In a *reactive* equilibrium, W's violation probability $\widetilde{\alpha}^*$ decreases. M's enforcement probability in case of an incident $\widetilde{\beta}^*$ remains unaffected, and M thus enforces with certainty. However, M's enforcement probability in case of no incident $\widetilde{\gamma}^*$ decreases as long as the reduction of W's violation benefits dominates the weighted increase of its compliance benefits.
2. In a *calculative/proactive* equilibrium, W's violation probability $\widetilde{\alpha}^*$ decreases. M's enforcement probability in case of an incident $\widetilde{\beta}^*$ also decreases. In case of no incident, M's enforcement probability $\widetilde{\gamma}^*$ remains unaffected, and M still does not enforce.

3. In a *generative* equilibrium, W's violation probability $\tilde{\alpha}^*$ remains unaffected, and W still does not violate. Furthermore, M's enforcement probabilities $\tilde{\beta}^*$ and $\tilde{\gamma}^*$ remain unaffected, and M still does not enforce.
4. In equilibrium, both RET and GET are affected. The RET line moves further to the left and reduces the reactive equilibrium's existence region. The GET line also moves further to the left, resulting in an increase of the generative culture's existence region.

These results can be interpreted as follows. If W observes that M is truly committed to safety and that there is less tolerance for violation, then it will certainly violate less. At the same time, once M observes that it has reached a high-level safety culture, it will reduce its enforcement efforts.

Table 3.21: Numerical parameter values of game Γ_2 with increased management commitment

Workforce (1)		Management (2)	
Parameter	Value	Parameter	Value
$\tilde{B}_C$	**3**	$\tilde{B}_E$	**20**
$\tilde{B}_D$	**4**	$\tilde{B}_G$	**6**
$\tilde{B}_V$	**4**	$\tilde{B}_S$	**8**
C_P	10	C_E	3
C_{I1}	5	C_H	2
		C_{I2}	4
Incident probability			
r_v	0.5	r_{nv}	0.1

The implications of the above proposition will be illustrated by the following numerical example. Table 3.21 reveals the payoff parameters of the interaction, while the equilibrium results are depicted in Table 3.22 and the corresponding PORT in Figure 3.11.

Figure 3.11: PORT with increased management commitment

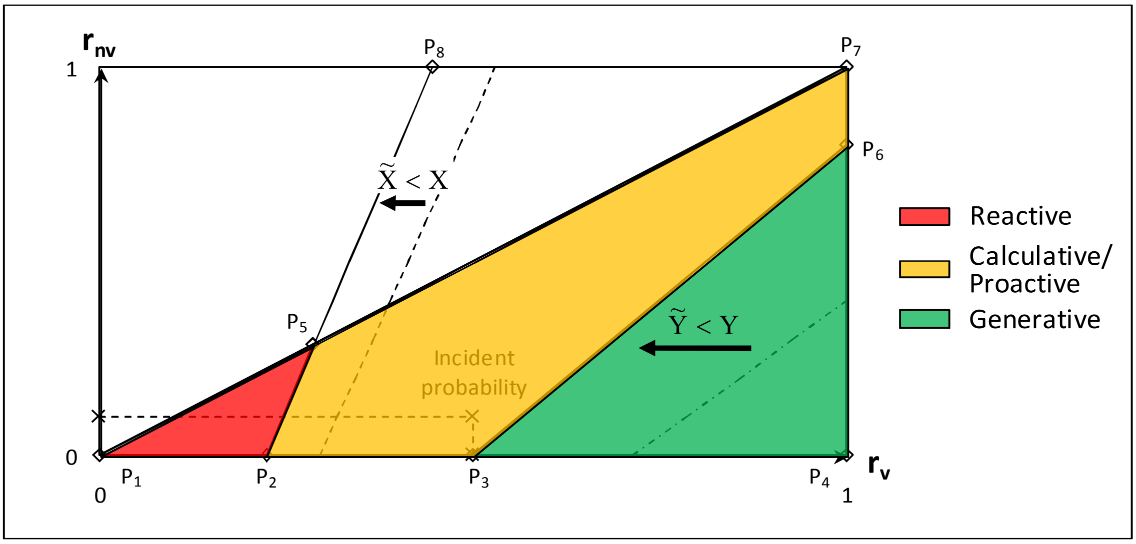


Table 3.22: Numerical effects of increased punishment on game Γ_2

Equilibrium parameters	α^*	β^*	γ^*	π_1^*	π_2^*	X	Y
Original game	0.038	0.392	0	1.539	3.635	0.318	0.786
Increased management commitment	**0.025**	**0.098**	**0**	**2.510**	**4.619**	**0.244**	**0.563**

By looking at the PORT of game $\tilde{\Gamma}_2$, it becomes obvious that increased management commitment results in two very favourable effects. Both RET and GET move further to the left, i.e., $\tilde{X} < X$ and $\tilde{Y} < Y$. Because incident probabilities remain constant, this change in equilibrium thresholds signifies that a generative safety culture becomes more "accessible". Thus, the petrochemical refinery is now very close to the edge of the calculative/proactive region, which results in a considerable improvement in violation behaviour. Table 3.22 also reveals that W will violate less and that M can drastically reduce its enforcement efforts. Furthermore, as the organisation climbs up the "safety ladder", the players' expected payoffs increase.

Finally, the PORT allows the conclusion to be drawn that a risk management strategy of increased management commitment causes an organisation to move further away from a reactive safety culture (and closer to a calculative/proactive culture) and, at the same time, closer to a generative culture. It thus seems that increased management commitment promises to be a more effective risk management strategy than increased punishment.

3.3.6 Contractor safety

As demonstrated in Chapter 3.2.5, safety measures do not show the same effect on contractors as on staff members, as represented by the following parameters: $\breve{B}_C < B_C$, $\breve{B}_D < B_D$, $\breve{B}_E < B_E$, $\breve{C}_H < C_H$ and $\breve{C}_P < C_P$. However, in comparison to the original game Γ_1, an important simplification is introduced. Contractor safety causes the benefits of having a clean safety record B_C and of having a documented clean safety record B_D to decrease equally or slightly in favour of B_D, which results in $\breve{B}_D - \breve{B}_C \leq B_D - B_C$.

The effects of contractor safety on all three equilibrium cases of the revised game $\breve{\Gamma}_2$ are summarised in Table 3.23. A detailed comparative statics analysis can be found in Appendix A.6.

Table 3.23: Effects of contractor safety on equilibrium parameters of game Γ_2

Contractor safety	$B_C \downarrow, B_D \downarrow, B_E \downarrow, C_H \downarrow, C_p \downarrow$				
Equilibrium parameters	α^*	β^*	γ^*	X	Y
Reactive	↓=↑	=	↑	↑	↑
Calculative/proactive	↓=↑	↑	=	↑	↑
Generative	=	=	=	↑	↑

The following proposition summarises the effects of contractor safety.

Proposition 9: In a sequential inspection game $\breve{\Gamma}_2$ with contractor safety:

1. In a *reactive* equilibrium, C's violation probability $\breve{\alpha}^*$ increases as long as the net benefits of the enforcement are smaller for C than they are for S. Considering that M also needs a contractor management programme with significant handling costs, it is realistic to assume that C violates more often than S does. On the on the hand, M's enforcement probability in case of an incident $\breve{\beta}^*$ remains unaffected; M thus enforces with certainty, and M's enforcement probability in case of no incident $\breve{\gamma}^*$ increases.
2. In a *calculative/proactive* equilibrium, C's violation probability $\breve{\alpha}^*$ increases as long as the net benefits of the enforcement are smaller for C than they are for S. Furthermore, M's enforcement probability in case of

an incident $\breve{\beta}^*$ also increases. In case of no incident, M's enforcement probability $\breve{\gamma}^*$ remains unaffected, and M still does not enforce.

3. In a *generative* equilibrium, C's violation probability $\breve{\alpha}^*$ remains unaffected, and C still does not violate. Furthermore, M's enforcement probabilities $\breve{\beta}^*$ and $\breve{\gamma}^*$ also remain unaffected, and M still does not enforce.
4. In equilibrium, both RET and GET are affected. The RET line moves further to the right, and the reactive equilibrium's existence region thus increases. The GET line also moves further to the right, resulting in a reduction of the area of the generative culture's existence region.

These results can be interpreted as follows. If M observes that it is dealing with C instead of S, it increases its enforcement efforts, knowing that C violates more often.

Table 3.24: Numerical parameter values of game Γ_2 with contractor safety

Contractor (1)		Management (2)	
Parameter	Value	Parameter	Value
$\breve{B}_C$	**1**	$\breve{B}_E$	**10**
$\breve{B}_D$	**2**	B_G	5
B_V	5	B_S	6
$\breve{C}_P$	**6**	C_E	3
C_{I1}	5	$\breve{C}_H$	**1**
		C_{I2}	4
Incident probability			
r_v	0.5	r_{nv}	0.1

The implications of the above proposition will be illustrated by the following numerical example. Table 3.24 reveals the payoff parameters of the interaction between M and C, while the equilibrium results are depicted in Table 3.25 and the corresponding PORT in Figure 3.12.

Figure 3.12: PORT with contractor safety

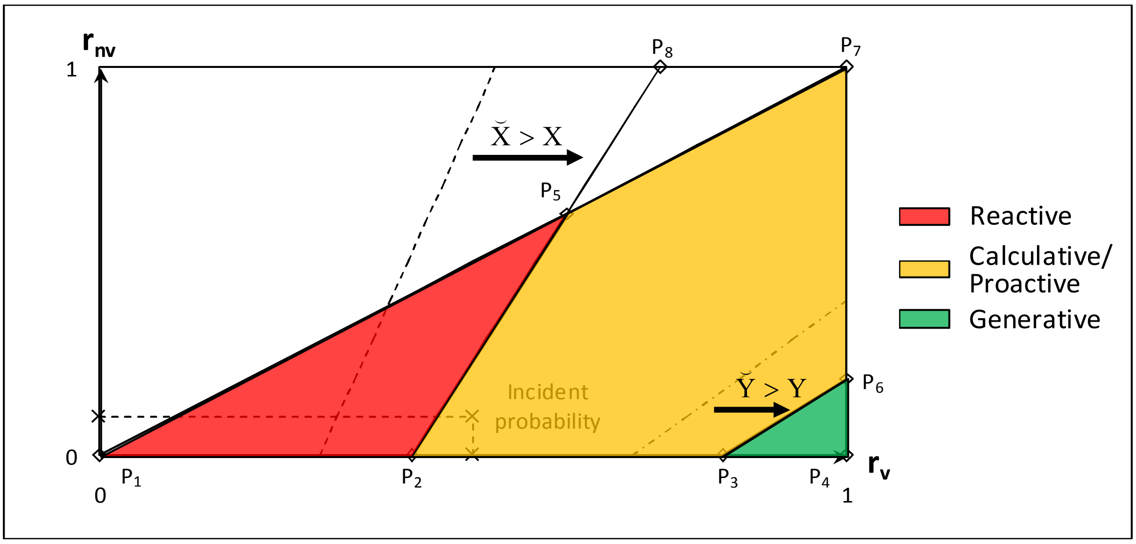


Table 3.25: Numerical effects of contractor safety on game Γ_2

Equilibrium parameters	α^*	β^*	γ^*	π_1^*	π_2^*	X	Y
Original game	0.038	0.392	0	1.539	3.635	0.318	0.786
Contractor safety	**0.048**	**0.807**	**0**	**0.581**	**3.524**	**0.450**	**0.917**

The PORT of game $\breve{\Gamma}_2$ reveals that when dealing with contractors, M has to cope with the undesirable effect that both RET and GET move further to the right, i.e., $\breve{X} > X$ and $\breve{Y} > Y$. Because incident probabilities remain constant, the change in equilibrium thresholds signifies that compared with an identical group of S, C are less advanced on the safety cultural ladder. They are closer to the reactive than to the generative stage and consequently commit more violations. Furthermore, M needs to enforce punishments more frequently to maintain the existing safety standard. Finally, Table 3.25 also reveals that compared with the original game, both players will receive a reduced expected payoff. In the case of C, this reduction is significant and explains why violations occur more often.

The PORT thus supports the conclusion that a successful contractor safety risk management strategy must achieve similar incentives among C and S. Otherwise, M can never expect the same type of safety performance from C. Furthermore, the use of C moves an organisation towards a reactive safety culture and, at the same time, further away from a generative culture.

Finally, the effects of an improved safety standard will be investigated in the following section.

3.3.7 Improved safety standard

An improved safety standard is closely connected to the two phenomena of *technological progress* and *organisational effectiveness* described in Chapter 3.3.3. In game theoretic terms, these phenomena are equivalent to a reduction of the overall *risk level*, i.e., a reduction of incident *probability* and c*onsequence*. As part of technological progress, the introduction of more advanced personal protective equipment or inherently safer process design leads to a reduction of incident probability, i.e., $\hat{r}_{nv} < r_{nv}$ and $\hat{r}_{v} < r_{v}$. As part of organisational effectiveness, a reduced number of incidents leads to a reduction of incident costs, i.e., $\hat{C}_{11} < C_{11}$ and $\hat{C}_{12} < C_{12}$. A detailed comparative statics analysis of both effects is presented in Appendix A.7.

The effects of an increased safety standard caused by technological progress are summarised in Table 3.26 for all three equilibria of game $\hat{\Gamma}_2$.

Table 3.26: Effects of technological progress on equilibrium parameters of game Γ_2

Improved safety standard due to technological progress	$r_{nv}\downarrow$, $r_{v}\downarrow$				
Equilibrium parameters	α^*	β^*	γ^*	X	Y
Reactive	↓=↑	=	↓=↑	=	=
Calculative/proactive	↓=↑	↓=↑	=	=	=
Generative	=	=	=	=	=

According to the initial assumptions, game model Γ_2 is a "one-shot" game. However, an improvement in incident probabilities over time can be simulated by inserting the new (improved) probabilities $\hat{r}_{nv}$ and $\hat{r}_{v}$ into the model for a new round of play. As incident probability improves over time, one could imagine continuous rounds of a revised game $\hat{\Gamma}_2$ being played.[210] The results of reduced incident probabilities are summarised by the following proposition.

[210] It should be noted that the repeated game itself is not part of this investigation, but it might be an interesting starting point for future research.

Proposition 10: In a sequential inspection game $\widehat{\Gamma}_2$ with improved safety standard due to technological progress:

1. In a *reactive* equilibrium, W's violation probability $\widehat{\alpha}^*$ depends on the variation of incident probabilities. As long as both incident probabilities decrease by the same amount, W's violation probability is bound to decrease. M's enforcement probability in case of an incident $\widehat{\beta}^*$ remains unaffected, and M thus enforces with certainty. However, M's enforcement probability in case of no incident $\widehat{\gamma}^*$ increases as long as both incident probabilities decrease by the same amount.
2. In a *calculative/proactive* equilibrium, W's violation probability $\widehat{\alpha}^*$ depends on the variation of incident probabilities. As long as both incident probabilities decrease by the same amount, W's violation probability is bound to decrease. M's enforcement probability in case of an incident $\widehat{\beta}^*$ increases as long as both incident probabilities decrease by the same amount. In case of no incident, M's enforcement probability $\widehat{\gamma}^*$ remains unaffected, and M still does not enforce.
3. In a *generative* equilibrium, W's violation probability $\widehat{\alpha}^*$ remains unaffected, and W still does not violate. Furthermore, M's enforcement probabilities $\widehat{\beta}^*$ and $\widehat{\gamma}^*$ remain unaffected, and M still does not enforce.
4. Because the variation of incident probabilities is set to be exogenous, there is no change in the equilibrium thresholds, i.e., RET and GET remain unaffected.

Considering that incident probabilities decrease by the same amount, i.e., that technological progress has an identical effect on both, there will be a reduction in violations but an increase in enforcement. It is important to note that this proposition only applies as long as the reduced incident probability does not lead to an unfavourable switch in equilibrium.

The numerical example in Table 3.27 highlights such an undesirable effect. In this case, all payoff parameters are identical to the initial game Γ_2 except for incident probabilities $\widehat{r}_{nv}$ and $\widehat{r}_v$, which are reduced by 50%.

Table 3.27: Numerical parameter values of game Γ_2 with technological progress

Workforce (1)		Management (2)	
Parameter	Value	Parameter	Value
B_C	2	B_E	14
B_D	3	B_G	5
B_V	5	B_S	6
C_P	10	C_E	3
C_{I1}	5	C_H	2
		C_{I2}	4
Incident probability			
$\hat{r}_v$	**0.25**	$\hat{r}_{nv}$	**0.05**

The corresponding equilibrium results are depicted in Table 3.28 and the PORT in Figure 3.13.

Figure 3.13: PORT with technological progress

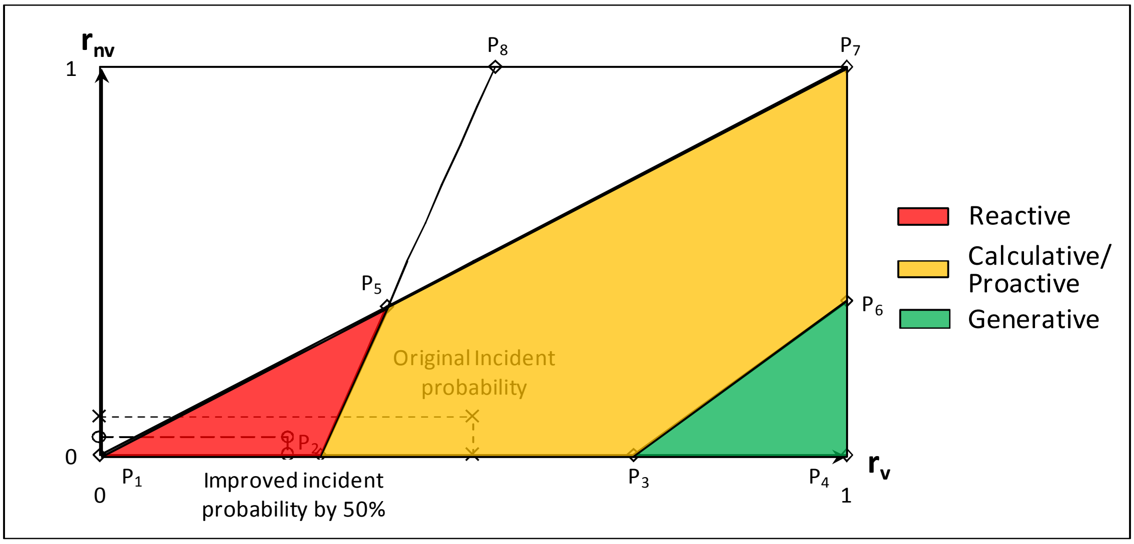


Table 3.28: Numerical effects of technological progress on game Γ_2

Equilibrium parameters	α^*	β^*	γ^*	π_1^*	π_2^*
Original game	0.038	0.392	0	1.539	3.635
Improved incident probability by 50%	**0.202**	**1**	**0.095**	**1.891**	**2.854**

The PORT demonstrates that violation and enforcement probabilities will rise drastically due to the switch in equilibrium from *calculative/proactive* to *reactive*.

Therefore, in light of technological progress, M must counteract the "erosion of compliance" (see Chapter 2.3.2) by improving its organisational effectiveness. Thus, achieving good safety performance is a continuous process that does not allow for a standstill. Otherwise, an organisation will "fall down" the safety culture ladder.

Finally, the effects of an increased safety standard caused by organisational effectiveness will be discussed. The results of the analysis for all three equilibria of game $\widehat{\Gamma}_2$ are shown in Table 3.29.

Table 3.29: Effects of organisational effectiveness on equilibrium parameters of game Γ_2

Improved safety standard due to organisational effectiveness	$C_{I1} \downarrow, C_{I2} \downarrow$				
Equilibrium parameters	α^*	β^*	γ^*	X	Y
Reactive	=	=	↑	↑	↑
Calculative/proactive	=	↑	=	↑	↑
Generative	=	=	=	↑	↑

The results of reduced incident costs are summarised by the following proposition.

Proposition 11: In a sequential inspection game $\widehat{\Gamma}_2$ with an improved safety standard due to organisational effectiveness:

1. In a *reactive* equilibrium, W's violation probability $\widehat{\alpha}^*$ remains unaffected. Thus, incident costs have no influence on W's decision to violate. M's enforcement probability in case of an incident $\widehat{\beta}^*$ also remains unaffected, and M thus enforces with certainty. However, M's enforcement probability in case of no incident $\widehat{\gamma}^*$ increases.
2. In a *calculative/proactive* equilibrium, W's violation probability $\widehat{\alpha}^*$ remains unaffected, while M's enforcement probability in case of an incident $\widehat{\beta}^*$ increases. In case of no incident, M's enforcement probability $\widehat{\gamma}^*$ remains unaffected, and M still does not enforce.
3. In a *generative* equilibrium, W's violation probability $\widehat{\alpha}^*$ remains unaffected, and W still does not violate. Furthermore, M's enforcement probabilities $\widehat{\beta}^*$ and $\widehat{\gamma}^*$ also remain unaffected, and M still does not enforce.
4. In equilibrium, both RET and GET are affected. The RET line moves further to the right, and the area of the reactive equilibrium's existence region thus increases. The GET line also moves further to the right, re-

sulting in a reduction of the area of the generative culture's existence region.

The above results can be interpreted as follows: the fact that M enforces more frequently can be considered an indication that M manages to capture the larger implications of possible incident consequences, whereas W does not consider these consequences from its own more limited perspective.

> *"... people are likely to downplay the potential negative consequences ... . It is, of course, very different, seen from the vantage point of a corporate centre, when millions of man hours are aggregated, as opposed to the viewpoint of an individual who will, in a well defended high risk industry, probably never personally experience a major accident such as a fatality."* (Sneddon et al., 2005, p. 9)

These implications will again be illustrated by a numerical example, shown in Table 3.30.

Table 3.30: Numerical parameter values of game Γ_2 with organisational effectiveness

Workforce (1)		Management (2)	
Parameter	Value	Parameter	Value
B_C	2	B_E	14
B_D	3	B_G	5
B_V	5	B_S	6
C_P	10	C_E	3
$\widehat{C}_{I1}$	**4**	C_H	2
		$\widehat{C}_{I2}$	**3**
Incident probability			
r_v	0.5	r_{nv}	0.1

The equilibrium results are depicted in Table 3.31 and the corresponding PORT in Figure 3.14.

Figure 3.14: PORT with organisational effectiveness

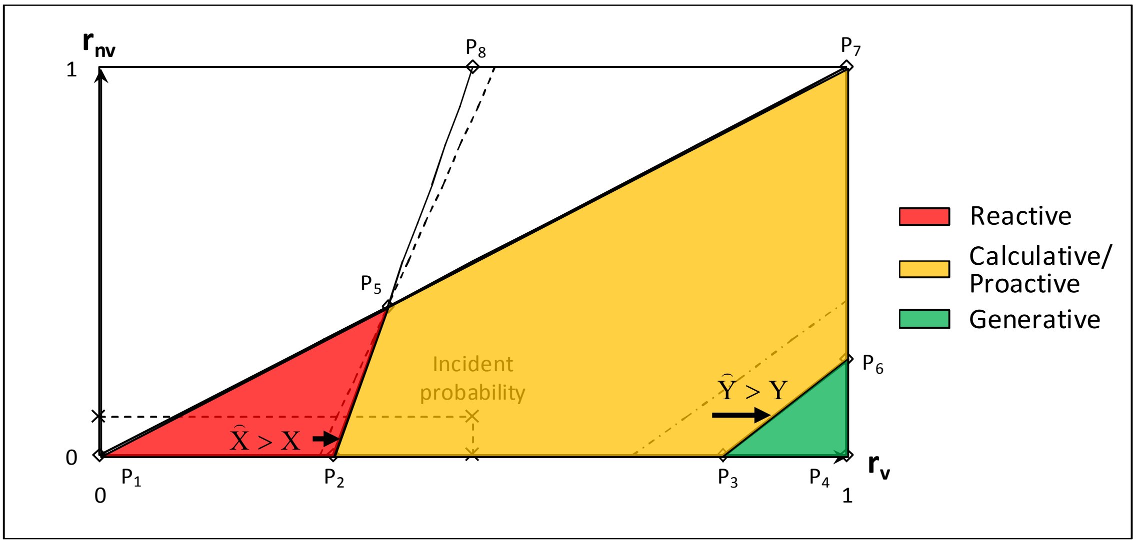


Table 3.31: Numerical effects of organisational effectiveness on game Γ_2

Equilibrium parameters	α^*	β^*	γ^*	π_1^*	π_2^*	X	Y
Original game	0.038	0.392	0	1.539	3.635	0.318	0.786
Reduced incident costs	**0.038**	**0.471**	**0**	**1.647**	**3.750**	**0.331**	**0.900**

The graphical representation indicates that a reduction of incident costs influences both RET and GET with $\hat{X} > X$ and $\hat{Y} > Y$. As the reactive region grows larger, the generative region grows smaller. Furthermore, despite M's increased enforcement efforts, there is a slight increase in both players' expected payoffs.

In light of organisational effectiveness, both players thus benefit from the reduction of incident costs, but this effect is marginal and has no influence on W's violation behaviour. This result stands in direct contrast to the findings of behavioural economics, which indicate that every variation of an individual's cost structure has a direct consequence on his violation behaviour.

It can therefore be deduced that a successful risk management strategy must combine technological progress and organisational effectiveness to improve the company's safety culture.

3.4 Concluding remarks

In the third chapter of this thesis, the interaction between management and the workforce of a petrochemical refinery in case of rule violations has been analysed by means of two game theoretic models. While the first model Γ_1 assumes a simultaneous interaction between both "players" without incident risks, the second model Γ_2 is more advanced and assumes both a sequential interaction and incident risks. Both models access a dedicated payoff structure that was developed based on the author's experience. This payoff structure is capable of reducing the complex interaction between workforce and management to simple costs and benefits and, even more importantly, allows structuring the "black box" of behavioural economics by means of an analytical mathematical language. This combination of game theory and behavioural economics is unique in the petrochemical industry.

Furthermore, based on the more sophisticated game model Γ_2, an innovative and easily understandable graphical model of an organisation's safety culture, named the "Petrochemical Organisation Risk Triangle" (PORT), has been developed. This graphical tool allows for an evaluation of the risk management practices that are used in the petrochemical industry and enables these practices to be classified in terms of effectiveness. The analysis delivered several interesting results.

Although research on behavioural economics has stated that violations occur due to an individual's internal motivation, this finding is not supported by game theory. Both game models indicate that in the interaction between two rational players, the reasons for rule violations are to be found exclusively outside of the individual as organisational factors. It has been demonstrated for the first time by means of an analytical mathematical model that the number of violations depends on a company's safety culture. This is the central finding of the conducted research. The finding thus supports the original statement by Hudson (1992, p. 45) that *"a culture allows or prevents violations."*

In general, the game theoretic analysis has demonstrated that a high-level safety culture leads to increased compliance and profitability. However, reaching a high-level safety culture also requires non-negligible investments in safety and, above all, perseverance. Furthermore, there is a fundamental difference in risk perception between the different types of safety cultures. Whereas in a *reactive* culture, incident risks are blinded out and only the chance that "everything will go well" is considered, risk perception in a *calculative/proactive* culture is characterised by a "chronic unease" that something "could go wrong". In a *generative* safety culture, there is an ideal state of intrinsic motivation to behave safely.

Each company or petrochemical operation thus has an individual "road map" towards a generative safety culture, which can easily be visualised by the PORT. However, even the PORT does not provide a magic formula for safety.

As it progresses towards a generative safety culture, an organisation must cope with an erosion of compliance caused by technological progress, i.e., with decreasing incident probabilities. Such a phenomenon needs to be carefully monitored by safety-conscious risk managers and counteracted with a strong safety culture approach and appropriate risk management practices. These practices need to be adapted to the local requirements, tackle the right problems and adjust the adequate organisational parameters. In this respect, the game theoretic framework and thus the PORT provide very important guidelines for petrochemical managers.

A risk management strategy of increased punishment, for example, can only be considered weakly effective. Although it is capable of moving an organisation further away from a reactive safety culture, it will not bring it any closer to a generative safety culture. Hence, there is a divergence between the recent developments in the petrochemical industry, i.e., harsh punishment for rule violations, and the results of the game theoretic analysis. However, the game theoretic framework also acknowledges that a safety culture will not persist if it is not supported by effective enforcement practices. Safety cultures need to be generated that are *just* and fairly balance punishment and rewards.

A risk management strategy of increased management commitment is considered much more effective than a strategy of increased punishment. As demonstrated by the PORT, management commitment has very positive effects on the workforce's violation behaviour and reduces management's enforcement costs. The result is a favourable development of an organisation moving closer to a generative and further away from a reactive safety culture.

Finally, the game theoretic analysis has highlighted that in today's petrochemical industry, contractors are key players in achieving good safety performance. Because contractors will most likely never achieve the same safety performance as a company's own staff members, the management of a petrochemical operation must build strong relationships with contract companies and provide them with adequate incentive structures, i.e., long-term, performance-oriented contracts.

In a nutshell, only if safety is the number one business goal, if strong management commitment and effective safety culture enforcement are in place and if contractors are integrated into risk management practices will an organisation eventually "climb" up the safety culture ladder.

4 Road towards industrial application

"The key is to adopt a balanced range of approaches, tailored to the specifics of the site." (Anderson, 2005, p. 115)

The above passage underlines that although game models Γ_1 and Γ_2 and, especially, the PORT offer a wide variety of recommendations for successful HSE risk management within the petrochemical industry, it has not yet been defined how these methods can be implemented in an industrial environment.

Up to this point, the recommendations resulting from the game theoretic analysis have been of a purely *qualitative nature*. However, in order for petrochemical risk managers to make informed decisions on HSE issues, *quantitative data* are required. The next logical step on the road towards industrial application thus lies in extending the developed models to incorporate "real life" industrial data. On this road, several "obstacles" need to be overcome. On one hand, the costs and benefits of safety need to be evaluated in monetary terms, and on the other hand, the corresponding incident probabilities need to be determined.

Consequently, a simple yet tangible economic cost and benefit analysis for an archetypal refinery will be developed in this chapter. Together with the related safety performance and human reliability data, all parameters will be inserted into game model Γ_2 and the PORT, allowing a quantification and evaluation of current risk management practices. The necessary data collection is performed with the help of various industrial databases.

In the first section, the data of an archetypal refinery will be presented, including its employee structure, economic data and safety performance. The first section also sets the scene for a detailed representation of the game model's payoff parameters. These payoff parameters will be expressed in monetary terms as costs C_i and benefits B_j in the second section. In the third section, the necessary risk and human reliability data will be assembled, allowing a calculation of the incident probabilities r_v and r_{nv}. All of the above parameters will then be entered into game model Γ_2 and the PORT. Finally, the results of this quantitative calculation and its implications for petrochemical risk management will be discussed.

4.1 Setting the scene

To demonstrate the applicability of game theory in the context of petrochemical risk management, all further calculations will be performed for an archetypal petroleum refinery.

This refinery is assumed to be a medium-sized, fully complex[211] refinery with one thousand employees working a total of two million hours per year, i.e., forty hours per week and fifty weeks per year.[212] Based on this data, the refinery's employee structure, its economic data and its safety performance will be specified.

4.1.1 Employee structure

As defined in the previous chapters, it is assumed that there are two interacting groups within the refinery, i.e., M and W. Although this classification will be upheld, entering "real-life" industrial data into the game model requires taking a closer look at these two groups. While the first group, M, consists of the refinery's *management team*, W consists of *line managers*, *first line supervisors*, *production/maintenance workers* and *others*. To better understand the refinery's organisational structure and working mechanism, it is worthwhile to discuss these subgroups in more detail.

- *Management:* M consists of the *general manager* and his/her *management team*. The general manager, who reports to PC, possesses the overall responsibility for all refinery activities and thus for a safe and profitable operation. Because operation of a refinery is complex and requires many specialised activities and functions, the general manager delegates several of his/her responsibilities to a management team. Hence, there is usually one management team member for each specialised func-

211 A fully complex refinery is characterised by its ability to process inferior crude oil while maximizing the amount of "white product" by means of several highly complex processes, such as hydrocracking and hydrodesulphurization. For further details on the refinery categorisation, types and setup, see United States Environmental Protection Agency (1996, p. 2) or Favennec and Baker (2001, p. 134).

212 The assumption of one thousand employees is based on the author's experience and is supported by Favennec and Baker (2001, p. 152).

tion, i.e., organisational entity. For example, the manufacturing manager possesses the overall operational responsibility and ensures a safe and reliable production of "on-spec" petroleum products by the refinery's production units. In addition to the manufacturing manager, there is also a manager at the head of each of the following entities: communications, economics, engineering, finance, human resources, maintenance, safety and technology.

Together, M sets out the operational objectives for the refinery, attributes the required resources and guides the refinery's continuous risk management process. In addition, M ensures that PC's business values and principles as well as all applicable industry standards are respected within the refinery.

- *Workforce:* A closer look at W reveals that it consists of several subgroups, where the first subgroup is considered the *line managers*. As the name indicates, line managers possess direct line responsibilities and usually serve as department heads. Typical jobs for line managers include production unit manager, maintenance workshop manager or project department head, all of whom report to their relevant entity managers; for example, the production unit manager reports to the manufacturing manager. It should be noted that department sizes vary greatly. Whereas a safety department usually consists of a handful of employees, a maintenance department or production unit can easily have more than fifty employees.

  Within these departments is also the second subgroup, namely the *first line supervisors*. The first line supervisors ensure that the department's goals and objectives are transmitted from the line managers down to the "shop floor". Furthermore, they organise daily operations such as permits to work, shift plans or maintenance work orders. For example, a chief maintenance technician and his/her team ensure that all maintenance tasks requested by the production units are executed within the defined timeframe.

  Another subgroup of W is the *maintenance/production workers,* who can be considered the refinery's "front line" personnel. This group includes operators controlling production from a unit's control room and maintenance technicians repairing broken equipment such as pumps or control valves. This group works closest to the refinery's hazards and performs the most safety-critical activities.

  Finally, there is the group of *others,* which includes several administrative and non-technical positions such as clerks and warehouse employees.

The above categorisation demonstrates that although most modern petrochemical refineries possess relatively flat organisational structures, there is still a clear hierarchical line. The further one moves down the hierarchy, or "ranks", the closer one gets to the high-risk activities of daily petrochemical operations. In that respect, a refinery is thus not much different from a military organisation.

Because this organisational structure will be very similar throughout the industry,[213] the simple group model described above will be sufficient for the purpose of the following analysis. In a first step, the group model will be used to determine the archetypal refinery's economic data.

4.1.2 Economic data

Based on the U.S. Bureau of Labour Statistics 2009 employment data for petroleum refineries,[214] the average hourly salaries for each of the above employee groups were deduced and the corresponding annual salaries calculated.

Table 4.1: Payroll of archetypal refinery

	Hourly wage [$][a]	Annual salary [$]	Employees[b]	Payroll [$]
Management	60.00	120,000	10	1,200,000
Workforce				
Line managers	45.00	90,000	50	4,500,000
First line supervisors	30.00	60,000	150	9,000,000
Production/maintenance workers	25.00	50,000	600	30,000,000
Other (administration etc.)	20.00	40,000	190	7,600,000
Average	26.15	Total	1000	52,300,000
Average (excl. Others)	27.59	Total (excl. Others)	810	44,700,000

Note.
[a]Data based on U.S. Bureau of Labour Statistics May 2009 Occupational Employment Statistics (OES) for petroleum refineries (NAICS code 324110)
[b]The employee numbers for each group were derived from the author's experience

Table 4.1 shows the results of this calculation as well as the refinery's average hourly wage and *total annual payroll*. The refinery's total annual payroll of $52.3 million indicates that a large number of qualified personnel are required to run such a complex operation. However, the annual payroll, i.e., the salary costs, is only the first pillar of the

213 For more detail on the organisational structure of a typical refinery, see Favennec and Baker (2001, pp. 489–502).

214 See United States Bureau of Labour Statistics (2010).

total annual labour costs. To present a complete picture of the refinery's labour costs, its annual *insurance premiums* and *administrative costs* also need to be taken into account.

The easiest method of calculating the respective insurance premiums consists of investigating the extensive data provided in (United States Census Bureau, 2008). Based on the survey, it can be estimated that between 11% and 12% of the refinery's total annual payroll is required as insurance premiums. This delivers an average *annual insurance premium* of approximately \$6.1 million. The same statistical source was also used to calculate the annual administrative costs per employee, which include all costs related to IT infrastructure, office space and communications. These costs amount to approximately \$34,000 per employee per year and thus a total of \$34 million in *annual administrative costs* for the archetypal refinery. Combining all costs, the *refinery's total annual labour costs* equal \$92.4 million.

However, the fact that a petrochemical operation is very cost intensive is not only underlined by its labour costs but also by the archetypal refinery's economic data, depicted in Table 4.2 and Table 4.3. Although reliable publications on this subject are rare and often require privileged access,[215] the following publications nevertheless provide a sophisticated data source for calculation of the archetypal refinery's *revenue*, *profit*, *operating costs* and *capital expenditures*: (United States Environmental Protection Agency, 2008), (United States Census Bureau, 2008) and (United States Census Bureau, 2004).

Table 4.2 shows that, despite a certain spread based on whether costs were calculated per employee or per refinery, all figures possess the same order of magnitude and thus allow calculating an average refinery *annual revenue* of approximately \$3.2 billion, *total annual operating costs* of \$2.9 billion and *annual profit* of \$300 million. It should be noted that these "Total Operating Costs" (TOC) include *labour*, *capital* and *materials*. Labour costs have been calculated in Table 4.1.

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215 Most industrial benchmarking studies are not publicly available, such as Solomon Associates (2011).

Table 4.2: Annual revenue, profit and total operating costs of archetypal refinery

	EPA 2008[a]	EPA 2008[b]	Census 2008[c]	Census 2002[d]	**Average**
Revenue [$]	4,000,000,000	1,040,000,000	5,196,655,489	2,691,378,468	**3,232,008,489**
Profit [$]	268,000,000	69,680,000	560,940,326	265,521,057	**291,035,346**
Total Operating Costs [$][e]	3,732,000,000	970,320,000	4,635,715,163	2,425,857,411	**2,940,973,144**

Note.
[a]Data based on U.S. Environmental Protection Agency 2008 Regulatory Impact Analysis for the Petroleum Refineries NSPS and mean refinery profit margin of 6.7% for refinery with 500-1000 employees
[b]Data based on U.S. Environmental Protection Agency 2008 Regulatory Impact Analysis for the Petroleum Refineries NSPS and mean refinery profit margin of 6.7% for average refinery
[c]Data based on U.S. Census Bureau 2008 Annual Survey of Manufactures (Petroleum Refineries NAICS code 324110) and 141 operable refineries
[d]Data based on U.S. Census Bureau 2002 Economic Census for Petroleum Refineries and 31 refineries with 500-999 employees. Prices are adjusted to 2008 values
[e]TOC include material, capital expenditure and salaries

According to (United States Environmental Protection Agency, 2008, pp. 3–10), material costs in the petrochemical industry amount to more than 90% of TOC because they include raw materials, such as crude oil, and all costs associated with energy consumption. The refinery's capital costs include both *operational* and *capital expenditures*. Based on (United States Census Bureau, 2008) and (United States Census Bureau, 2004), it can be deduced that the average *total capital expenditures* per refinery amount to approximately $200 million per year; see Table 4.3.

Table 4.3: Annual capital expenditures of archetypal refinery

	Census 2008 per 1000 employees[a]	Census 2008 per refinery[a]	Census 2002 per 1000 employees[b]	Census 2002 per refinery[b]	**Average**
Total Capital Expenditure (new and used equipment) [$]	266,245,669	127,206,894	241,695,613	173,677,789	**207,686,701**
Total Capital Expenditure (new equipment) [$][c]	53,249,134	25,441,379	48,339,123	34,735,558	**41,537,340**

Note.
[a]Data based on U.S. Census Bureau 2008 Annual Survey of Manufacturers (Petroleum Refineries NAICS code 324110) and 141 operable refineries
[b]Data based on U.S. Census Bureau 2002 Economic Census for Petroleum Refineries and 31 refineries with 500-999 employees. Prices are adjusted to 2008 values
[c]The author assumes that 20% of Total Capital Expenditure (new and used equipment) will be invested in new equipment. This assumption is also supported by Favennec (2001)

According to the author's experience, 80% of these capital expenditures are maintenance and operating costs for the refinery's production units, while the remaining 20% are capital investments in new equipment and machinery.

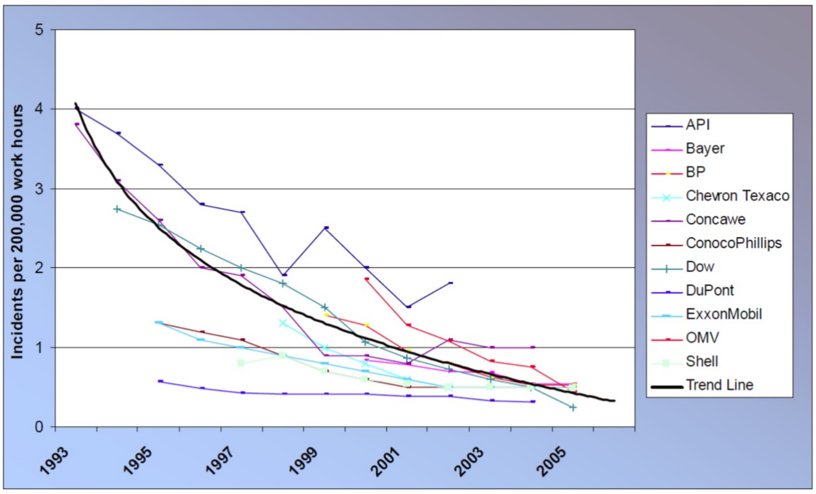
These figures correspond very well with the economic data of a medium-sized refinery with standard conversion processes.[216] They also indicate that a refinery usually operates in a challenging economic environment with extensive operating costs of several hundred million dollars per year. To generate the required revenue and profit, the archetypal refinery must thus produce as many high-quality petroleum products, such as gasoline or jet fuel, as possible and sell them at the best possible margins. One could also say that *"... a chemical plant (or refinery) has been designed with one thing in mind: to chum out its products as cheaply and efficiently as possible."*[217]

As a consequence, M and W are constantly faced with the dilemma of safety versus production described in Chapter 2.1. In this challenging environment, with economic pressure and hazardous chemical processes, the archetypal refinery's safety performance is of pivotal importance.

4.1.3 Safety performance

Although the petrochemical industry has achieved significant success in reducing incident rates within its operations over the past two decades, as shown in Figure 4.1, accidents still happen; see Chapter 2.2. Despite these setbacks, incident rates within the petrochemical industry are still considerably lower than within general manufacturing; see Figure 4.3.

Figure 4.1: Incident profile of major petrochemical companies



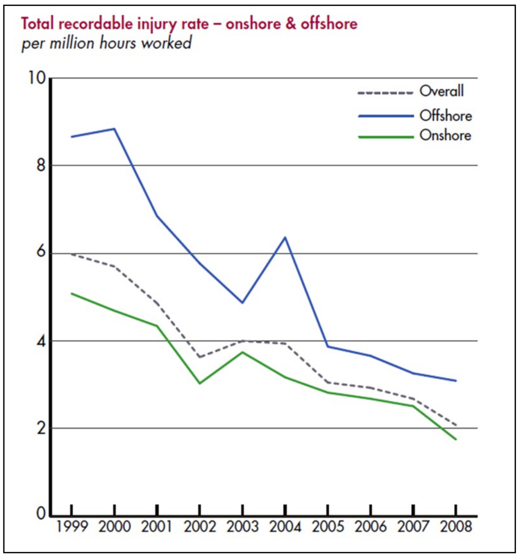
Source: (Schouwenaars, 2008, p. 6)

[216] See Favennec and Baker (2001, pp. 152–154).
[217] Wolf (2002, p. 100).

To provide an estimation of the archetypal refinery's incident rate, several occupational health and safety publications for the petrochemical industry, such as (International Association of Oil & Gas Producers, 2009), (American Petroleum Institute, 2009) and (WorkSafeBC, 2008), were investigated.[218] Based on the archetypal refinery's one thousand employees working a total of two million hours per year, the corresponding incident rates were calculated.

The first well-respected publication on occupational health and safety within the petrochemical industry is the International Association of Oil and Gas Producers' (OGP) safety performance indicator series. Because all of the industry's "big players," such as BP, ExxonMobil, and Royal Dutch Shell, participate in this annual survey, it represents a very reliable and extensive data source. For the purpose of calculating the archetypal refinery's incident rate, the "Total Recordable Injury Rate" (TRIR), as shown in Figure 4.2, seemed to be the best fit because it comprises all fatalities, "Lost Work Day Cases" (LWDC), "Restricted Work Day Cases" (RWDC) and "Medical Treatment Cases" (MTC). For the archetypal refinery, which is an "onshore" installation, the corresponding annual injury rate based on the 2008 data equals 3.5, i.e., 1.75 injuries per million hours.

Figure 4.2: Injury rate in the petrochemical industry from 1999-2008



Source: (International Association of Oil & Gas Producers, 2009, pp. 2-2)

The next well-known industry statistic is the API's workplace safety publication; see Figure 4.3. Very similar to the OGP statistic, it considers LWDC, RWDC and MTC.

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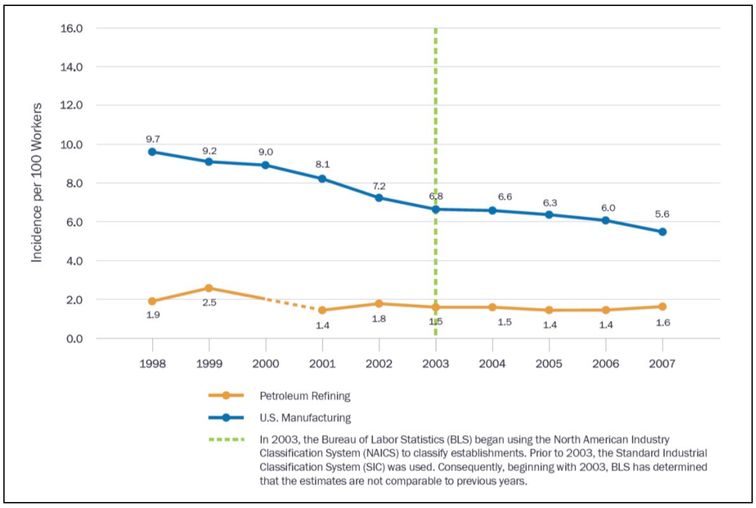
[218] It is important to note that each publication uses a slightly different definition of the term "incident".

However, fatalities are not taken into account. Based on the 2007 data, the archetypal refinery's annual injury rate equals 16, i.e., 1.6 per 100 workers.

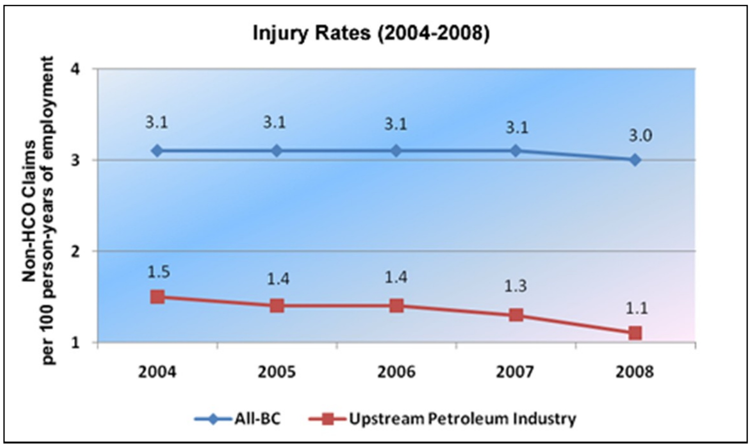
Figure 4.3: Job-related nonfatal injuries and illnesses in U.S. petroleum refining from 1998-2007



Source: (American Petroleum Institute, 2009, p. 3)

Another data source is provided by the Workers' Compensation Board of British Columbia. The board regularly publishes various statistics on the safety performance of its local petroleum industry. The best fit for the purpose of calculating an archetypal refinery's injury rate is the non-health care only injury statistic, as depicted in Figure 4.4. Based on the 2008 data of 1.1 injuries per 100 workers, the archetypal refinery's injury rate equals 11.

Figure 4.4: Injury rate in upstream petroleum industry of British Columbia from 2004-2008



Source: (WorkSafeBC, 2008)

Finally, all of the above results are summarised in Table 4.4, and an average annual incident rate is calculated. In the case of the archetypal refinery, 10.2 incidents are expected in the course of one year, i.e., 0.2 incidents per week.

Table 4.4: Annual and weekly incident rates of archetypal refinery

	OGP 2008[a]	API 2007[b]	Work Safe BC 2008[c]	**Average**
Annual frequency	3.5	16.0	11.0	**10.2**
Weekly frequency	0.07	0.32	0.22	**0.20**

Note.
[a]TRIR (fatalities, LWDC, RWDC, MTC) on-shore data
[b]Nonfatal injury or illness (LWDC, RWDC, MTC) petroleum refining data
[c]Non-health care only (non-HCO) petroleum sector data

Now that the scene has been set and the refinery's employee structure, economic data and safety performance have been presented, the analysis proceeds by determining the costs and benefits of safety.

4.2 Costs and benefits

There is a common understanding among most petrochemical companies that safety generates profit[219] and can boost operating performance.[220] This statement is underlined by the following quotation, which also provides a first definition of the costs and benefits of safety:

> *"The benefit that has to be set against those costs is, generally, the benefit from being allowed to operate (license withdrawal cost) plus the opportunity benefit of feeling capable of running a hazardous operation without incurring incidents that will stop or severely limit production."* (Hudson & Stephens, 2000, p. 7)

But to what extent do these costs and benefits affect the game theoretic approach to petrochemical risk management? The game theoretic models developed in this thesis are based on a payoff structure that relies on the findings of behavioural economics. Thus, the interaction between M and W is described in terms of costs and benefits. However, the interaction has so far only been investigated in *qualitative* terms. An exclusively

219 See, for example, Arrow et al. (1996), ASSE Council on Practices & Standards (2009), Center for Chemical Process Safety (2006), Hudson (2001, p. 28) or Knegtering and Pasman (2009, p. 167).

220 Veltri, et al. (2007) provides empirical proof of this statement.

qualitative analysis is not sufficient to develop a game theoretic framework that is suitable for industrial application. To make informed decisions, petrochemical risk managers will demand "fact-based" data, and, consequently, the costs and benefits of safety also need to be defined in *quantitative* terms.

The key problem is that although various quantification methods have already been developed,[221] a high level of uncertainty remains concerning their accuracy. This is because incident costs can typically be compared to an iceberg.[222] The iceberg analogy demonstrates that only the tip of the iceberg, i.e., the *direct costs,* such as material damage, can be determined with sufficient statistical accuracy. The rest of the iceberg, i.e., the *indirect costs,* such as production inefficiencies, is much harder to assess, and often only very rough estimates of the actual costs can be generated.[223]

Therefore, a number of different cost and benefit studies that have been performed in the petrochemical industry will be analysed in this chapter. However, it must be noted that the goal of this analysis is not to attain new levels of accuracy. To demonstrate the suitability of the developed game theoretic models for the petrochemical industry, a simple and understandable method is favoured.

Thus, after a presentation of several cost and benefit studies, *average costs* and *benefits* will be calculated. These average values, which represent the direct cost and benefit components, will then be adjusted by a *qualitative factor* in order to also incorporate *indirect components*.

4.2.1 Method

In a first step, all quantitative components, i.e., the direct costs (DC) and direct benefits (DB), will be added, delivering the total direct costs (TDC) and total direct benefits (TDB) for each of the players' payoff parameters, as shown in equations (4.1) and (4.2):

$$\mathrm{TDC}_i = \sum_m \mathrm{DC}_{im} , \tag{4.1}$$

[221] See, for example, Bergström (2005), Health and Safety Executive (2002), Hudson & Stephens (2000), Lahiri, Gold, and Levenstein (2005), Meel, et al. (2007) or Oxenburgh & Marlow (2005). An excellent literature review of various cost studies in an ergonomics context is provided by Tompa, Dolinschi, and de Oliveira (2006).

[222] For more information on the iceberg model, see Health and Safety Executive (2003b) or Sadhra & Rampal (1999, pp. 232–243).

[223] For an example of hidden costs, see International Association of Oil & Gas Producers (1996) or Rockwell Automation (2007, p. 12).

$$\mathrm{TDB_j} = \sum_{n} \mathrm{DB_{jn}} \quad (4.2)$$

In a second step, the idea of indirect costs and benefits is introduced by means of qualitative factors (QFs). These QFs, which represent the various indirect effects on each player's payoff parameters, will then be combined to yield a single "Total Qualitative Factor" (TQF), as shown in equations (4.3) and (4.4). The TQF represents the simple arithmetic mean of the respective QFs:

$$\mathrm{TQF_i} = \frac{\sum_{k} \mathrm{QF_{ik}}}{k}, \quad (4.3)$$

$$\mathrm{TQF_j} = \frac{\sum_{p} \mathrm{QF_{jp}}}{p}. \quad (4.4)$$

The final cost and benefit parameters C_i and B_j for both players, M and W, will be obtained by multiplying the TDC and TDB with their corresponding TQFs, as demonstrated in equations (4.5) and (4.6):

$$C_i = \mathrm{TDC_i} \cdot \mathrm{TQF_i}, \quad (4.5)$$

$$B_j = \mathrm{TDB_j} \cdot \mathrm{TQF_j}. \quad (4.6)$$

According to the defined method, the TDC, TDB, TQF and the players' payoff parameters C_i and B_j will be calculated in the following sections for the archetypal refinery. To provide solid grounds for the calculation, several cost studies that have been performed in the petrochemical industry will be presented. These studies reveal the complex nature of incident cost estimation.

4.2.2 Cost studies

The following publications represent a cross-section of incident cost estimations in the petrochemical industry. In game theoretic terms, these studies deliver an estimate of M and W's incident costs. It should be noted that whereas M suffers *organisational incident costs*, W suffers *personal incident costs*, i.e., injury costs. On the following pages, these studies will be discussed in detail. A brief summary is provided in Table 4.5 and Table 4.6.

Table 4.5: Cost studies on annual refinery incident costs

Hudson/Stephens 2000 (offshore platform)[a]		HSE 1993 (large facility)[b]		HSE 2008 cost calculator (total losses)		API 2007 (sixty-nine refineries)		Work Safe BC 2008 (petroleum sector)		Meel 2007 (five companies)		**Average costs per refinery [$]**
Actual costs per platform [$]	1,080,067	Actual costs per facility [$]	7,930,695	Estimated costs [$][c]	60,668,000	Estimated costs per refinery [$][f]	1,173,551	Claim costs per 1000 pers. [$]	514,189	Capital at Risk (CaR) [$][g]	3,760,000	**3,615,103**
Typical costs per platform [$]	1,842,646			Estimated costs [$][d]	6,401,800							
Potential costs per platform [$]	3,677,343			Estimated costs [$][e]	6,155,636							

Note.
[a]Costs converted from GBP to U.S. dollars and adjusted to 2008 prices
[b]Costs converted from GBP to U.S. dollars and adjusted to 2008 prices
[c]Calculation method 1: Ten times value of 2008 insurance premium. Note that this value is not taken in account during further calculations, since it is clearly out of range.
[d]Calculation method 2: 2008 insurance premium plus incident costs
[e]Calculation method 3: 2008 insurance premium plus costs for first-aid and damage-only cases
[f]Figure probably underestimates the true costs due to the high number of incidents with no costs in the study
[g]CaR in terms of safety for petrochemical company B

Table 4.6: Annual injury costs of archetypal refinery

	Fatality	Disability	LWDC	MTC	**Average per facility[b]**
Annual Injury Costs [$][a]	3,162,278	316,228	31,623	3,162	**1,016,667**

Note.
[a]Geometric average due to logarithmic scale of risk assessment matrix
[b]Calculation based on average annual incident frequency

The presentation of cost studies starts with M's incident costs:

- *Hudson study:* A first estimate of the incident costs within a petrochemical environment can be deduced from a study performed by Hudson, the "father" of Royal Dutch Shell's Health and Safety programme.[224] The study used three different methods to determine the annual incident costs for a typical offshore platform.

  The first method consisted of assessing the actual incident costs of a random sample of 60 incidents by working up the corresponding incident reports. The incident sample contained both personal injuries, e.g., LWDC, as well as process safety incidents, e.g., loss of containment. The actual costs were then scaled up for a total of 730 incidents within all 16 participating offshore installations, delivering an actual annual incident cost of GBP 0.62 million per platform. Converted from GBP into U.S. dollars and adjusted to 2008 prices, the actual incident costs amount to approximately $1.1 million per year.

  The second method calculated typical incident costs for each type of incident. A fire/explosion was estimated at GBP 20,000, whereas a fall/trip incident would cost GBP 29,000. By multiplying by the weighted incident frequency for one platform, a value of GBP 1.06 million was obtained. After conversion to 2008 prices, this delivers approximately $1.84 million per platform.

  The third and final method calculated the potential incident costs by means of a statistical approach. The total expected costs for a platform were calculated by multiplying an incident probability distribution for different levels of incidents, i.e., "level 1" minor incident to "level 5" major incident, by the corresponding expected incident costs. The resulting figure of GBP 2.1 million translates to $3.67 million in 2008 prices.

  Although the study was set in an offshore environment, its findings can nevertheless be transferred to an onshore refinery. Of course, costs in an offshore environment are usually higher due to the difficult logistical situation; obtaining material, spare parts and people can be a real challenge. However, if one compares the costs of a small platform to those of a medium-sized refinery, one will most likely find

224 See Hudson and Stephens (2000). More information on Royal Dutch Shell's "Hearts&Minds" programme is available online at http://www.eimicrosites.org/heartsandminds.

costs of the same order of magnitude. Hence, according to this study, *annual incident costs* in a petrochemical refinery range from $1.1 million to $3.7 million.

- *HSE study:* In 1993, the U.K. Health and Safety Executive performed an incident cost investigation for companies operating in five different industry segments.[225] The most relevant case study for the purpose of this thesis was performed on a North Sea oil platform. Over a period of thirteen weeks, all incidents were recorded, and the costs were assembled and extrapolated. In the end, the *annual incident costs* were estimated at GBP 3.7 million, which equals $7.9 million after conversion and adjustment to 2008 prices.

  Based on this calculation method and its use in almost two decades of research on accident costs, the U.K. Health and Safety Executive provides an online calculator for incident costs.[226] The calculator uses three different calculation methods.[227] In the case of the archetypal refinery, the annual insurance premium of approximately $6.1 million serves as the main input parameter for the online calculator. Together with the calculator's standard accident costs per employee per year of approximately $4000, the refinery's estimated annual incident costs vary between $6.2 million and $60 million.

  Because the value of $60 million, which is an indication of the refinery's uninsured costs (i.e., ten times the insurance premium), is not of the same order of magnitude as in all other cost studies, the value was disregarded. Only the remaining two calculation methods delivered plausible results, with *annual incident costs* of $6.2 million and $6.4 million, respectively.

- *API study:* Another report that enables conclusions to be drawn on a refinery's annual incident costs was issued by the API in 2007. Incident data and cost ranges for 69 refineries were assembled in the course of this study.[228] By totalling all incident costs and multiplying them by the relevant cost ranges, an estimate of the *annual incident costs* per refinery of approximately $1.2 million can be obtained. It should

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225 For further detail, see Health and Safety Executive (1993).

226 See Health and Safety Executive (2003a).

227 For a detailed description of the different calculation methods, see Health and Safety Executive (2003b).

228 See American Petroleum Institute (2008).

be noted that this figure is probably low due to the high number of incidents involving no costs in the report.[229]

- *WorkSafeBC study:* The Worker's Compensation Board of British Columbia regularly provides an indication of the claim costs per employee, which can be considered a very important part of a company's annual incident costs.[230] Scaled up to the one thousand employees for the archetypal refinery, the *annual claim costs* are estimated at $500,000. Once again, this value is probably low because the costs of material damage are not included.
- *Meel study:* Of all cost studies cited in this thesis, (Meel et al., 2007) provides the most sophisticated method for calculating the annual refinery incident costs. Based on the U.S. National Response Centre database,[231] the study calculates the capital at risk for several U.S. petrochemical companies. The capital at risk is an indication of the company's operational risk and is determined via several statistical methods.

  First, incident frequency distributions are determined by using a Gamma-Poisson-Bayesian[232] approach. In a second step, a loss-severity distribution is calculated by using extreme value theory, which provides a quantitative index for the loss as a weighted sum of different incident consequences. The capital at risk is computed by applying fast Fourier transforms[233] to the product of frequency and loss-severity distribution. Finally, one obtains a total loss distribution of approximately $3.8 million for a petrochemical company, which provides a good indication of a refinery's *annual incident costs*.

Based on this data pool, the *average annual incident costs* of the archetypal refinery equal approximately $3.6 million. This value equals 0.12% of the archetypal refinery's TOC, which is very well in line with findings from (Behm, Veltri, & Kleinsorge, 2004), who estimated the costs of safety to equal between 0.07% and 0.25% of TOC.

In case of an incident, W also suffers costs, which can be estimated as follows:

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229 The category of incidents with no associated costs is not supported by the author's experience. Every incident immediately causes costs, e.g., of reporting, investigation, and remediation.

230 See WorkSafeBC (2008).

231 Available online at http://www.nrc.uscg.mil.

232 See Carlin & Louis (2008).

233 See Smith (2003a).

- *Private industry study:* An excellent study investigating personal incident costs in all U.S. private industry is provided by (Waehrer, Dong, Miller, Haile, & Men, 2007). The study calculates the average injury costs based on a three-step approach. Direct costs (salary), indirect costs (productivity and medical) and quality of life costs (pain) are assembled and added. According to these calculations, the average injury costs per "days away from work case" amount to $38,000 for all U.S. private industry. Although there are no values for the petrochemical industry, this value nevertheless seems to be a good indication of W's injury costs. Together with the annual incident frequency of 10.2, the total *annual injury costs* can be estimated at approximately $400,000.
- *Risk Assessment Matrix study:* An alternative method of determining W's annual injury costs consists of applying numerical values to the injury types used in the standard RAM. A small injury such as an MTC, for example, costs between $1000 and $10,000. Due to its logarithmic scale, determining an average cost per MTC requires using the geometric average, which yields a value of approximately $3200 per MTC. Accordingly, costs for all injury types can be calculated as depicted in Table 4.6. Multiplying the overall geometric average by the annual incident frequency of 10.2 yields a value for W's *annual injury costs* of approximately $1 million.

In further calculations, the average value of both of the above methods, i.e., $700,000, will be used as an estimate of W's injury costs.

4.2.3 Quantitative calculation

Together with the data provided by the different cost studies, the quantitative cost calculation proceeds by determining the TDC and TDB. These calculations are performed separately for each of M and W's payoff parameters. The corresponding results are depicted in Table 4.7 and Table 4.8, and a detailed explanation of each calculation is presented on the following pages.

Table 4.7: Annual Total Direct Costs (TDC)

Payoff parameter	Management (M)						Workforce W			
	C_E	Value [k$]	C_H	Value [k$]	C_{I2}	Value [k$]	C_{I1}	Value [k$]	C_P	Value [k$]
Direct Costs (DC)	Salary and wages for safety department[a]	600	Safety council meetings by management[e]	60	People, environmental and asset costs[h]	3,615	Accumulated injury costs (pay loss, medical costs, pain etc.)[i]	702	Formal dismissal[k]	250
	Administrative costs for safety department[b]	340	Safety discussions[f]	281			Performance bonus reduction (10%)[j]	418	Performance bonus reduction[l]	586
	Total safety inspection manhours[c]	131	Legal expenses[g]	107						
	Total safety meeting manhours[d]	517								
Total Direct Costs (TDC)		**1,588**		**448**		**3,615**		**1,120**		**836**

Note.
[a]The author assumes that the safety department consists of ten employees. Salary is based on U.S. Bureau of Labour Statistics May 2009 Occupational Employment Statistics (OES) for petroleum refineries (NAICS code 324110)
[b]According to U.S. Census Bureau 2008 Annual Survey of Manufacturers (Petroleum Refineries NAICS code 324110) administrative costs per employee and year equal approx. $34,000
[c]According to the author's experience, each employee will perform five safety inspections per year each lasting approx. 1 hr
[d]According to the author's experience, all employees except "Others" will participate in weekly safety meetings lasting approx. 0.5 hrs
[e]According to the author's experience, each management team member will spend approx. 2 hr per week on the handling of safety infractions during safety council meetings
[f]According to the author's experience, each line manager will spend approx. 0.5 hrs per week on discussion safety infractions with his team. First line supervisors will spend approx. 1 hr per week on these issues
[g]According to author's experience, per refinery there will be approx. five litigation cases per year (approx. 40 hrs of litigation) and one settlement (resulting in a payment of one year's production workers salary)
[h]Annual incident costs vary between $0.5 million and $10 million per facility. The author calculated approx. $3.6 million as average annual incident costs
[i]Injury costs are calculated based on average annual incident frequency
[j]The author assumes that after an incident, the workforce will receive a bonus payment reduction by 10%. Bonus payments vary from half a month's salary (worst case) to twice a month's salary (best case)
[k]The author assumes that there will be one formal dismissal per year resulting in a significant loss of income for the offender. A reasonable approach seems to be estimating a 25% loss in income over a period of twenty years after a dismissal
[l]The author assumes that in one year, 10% of all employees will receive a formal warning resulting in a bonus payment reduction by 50%. As a consequence of these violations, there will also be a reduction in bonus payments for all other employees by 10% reflecting the overall safety performance

Table 4.8: Annual Total Direct Benefits (TDB)

Payoff parameter	Management (M)						Workforce W					
	B_E	Value [k$]	B_G	Value [k$]	B_S	Value [k$]	B_C	Value [k$]	B_D	Value [k$]	B_V	Value [k$]
Direct Benefits (DB)	Decreased capital costs (1%)[a b]	415	Performance bonus increase (20%)[e]	240	Increased incident costs (10%)[g]	362	Performance bonus increase (10%)[i]	418	Performance bonus increase (20%)[j]	837	Time savings[l]	785
	Reduced production costs (3%)[a c]	4,984	Increase in capital investment (5%)[f]	2,077	Performance bonus decrease (20%)[h]	240			Extra premium[k]	100	Performance bonus increase (10%)[m]	418
	Lower insurance premiums (20%)[a d]	1,213									Extra premium[n]	100
Total Direct Benefits (TDB)		**6,613**		**2,317**		**602**		**418**		**937**		**1,303**

Note.
[a]Percentages are based on study conducted in Center for Chemical Process Safety (2006)
[b]Capital costs (new equipment) are calculated based on U.S. Census Bureau 2002 and 2008 data for petroleum refineries. The average capital expenditure per facility equals approx. $40 million
[c]Production costs (operational expenditure) are calculated based on U.S. Census Bureau 2002 and 2008 data for petroleum refineries. The average operational expenditure per facility equals approx. $170 million
[d]Average insurance premium for petroleum sector based on U.S. Census Bureau 2008 data equals between 10-15% of assessable payroll. In this case, average insurance premiums amounts to approx.$6 million
[e]The author assumes that due to a clean safety record, management will receive a bonus payment increase by 20% based on its annual salary
[f]According to the authors experience, a company with a good safety performance is more likely to receive capital budget (new equipment) from its parent company. The increase is assumed to equal 5%
[g]The author assumes that not enforcing safety violations, will lead to a 10% increase in incidents
[h]The author assumes that management will receive a 20% bonus reduction, due an increase in incidents
[i]The author assumes that due to a clean safety record, the workforce will receive a bonus payment increase by 10%. Bonus payments vary from half a month's salary (worst case) to twice a month's salary (best case)
[j]The author assumes that due to a documented clean safety record, the workforce will receive a bonus payment increase by 20%
[k]The author assumes that having a documented clean safety record will lead to 10% of all employees receiving an extra safety premium of $1,000 per year
[l]The author assumes that committing a violation will save up to 5 minutes per day and employee
[m]The author assumes that committing a violation can result in increased productivity (quicker ways of working) thus resulting in an increased bonus payment by 10%
[n]The author assumes that committing a violation will lead to 10% of all employees receiving an extra premium of $1,000 per year as recognition for their "trouble shooting" competencies

- C_E : M’s enforcement costs consist of several direct components. Being able to enforce safety procedures requires a s*afety department*. It is the purpose of this department to regularly interact with W and strengthen the existing safety culture, for example, by means of safety workshops, incident investigations or safety procedures. Based on the size of the archetypal refinery, it seems reasonable to assume that the safety department consists of ten employees. The total salary of these employees equals the first direct cost component. Because safety department employees are usually senior and/or experienced staff members, they are considered first line supervisors based on Table 4.1, yielding annual costs of $600,000. Furthermore, *administrative costs* also need to be taken into account, and they add another $340,000 to the equation.

  Because it has become very common in the petrochemical industry for not only the safety department but also the rest of W to participate in regular safety meetings and perform safety inspections, these costs also need to be calculated. The time devoted to safety meetings is estimated at half an hour per week. If all employees participate in these weekly meetings, then the annual costs amount to approximately $130,000 per year. Assuming that each safety inspection lasts approximately one hour and each employee has to perform five inspections per year, another $520,000 is required. In summary, M’s annual TDC for the enforcement amounts to approximately $1.6 million, which corresponds very well with the estimated costs of a dedicated process safety programme according to (Bridges, 1994), i.e., $1.3 million ($1.96 million in 2008 prices).

- C_H : M’s handling costs for delivering a punishment also consist of several components. After a violation of a safety procedure is detected, the “case” will usually be discussed in a *safety council meeting* before M decides on the type of punishment. According to the author’s experience, M needs to devote approximately two hours per week to these meetings. Based on M’s salary according to Table 4.1, an annual cost of $60,000 is deduced.

  Furthermore, the outcome of these meetings needs to be discussed with W, which requires first line supervisors and line managers to devote a certain amount of their time, i.e., one hour and one half hour per week, respectively, to *safety discussions*. The costs for these safety discussions are estimated at $280,000 per year.

As already mentioned, punishment can take the form of instant dismissal. This sometimes results in trials before a labour court. The corresponding *legal expenses* of approximately \$110,000 also need to be added to the equation. These costs are based on the estimate that there are approximately five litigation cases per year. For each case, forty hours of attorney fees will be required.[234] In one out of five cases, there will be a settlement resulting in payment of one production worker's annual salary. In summary, the TDC for handling of violations amounts to approximately \$450,000 per year.

- C_{I2}: M's incident costs consist of the refinery's average annual incident costs, including people, environmental and asset costs, as described in Chapter 4.2.2 and, more specifically, in Table 4.5. This calculation delivers an annual TDC of \$3.6 million.
- C_{I1}: W's incident costs consist of two components. On one hand, there are the average *injury costs,* which were calculated in the previous section to be \$700,000 per year. On the other hand, if an incident occurs, W's *performance bonus* will also be affected. Almost all petrochemical companies have both fixed and variable salary components. The variable portion of the salary, or performance bonus, is determined by the individual's as well as the company's performance. A consistent safety programme also requires that bonus payments be reduced if safety performance is unsatisfactory. The author assumes that in case of an incident, there will be a 10% reduction of W's bonus payment, i.e., \$420,000. In summary, this results in an annual TDC of \$1.1 million.
- C_P: The last of W's cost parameters is the cost of punishment. It is assumed that, on average, one member of W will be dismissed per year. This *dismissal* will have serious consequences for the "offender", i.e., a loss of income of 25% over a period of twenty years,[235] amounting to \$250,000. This figure can be explained by the fact that jobs in the petrochemical industry are much better paid than jobs in other industries and it will be virtually impossible for the offender to find a new job with another petrochemical company.

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234 According to LexisNexis (2011), the average billing rate equals \$284 per hour.

235 The period of twenty years was chosen because it represents the time until retirement for an average U.S. production worker aged around 40; see Welch (2010).

Furthermore, there will also be a *performance bonus reduction* for W. It is assumed that in one year, 10% of all members of W will receive a formal warning resulting from a safety infraction. A formal warning is connected to a bonus payment reduction of 50%. The overall reduction is thus estimated at $590,000. In summary, an annual TDC for punishment of $840,000 is obtained.

- B_E: Demonstrating commitment to safety and enforcing safety procedures results in a number of benefits for M. These include *decreased capital costs*, *reduced production costs* and *lower insurance premiums*. According to (Center for Chemical Process Safety, 2006), these effects can reduce capital costs by 1%, production costs by 3% and insurance premiums by 20%. Based on these percentages and the archetypal refinery's economic data depicted in Table 4.2 and Table 4.3, the annual TDB for enforcement was calculated as $6.6 million.
- B_G: Delivering a good safety performance will lead to a significant *bonus payment* increase for M because safety is PC's most important business goal. It is assumed that such an increase can reach 20%. In addition, a company with a good safety record is more likely to receive *capital budgeting* from PC. New projects pay off faster in a refinery that operates safely and therefore reliably. The author assumes the increase in capital budget to equal approximately 5% of the archetypal refinery's capital expenditures for new equipment; see Table 4.3. Altogether, a TDC for good safety performance of $2.3 million was calculated.
- B_S: If M does not enforce safety procedures, it will lose several benefits. As a result of the deteriorating safety culture, it is assumed that a *performance bonus reduction* of 20% and an *increase in incident rates* of 10% will occur. This leads to a loss of the annual TDB for being committed to safety of $600,000.
- B_C and B_D: In case of a clean safety record, W will receive a *performance bonus* increase of 10% or, in case of a documented clean safety record, even 20%. In addition, as safety has very high relevance within the refinery, it is not uncommon that members of W receive extra premiums for exemplary safety leadership. The author assumes that 10% of W will receive such a $1000 premium. As a result, one obtains a TDB for a clean safety record of $420,000 and a TDB for a documented clean safety record of $940,000.

- B_V : The last parameter is W's benefits for a successful violation. The most obvious benefit component is *time savings*. It is assumed that W will save up to five minutes per day per employee as a result of violations. As presented in Chapter 2.2.3, violations usually represent shortcuts around safety procedures that save time but expose the offender to considerable risks. In the petrochemical industry, quick decisions and actions are often required to keep an operation running. Hence, members of W are sometimes drawn towards these optimising violations. If such a violation is performed successfully, i.e., no incident happens, the plant stays in operation and the offender does not get caught, W may be celebrated as the "saviour of production" or as an outstanding "fire fighter". As a result, *performance bonus* increases of up to 10% and *extra premiums* might be attributed. The above components deliver an overall annual TDB for violation of $1.3 million.

4.2.4 Qualitative adjustment

Although the direct costs and benefits can be determined with sufficient statistical accuracy, the indirect costs and benefits of safety remain very difficult to assess. Fortunately, several studies have been performed in the petrochemical and other industries that can help to determine these indirect costs.

In a recent study, (Huang et al., 2009) questioned senior financial executives of several U.S. companies on the indirect costs of workplace safety and found that costs are estimated to range between two and five times the direct costs. This finding is also supported by a study from (Hudson & Stephens, 2000), who used weighting factors between two and five in a study of North Sea oil platform incidents. More elevated weighting factors were calculated in another well-documented study of five U.K. industry segments by (Health and Safety Executive, 1993, p. 18). In this study, the indirect costs were estimated between eight and eleven times the direct cost values.

Despite such empirical support, it must be acknowledged that attributing numerical values to indirect costs will always be a subjective exercise that can hardly be grasped with conventional scientific methods. Thus, this thesis applies an approach that reveals the author's subjective assessment in a very transparent way.

The method used in this thesis has been described in Chapter 4.2.1. It attributes qualitative weighting factors, i.e., the QFs, to the TDC and TDBs. For the purpose of the investigation, the QFs will be assigned values between 1 (weak influence) and 5 (strong influence). Furthermore, these weighting factors were not simply derived from the author's experience; they were also based on the data gathered among a considerable number of company board members and published in (Health and Safety Executive, 2006a). The results of the QF assessment for both players' payoff parameters are revealed in Table 4.9 and Table 4.10 and are further explained on the following pages.

Table 4.9: Total Qualitative Factor (TQF) for cost payoff parameters

Payoff parameter	Management (M)						Workforce W			
	C_E	Factor	C_H	Factor	C_{I2}	Factor	C_{I1}	Factor	C_P	Factor
Qualitative Factors (QF)[a]	Inefficiencies in daily operation due to safety focus	2	Inefficiencies due to discussion of punishment cases within workforce	2	Decreased business performance	4	Increased workload (stress and overtime)	4	Increased workload (stress and overtime)	5
			Deteriorating relations with work council/trade unions	3	Deteriorating relations with parent company	3	Reputational loss (company and family etc.)	2	Reputational loss (job market, comany and family)	4
					Deteriorating relations with external regulators and public	5				
Total qualitative factor (TQF)		**2.0**		**2.5**		**4.0**		**3.0**		**4.5**

Note.
[a]Qualitative factors were selected according to author's experience and Health and Safety Executive (2006) study of executive board members. Factors vary from 1 (very weak influence) to 5 (very strong influence)

Table 4.10: Total Qualitative Factor (TQF) for benefit payoff parameters

Payoff parameter	Management (M)						Workforce W					
	B_E	Factor	B_G	Factor	B_S	Factor	B_C	Factor	B_D	Factor	B_V	Factor
Qualitative Factors (QF)[a]	Deterrence effects (less violation, i.e. reduction in corporate risk)	4	Improvement in business performance, e.g. less absence, more sales	5	Adverse deterrence effects (violation pays off and thus increase in corporate risk)	5	Reputational increase with supervisors and peers	3	Reputational increase with supervisors and peers	4	Reputational increase with supervisors and peers	3
	Improved relations and respect with parent company	2	Improved relations and respect with parent company	3	Deteriorating relations and respect with parent company	4	Job Security	2	Job Security	3	Job Security	2
	Improved relations with external regulators and public	1	Improved relations with external regulators and public	3	Deteriorating relations with external regulators and public	1	Less work pressure and stress	2	Less work pressure and stress	3	Less work pressure and stress	2
Total qualitative factor (TQF)		**2.3**		**3.7**		**3.3**		**2.3**		**3.3**		**2.3**

Note.
[a]Qualitative factors were selected according to author's experience and Health and Safety Executive (2006) study of executive board members. Factors vary from 1 (very weak influence) to 5 (very strong influence)

- C_E: The first TQF that needs to be discussed corresponds to M's enforcement costs. Besides the direct costs of the enforcement, additional safety requirements will always result in additional indirect costs. This can easily be demonstrated by the following practical example: consider a leaking flange on a cooling water pipe in a pipe bridge at approximately three metres above the ground. While it might have been possible to simply replace the gasket by using a ladder in the past, stronger safety requirements now require that scaffolding be built. Not only is scaffolding more expensive, but it also takes more time to set up and therefore causes a delay in the repair process. Considering these additional costs and *inefficiencies*, a QF of 2 and therefore a TQF for the enforcement of 2 seem to be justified.
- C_H: A similar logic applies to the handling costs for delivering a punishment. If M punishes W, the current "case" will be discussed during work, and W might be intimidated. M must counteract this feeling of intimidation with additional communication efforts, i.e., it needs to credibly explain why a certain punishment has been chosen and create an environment of trust. This can be very time consuming, and it is even estimated by some researchers that members of M devote up to 50-60% of their time to HSE issues.[236] Even if HSE is the most important business goal, on the bottom line, discussions about punishment cases distract M and prevent it from using its time more efficiently. When adding up these distractions and inefficiencies, a rather cautious QF of 2 has been assigned. Furthermore, punishment cases can result in discussions with the local work council and trade unions and thus the *deterioration of relations* between M and W. Hence, a QF of 3 is attributed to this effect, which delivers a TQF for the handling of punishment of 2.5.
- C_{I2}: M's incident costs are influenced by several components. On one hand, every incident decreases the refinery's *business performance* due to consecutive production upsets and incident investigations. It usually takes hours or even days until these upsets are compensated. For example, consider a fire due to a leaking line within a crude oil distillation unit. In this case, the unit has to be put on "recycle" or even shut down. Ramping up the process after repair involves draining the pipe work, starting the furnaces, heating up the oil, and getting all machines running again before finally starting the distillation column. In the meantime, the refinery loses a

236 Health and Safety Executive (2006a, p. 204).

considerable margin and manpower, i.e., a crude oil distillation unit that is shut down for one day can easily cost several hundred thousand dollars. Because margin and profitability are of very high importance to M, a QF of 4 is attributed. Production upsets also do not remain undetected by PC, and *internal relations* can be seriously disturbed by such incidents. Although this influencing factor is not as strong as the overall profitability, it is still attributed a QF of 3. In addition to internal relations, incidents such as fires or explosions rarely remain unnoticed by external regulatory bodies and/or the public. Deteriorating *external relations* caused by such incidents can even endanger a refinery's license to operate or result in heavy fines.[237] Therefore, a strong influence with a QF of 5 is estimated, resulting in a TQF of 4.

- C_{I1}: In case of the W's incident costs, several effects need to be considered. Assume that a member of W needs to stay home for several days after an incident. Other members of W must then take up the workload and work overtime. Because incidents have a negative effect on the overall refinery performance, M will also put additional pressure on W to perform well and make up for the lost production. This results in increased *workload and stress* and even creates opportunities for further mishaps. Because members of W, like all human beings, are very sensitive to external influencing factors, such as stress and increased workload,[238] this factor has a strong influence and is rated at a QF of 4. Less important, but nevertheless non-negligible, is the effect of *reputational loss* within the company. Most people strive to perform well at their jobs. If an incident occurs, many members of W consider this a personal failure. This factor is not as strong as the workload effect but is still rated at a QF of 2 and leads to a TQF of 3.0.
- C_P: In case of W's punishment, the most significant indirect costs can be observed. The first component is a strong *reputational loss* following a punishment. Within W, the offenders will experience the most significant indirect costs, for example, due to limited chances on the job market. However, the consequences of a punishment do not only affect the offender; they also reflect on W's overall per-

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[237] For example, after the 2005 Texas City refinery explosion, BP was not allowed to operate the refinery for several weeks and had to pay several hundred million dollars in fines.

[238] For an extensive discussion of the effects of stress on workplace injuries and related safety risks, see Glendon, et al. (2006, pp. 227–268).

formance. A punishment thus reduces W's reputation and therefore its job satisfaction. For many people, work is the most important part of their life,[239] and a high QF of 4 is therefore attributed. In addition, following a punishment such as a dismissal, W will not only need to compensate with overtime but will also feel M's pressure to deliver the required HSE results. The *stress* level is even higher than after an incident without violation and is therefore attributed the highest possible QF of 5. Finally, a TQF of 4.5 is reached.

- B_E: M's enforcement benefit can be assessed as follows: if M enforces safety procedures, there will not only be direct benefits such as lower insurance premiums but also *deterrence effects* resulting in reduced corporate risk, which is of special importance to M. A strong QF of 4 is therefore attributed to this parameter. Furthermore, demonstrating a commitment to safety also fulfils M's obligations towards PC. This *internal relations* effect is less important because having enforcement strategies in place has become standard in most refineries and is thus only rated at a QF of 2. Although enforcing safety procedures can be crucial in the *external relations* with regulatory bodies and especially the public, only "seeing is believing". Hence, the best enforcement is superfluous if it does not lead to a good safety record. The component therefore has only a very week influence, with a QF of 1. The overall TQF for B_E equals 2.3.
- B_G: M's benefits of a good safety performance are very similar to the benefit of enforcement except that all QFs are higher for the following reason. As previously mentioned, merely demonstrating enforcement practices and a commitment to safety is not enough. Improved *internal relations* with PC and *external relations* with regulatory bodies and the public can only be achieved if the desired result, and thus good safety performance, occurs. If this is the case, a QF of 3 is attributed in both cases. In addition, improvement in *business performance* is a very important side effect of safe operation and is thus attributed the highest possible QF of 5. Combining these effects yields a TQF of 3.7.
- B_S: In the same line of argument, M's reputational benefits arising from safety commitment have to be considered. It has to be noted that this parameter possesses

239 See Harvard University John F. Kennedy School of Government (2001, p. 30).

a negative sign in both game models and can thus be considered M's reputational loss for not reacting to violations. At first, there are the *adverse deterrence effects* and the corresponding increase in corporate risk. If, through either action or inaction, M sends the message to W that violations are tolerated, this has a very strong indirect effect and is rated at a QF of 5. However, M's reputation is rarely known outside of the refinery, so there will be virtually no effect on the *external relations* with regulators or the public. A QF of 1 thus seems to be justified. On the other hand, M can hardly conceal the situation in its refinery from PC. By means of regular employee surveys, PC will be very well informed about the situation and will not be satisfied if M suffers reputational losses from not reacting to violations. A strong QF of 4 is therefore attributed, which finally leads to a TQF of 3.3.

- B_C and B_D: W's reputational benefits for having a clean safety record or a documented clean safety record have similar qualitative influences with slightly different weights. Whereas the *reputational increase* with supervisors and peers in case of a clean safety record is rather important to W, with a QF of 3, its influence is even stronger if the safety record is also documented, with a QF of 4. Another qualitative component is *job security*. Although working safely and "sticking to the rules" helps to increase job security, it is no guarantee because economic considerations always prevail in these situations. The component thus has limited influence, with a QF of 2. In case of a documented clean safety record, a slightly higher weight with a QF of 3 seems to be justified. The same QF distribution also holds for the component of *work pressure and stress*. Although having a good safety record sometimes helps W to experience less stress and pressure at work, the main pressure from production remains unaltered. The resulting TQFs are 2.3 in case of a clean safety record and 3.3 in case of a documented clean safety record.
- B_V: W's benefits from violations are also affected by the same qualitative components as in the case of a clean safety record. Because violators who have not been caught can unfortunately not be distinguished from members of W with clean safety records, an identical QF with a weight of 3 is attributed as a *reputational increase*. Furthermore, although *job security* and *work pressure* are positively affected by the image of a successful "fire fighter", production pressure still dominates, and therefore a QF of 2 is justified in both cases. Overall, this leads to a TQF for violation of 2.3.

4.2.5 Payoff parameters

Now that all TQFs have been calculated, the final cost and benefit parameters C_i and B_j for M and W can be deduced by multiplying the TDC and TDB by the corresponding TQFs, as depicted in Table 4.11 and Table 4.12.

Table 4.11: TDC adjusted by TQF

	Management (M)			Workforce W	
Payoff parameter	C_E	C_H	C_{I2}	C_{I1}	C_P
Annual Total Direct Costs (TDC) [k$]	1,588	448	3,615	1,120	836
Total Qualitative Factor (TQF)	2.0	2.5	4.0	3.0	4.5
Annual TDC adjusted by TQF [k$]	3,176	1,120	14,460	3,360	3,761
Weekly TDC adjusted by TQF [k$]	**64**	**22**	**289**	**67**	**75**

Table 4.12: TDB adjusted by TQF

	Management (M)			Workforce W		
Payoff parameter	B_E	B_G	B_S	B_C	B_D	B_V
Annual Total Direct Benefits (TDB) [k$]	6,613	2,317	602	418	937	1,303
Total Qualitative Factor (TQF)	2.3	3.7	3.3	2.3	3.3	2.3
Annual TDB adjusted by TQF [k$]	15,431	8,495	2,005	976	3,123	3,040
Weekly TDB adjusted by TQF [k$]	**309**	**170**	**40**	**20**	**62**	**61**

Before the above payoff parameters can finally be merged into game model Γ_2 and the PORT, the incident probabilities remain to be determined.

4.3 Incident probabilities

As depicted by the original game tree in Figure 3.6, determining the incident probabilities for game model Γ_2 requires calculating the conditional probabilities that an incident happens if W violates, $r_v = p(I \mid v)$, or does not violate, $r_{nv} = p(I \mid nv)$. Although this calculation sounds straightforward, gathering the required data on *incident causes* and *human reliability* is a challenge. The following equations reveal why this calculation is non-trivial.

4.3.1 Method

To determine the relevant conditional probabilities, the law of Bayes[240] must be applied for both events:

$$r_v = p(I \mid v) = \frac{p(v \mid I) \cdot p(I)}{p(v \mid I) \cdot p(I) + p(v \mid NI) \cdot p(NI)}, \tag{4.7}$$

$$r_{nv} = p(I \mid nv) = \frac{p(nv \mid I) \cdot p(I)}{p(nv \mid I) \cdot p(I) + p(nv \mid NI) \cdot p(NI)}. \tag{4.8}$$

The parameters are defined as follows:

- $p(I)$ a priori probability that an incident occurs
- $p(NI)$ a priori probability that no incident occurs
- $p(v \mid I)$ probability of violation in case an incident has occurred
- $p(v \mid NI)$ probability of violation in case an incident has not occurred
- $p(nv \mid I)$ probability of compliance in case an incident has occurred
- $p(nv \mid NI)$ probability of compliance in case that an incident has not occurred

Inserting the following equations:

$$p(NI) = 1 - p(I) \tag{4.9}$$

$$p(nv \mid I) = 1 - p(v \mid I) \tag{4.10}$$

$$p(nv \mid NI) = 1 - p(v \mid NI) \tag{4.11}$$

into equations (4.7) and (4.8) delivers the final terms:

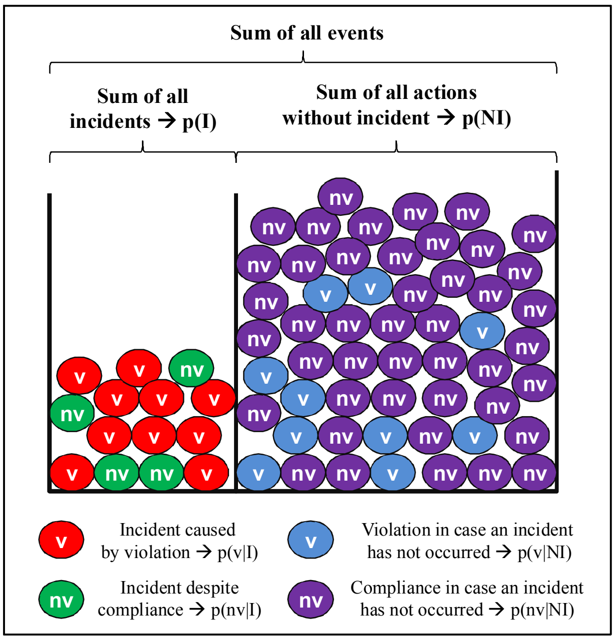
$$r_v = p(I \mid v) = \frac{p(v \mid I) \cdot p(I)}{p(v \mid I) \cdot p(I) + p(v \mid NI) \cdot (1 - p(I))}, \tag{4.12}$$

$$r_{nv} = p(I \mid nv) = \frac{(1 - p(v \mid I)) \cdot p(I)}{(1 - p(v \mid I)) \cdot p(I) + (1 - p(v \mid NI)) \cdot (1 - p(I))}. \tag{4.13}$$

To make this calculation more accessible, Figure 4.5 illustrates the underlying probability distribution.

[240] For further information, see Aliprantis and Chakrabarti (2000) or Sieg (2005, pp. 96–97)

Figure 4.5: Probability distribution for game Γ_2



The sum of all events is the sum of all individual incidents (red and green balls in the left box) and the sum of all actions without incident (blue and purple balls in the right box). Counting reveals the overall probability distribution for an event being an incident p(I) or not an incident p(NI). Within these two boxes, another distinction can be made. An incident (left box) can be caused by a violation (red ball) or can happen despite compliance (green ball). Once again, counting delivers the probability distributions for an incident caused by a violation, $p(v \mid I)$, and for an incident that occurs despite no violation, $p(nv \mid I)$. The same exercise can be performed for the right box by counting the blue and purple balls, yielding the values for $p(v \mid NI)$ and $p(nv \mid NI)$.

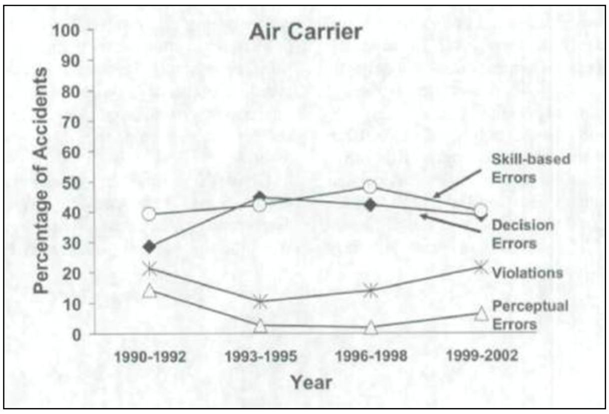
When looking at Figure 4.5 and its differently coloured balls, it seems that the corresponding probabilities can easily be obtained. Although this might be true in a laboratory environment, in reality, many different industrial data sources[241] have to be consulted to determine the correct input parameters for equations (4.12) and (4.13). For example, assigning a value to $p(v \mid I)$ requires knowledge of the percentage of incidents caused by rule violations within the petrochemical industry.

241 For a very good overview of existing petrochemical databases, see Nivolianitou, Konstandinidou, Kiranoudis, and Markatos (2006).

4.3.2 Incident and human reliability studies

Due to their sensitive nature, very few specific data on the actual number of rule violations within petrochemical refineries are published. Thus, besides petrochemical data sources, data from other industries had to be consulted before proceeding with the calculation. The aviation industry provides excellent publications on this type of sensitive data, likely because of its long history of rigorous accident investigation. Of the many studies on rule violations, (Wiegmann & Shappell, 2001) and (Shappell et al., 2007) provide the most relevant data for the purpose of this analysis. As depicted in Figure 4.6, approximately 23% of commercial aviation incidents in the years 1999-2002 were caused by rule violations.

Figure 4.6: Causes of commercial aviation incidents



Source: (Shappell et al., 2007, p. 233)

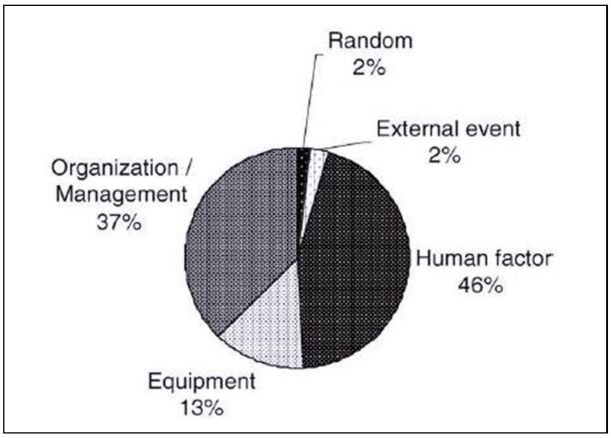
Of course, the petrochemical industry also provides studies on the contribution of human factors to accident causation. Several researchers argue that the human contribution can account for up to 80% of all accidents; see Chapter 2.3.1. Unfortunately, these studies do not explicitly address the subject of rule violations and the associated quantitative data.

Nevertheless, the existing studies on human factors allow conclusions to be drawn on the underlying violation frequencies. (Health and Safety Executive, 1999) investigated the human contribution to pipe work failure and found that about 41% of failures were caused by human error and/or violations. Using similar techniques as the European Commission's Major Accident Reporting System (MARS),[242] (Konstandinidou, Nivolianitou, Markatos, & Kiranoudis, 2006) found that the contribution of the human factor

[242] Available online at http://emars.jrc.ec.europa.eu.

to incidents within the Greek petrochemical industry amounted to 46%; see Figure 4.7. The resulting violation percentage is estimated at approximately 15%.

Figure 4.7: Human factor accident contribution in the Greek petrochemical industry



Source: (Konstandinidou et al., 2006, p. 7)

There are further MARS-based studies by (Nivolianitou, Konstandinidou, & Michalis, 2006) and (Baranzini D. & Christou, 2010) that indicate that between 40% and 43% of all accidents are caused by human factors. Furthermore, (Baranzini D. & Christou, 2010) provides a figure for the contribution of operator errors of 28%. (Meel et al., 2007) estimated the operator error contribution to incidents within the petrochemical industry to equal between 20% and 50%.[243]

Table 4.13 summarises the results of the above studies and calculates an average Human Factor Incident Percentage (HFIP) of 33%.

Table 4.13: Human Factor Incident Percentage (HFIP)

HSE 1989 (error + violation)	Konstandinidou et al. 2006 (human factor)	Konstandinidou et al. 2006 (violation)	Nivolianitou et. al 2006 (human factor)	Meel et al. 2007 (operator error)	Shappell 2001, 2007 (violation)	Baranzini 2010 (human factor)	Baranzini 2010 (operator error)	**Average HFIP[a] p(I|V)**
0.41	0.46	0.15	0.4	0.2-0.5	0.23-0.27	0.43	0.28	**0.33**

Note.
[a]HFIP = Human factor incident percentage

Because there are obvious variations in the available data and, except for two cases, the underlying violation percentages could not be determined directly, the author decided to assign a discrete *probability distribution* to $p(v \mid I)$ to allow a sensitivity analysis at a later stage.

$$p(v \mid I) = \{0.15;\ 0.20;\ 0.27;\ 0.33;\ 0.41;\ 0.46;\ 0.50\} \tag{4.14}$$

[243] Please note that there are several other accident databases requiring privileged access, such as CORE-DATA by Health and Safety Executive (1999) or FACTS, which could not be investigated.

The next parameter, $p(I)$, which is required for calculation of r_v and r_{nv}, has been determined by the average *weekly incident frequency* (see Table 4.4) and is therefore set at a value of

$$p(I) = 0.20 \quad (4.15)$$

The final parameter, $p(v \mid NI)$, is the most difficult one to assess. How can one possibly know the violation probability when there is no incident and therefore no record of the infraction?

Due to the lack of accessible records and the fact that human reliability is extremely hard to assess, one can only rely on very rough estimates of the corresponding violation probability and the experience of several respected researchers. A very good overview of human reliability data has been assembled by (Kletz, 2001, p. 136). (Kirwan, Kennedy, Taylor-Adams, & Lambert, 1997), (Salvendy, 2006, pp. 738–739) and (Greenberg & Cramer, 1991, p. 240) have gathered similar data. Finally, a very interesting experiment on rule violations was recently performed by (Kluge, Urbas, Badura, Lippmann, & Vogel, 2010).

In summary, these studies assume a *violation probability* in an industrial/petrochemical environment of between 0.1% and 50%.

$$p(v \mid NI) = \{0.001..0.5\} \quad (4.15)$$

4.3.3 Probability parameters

Finally, with all of the above data, the conditional *incident probabilities* r_v and r_{nv} for game Γ_2 can be calculated according to equations (4.12) and (4.13). The resulting conditional probability distribution is shown in Table 4.14 for the average incident probability of $p(I) = 0.20$. Table 4.14 reveals the huge spread of $p(v \mid NI)$, which makes a reliable calculation of the associated risk level almost impossible.

Based on a thorough literature review and his own experience, the author decided to reduce the data spread by assuming a violation probability in case of no incident of between 1% and 10%, which is supported by findings from (Glendon et al., 2006, pp. 125–127). Furthermore, the HFIP was also narrowed down by omitting its maximum and minimum values.

Table 4.14: Incident probabilities for game Γ_2 with p(I)=0.20

HFIP	r_v=p(I|v)					r_{nv}=p(I|nv)				
	Estimates of p(v|NI)				Mean value	Estimates of p(v|NI)				Mean value
	0.001	0.01	0.1	0.5		0.001	0.01	0.1	0.5	
0.15	0.974	0.787	0.270	0.069	0.529	0.179	0.181	0.195	0.304	0.188
0.2	0.981	0.836	0.338	0.093	0.587	0.170	0.171	0.185	0.290	0.178
0.27	0.986	0.873	0.408	0.121	0.641	0.157	0.158	0.172	0.271	0.165
0.33	0.988	**0.894**	**0.459**	0.145	**0.677**	0.146	**0.147**	**0.159**	0.254	**0.153**
0.41	0.991	0.913	0.511	0.173	0.712	0.131	0.132	0.143	0.231	0.138
0.46	0.992	0.922	0.540	0.190	0.731	0.121	0.122	0.133	0.216	0.128
0.5	0.992	0.927	0.561	0.203	0.744	0.113	0.114	0.124	0.203	0.119

The remaining probability distribution for r_v and r_{nv}, which will serve as the final input for game model Γ_2 with mean values of r_v=0.677 and r_{nv}=0.153, is indicated by the dark grey colour in Table 4.14.

4.4 Results

The final step on the road towards industrial application lies in entering the calculated payoff and incident probability parameters into the game model Γ_2.

4.4.1 PORT of archetypal refinery

The result of this calculation is the input for game model Γ_2, as shown in Table 4.15. The PORT of the archetypal refinery as well as the consequences of different risk management strategies can now be discussed based on "real-life" industrial data.

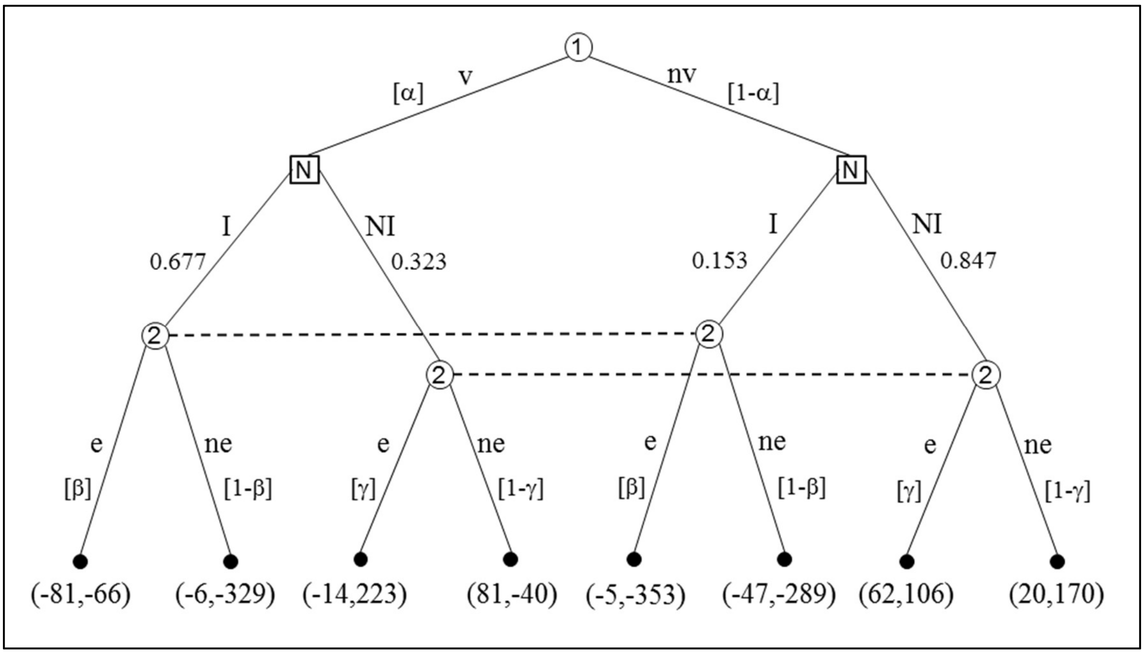
Table 4.15: Weekly monetary payoff parameters of game Γ_2 with industrial data

Workforce (1)		Management (2)	
Parameter	Payoff [k$]	Parameter	Payoff [k$]
B_C	20	B_E	309
B_D	62	B_G	170
B_V	61	B_S	40
C_P	75	C_E	64
C_{I1}	67	C_H	22
		C_{I2}	289
Average conditional incident probability			
r_v	0.677	r_{nv}	0.153

It has to be noted that the payoff parameters in Table 4.15 are expressed in thousands of dollars per week and the conditional incident probabilities are given on a *weekly basis*. The main reason for using a weekly basis instead of an annual basis is that the PORT, to work properly, requires incident probabilities less than 1. An annual basis could not be used because an incident would have happened with certainty. Only monthly, weekly or daily calculations deliver probabilities in the required ranges. Besides this strictly mathematical requirement, there is another very practical and comprehensive reason why the choice was made to use weekly figures.

In the archetypal refinery, the interaction between M and W is strongly determined by the weekly safety meetings. M communicates its priorities on HSE matters or current violations of safety procedures during these meetings. Hence, it seems reasonable to assume that the interaction between M and W takes place on a weekly basis and the game Γ_2 is played once per week, i.e., fifty times per year. The corresponding game tree, complete with monetary values, is depicted in Figure 4.8.

Figure 4.8: Game tree representation of game Γ_2 with monetary payoff parameters



The corresponding equilibrium results of game Γ_2 with monetary payoffs and incident probabilities based on industrial data are depicted in Table 4.16 and the PORT in Figure 4.9.

Figure 4.9: PORT with industrial data of archetypal refinery

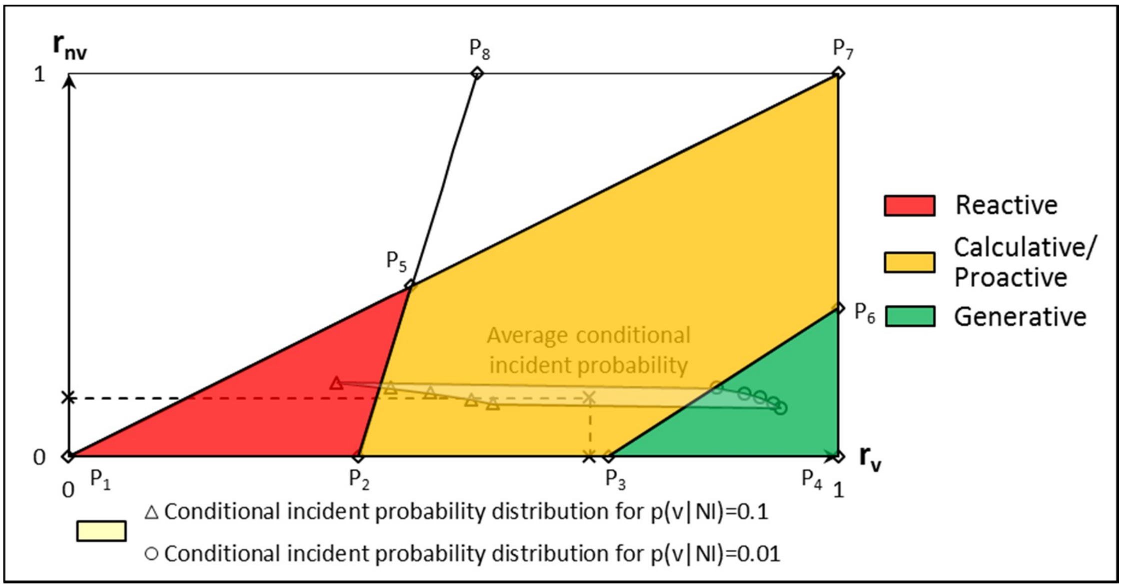


Table 4.16: Monetary results of game Γ_2 with industrial data

Equilibrium parameters	α^*	β^*	γ^*	π_1^*	π_2^*	X	Y
Game results	0.052	0.216	0	11.14	82.29	0.400	0.819

As indicated by Table 4.16, in equilibrium, W's violation probability equals 5.2%, while M enforces in 21.6% of all incident cases. These individual equilibrium strategies yield an expected payoff of approximately \$82,000 per week (\$4.1 million per year) for M and \$11,100 per week (\$560,000 per year) for W.

These game results emphasise that in the case of the archetypal refinery, enforcing safety procedures is worthwhile and profitable. Not surprisingly, the refinery possesses *a calculative/proactive* safety culture that is common in today's petrochemical industry; see Chapter 2.4.3. In such a calculative/proactive safety culture, both players receive a positive expected payoff in the order of several million dollars per year. It can thus be concluded that the existing safety culture and the chosen enforcement are "fit for purpose".

However, the PORT does not only support conclusions about the refinery's current position on the safety culture ladder. Its most innovative aspect is that it helps M to design an individual roadmap towards an improved safety culture in *quantitative* terms. The PORT thus assists M in finding the optimum balance between safety investment and safety payoffs due to its strong mathematical foundation, i.e., the underlying Nash equilibrium.

But how can M increase its return on investment, i.e., its expected payoff, and which risk management practices are appropriate?

4.4.2 Comparison of risk management strategies

To answer the above question, M must simply compare the numerical results, i.e., the expected monetary benefits, of the different risk management strategies. Consider, for example, that M can choose between a risk management strategy of *increased punishment* and one of *management commitment*. These two alternatives served as the baseline for the theoretical investigations performed in Chapter 3.

If M decides to opt for a strategy of *increased punishment*, it is assumed that there will now be two formal dismissals per year (instead of one) and that deterrence effects as well as the corresponding benefits will increase by 25%. However, in return, twice as many litigation cases and safety council meetings will be required. If M decides to increase its *management commitment*, then it is assumed that all benefits will be increased by 10%. The corresponding payoff parameters for both risk management strategies are shown in Table 4.17.

Table 4.17: Weekly monetary payoff parameters for game Γ_2 with industrial data and different risk management strategies

Increased punishment				**Increased management commitment**			
Workforce (1)		Management (2)		Workforce (1)		Management (2)	
Parameter	Payoff [k$]	Parameter	Payoff [k$]	Parameter	Payoff [k$]	Parameter	Payoff [k$]
B_C	20	$\hat{B}_E$	**386**	$\tilde{B}_C$	**22**	$\tilde{B}_E$	**340**
B_D	62	B_G	170	$\tilde{B}_D$	**68**	$\tilde{B}_G$	**187**
B_V	61	B_S	40	$\tilde{B}_V$	**55**	$\tilde{B}_S$	**44**
$\hat{C}_P$	**98**	C_E	64	C_P	75	C_E	64
C_{I1}	67	$\hat{C}_H$	**44**	C_{I1}	67	C_H	22
		C_{I2}	289			C_{I2}	289
Average conditional incident probability							
r_v		0.677		r_{nv}		0.153	

The equilibrium results for both risk management strategies are shown in Table 4.18, and the corresponding PORTs are depicted in Figure 4.10 and Figure 4.11.

Table 4.18: Monetary results for game Γ_2 with industrial data and different risk management strategies

Equilibrium parameters	α^*	β^*	γ^*	π_1^*	π_2^*	X	Y
Original game	0.052	0.216	0	11.14	82.29	0.400	0.819
Increased punishment	0.044	0.170	0	10.84	85.18	0.350	0.819
Increased management commitment	**0.046**	**0.086**	**0**	**12.36**	**97.79**	**0.355**	**0.733**

The numerical results in Table 4.18 clearly demonstrate that the theoretical findings of Chapter 3 are supported and that a strategy of management commitment is more effective than a strategy of increased punishment.

Although increased punishment reduces W's violation probability to a value of 4.4% ($\hat{\alpha}^* = 0.044$), M must still enforce in 17% ($\hat{\beta}^* = 0.170$) of all cases. M's main advantage in applying a strategy of increased management commitment thus lies in a significantly reduced enforcement requirement. The new enforcement probability drops to 8.6% ($\tilde{\beta}^* = 0.086$), which equals a reduction of 13% compared with the original game.

Furthermore, Table 4.18 reveals that both M and W's expected payoffs increase significantly in case of increased management commitment. The annual payoffs amount to $\tilde{\pi}_1^*$ = \$620,000 for W and $\tilde{\pi}_2^*$ = \$4.9 million for M. In case of increased punishment, these numbers are lower, with annual payoffs of $\hat{\pi}_1^*$ = \$540,000 for W and $\hat{\pi}_2^*$ = \$4.3 million for M.

An increased commitment by M thus clearly offers more incentives for compliant behaviour to W. By reducing its enforcement efforts, M can save up to \$15,500 per week ($\tilde{\pi}_2^* - \pi_2^*$) compared with the original game and \$12,600 ($\tilde{\pi}_2^* - \hat{\pi}_2^*$) compared with the game of increased punishment. W also profits from this risk management strategy with an increased payoff of \$1200 per week ($\tilde{\pi}_1^* - \pi_1^*$).

The PORTs of both strategies are shown in Figure 4.9 and Figure 4.10. They help to explain the difference between the risk management strategies in an easily understandable manner and highlight the road towards an improved safety culture. It is important to understand that incident probabilities will remain fixed during further analysis.

Figure 4.10: PORT with industrial data and increased punishment

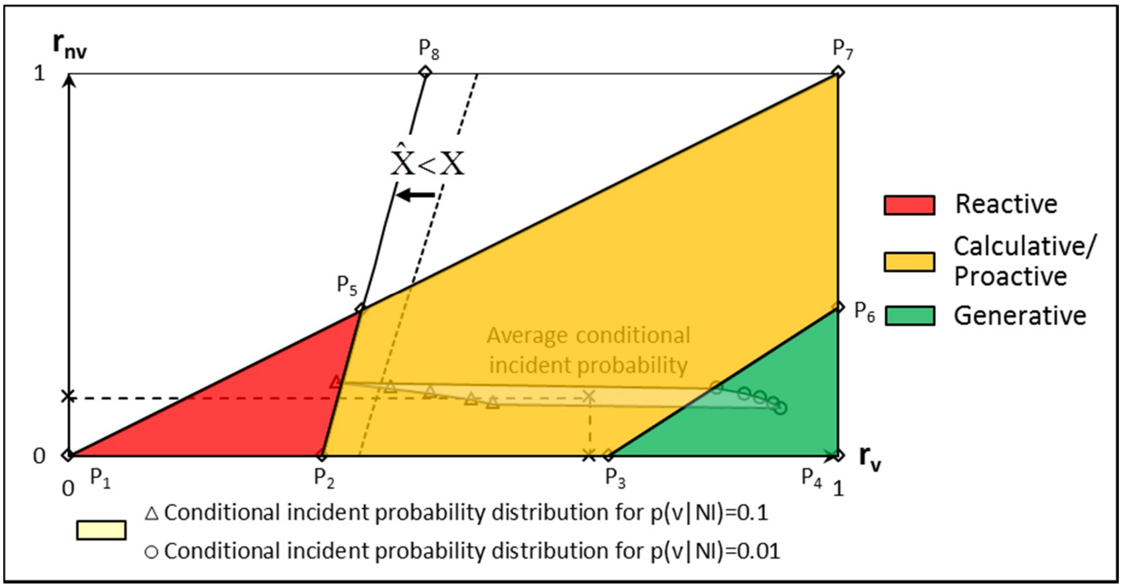
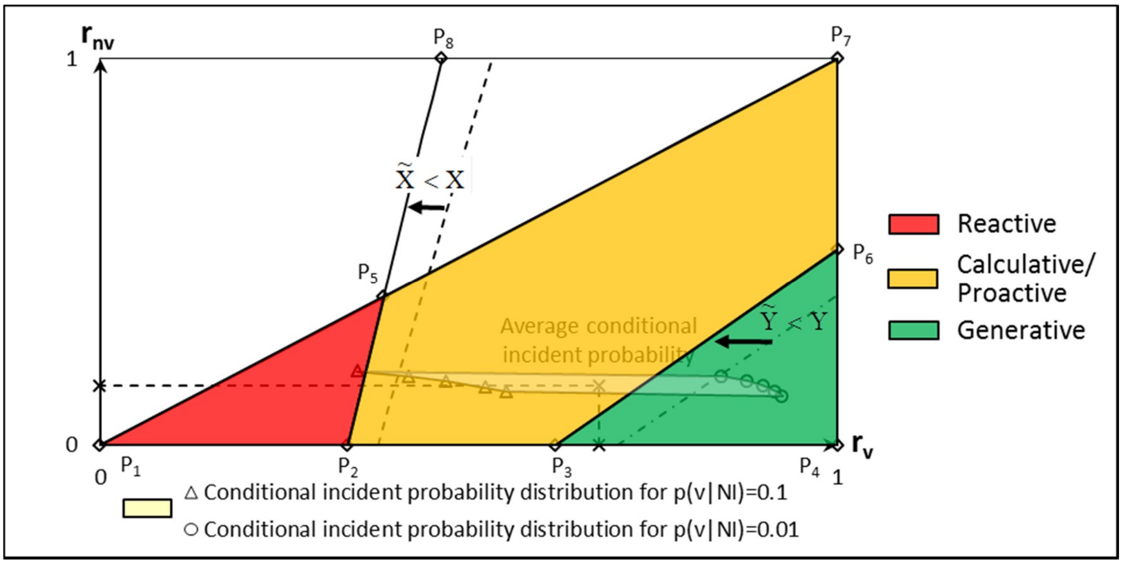


Figure 4.11: PORT with industrial data and increased management commitment



In the original game, the archetypal refinery possesses a calculative/proactive safety culture (yellow area). Hence, it already has a risk management system in place that works well but offers room for improvement.

The PORT in Figure 4.10 shows that a strategy of *increased punishment* only alters the left border of the calculative/proactive safety culture's existence region. Consequently, the refinery moves further away from a reactive safety culture. However, no progress will be made towards a generative safety culture. It can thus be concluded that by adopting a strategy of increased punishment, there will never be a significant improvement in violation behaviour and safety performance.

Increased *management commitment* offers a very different picture, as shown in the PORT in Figure 4.11. The border of the generative safety culture's existence region is altered, and it moves further towards the refinery's current position within the PORT. Hence, the refinery finds itself on a road towards a generative safety culture, which is also reflected in the monetary payoffs of Table 4.18.

Thus, by simply comparing both PORTs, the developed game theoretic model allows a quantification of the benefits of different risk management strategies. In addition, it allows the optimum equilibrium point to be determined while maximising the refinery's expected payoff.

Although similar studies, such as (Behm et al., 2004), have tried to find the best balance between safety investment and return on investment, the model presented in this thesis offers a new quality of scientific systematisation. For the first time, an analytical mathematical language, i.e., game theory, was used to analyse the interaction between "safety actors" within a petrochemical environment. Furthermore, this thesis also developed an easily understandable graphical tool, the PORT, which was tested with "real-life" industrial data.

4.5 Concluding remarks

In the fourth chapter of this thesis, the road towards industrial application of the PORT was presented. Whilst the game model in the previous chapters had relied only on theoretical input parameters, it was now tested with "real-life" data from the petrochemical industry.

In a first step, new payoff parameters representing the costs and benefits within an archetypal petrochemical refinery were developed and expressed in monetary terms. This process required not only an extensive investigation of various cost studies and industrial databases but also the definition of the archetypal refinery's organisational and salary structures as well as its economic and safety performance. Furthermore, both direct and indirect cost components were included in the model.

In a second step, the incident and human reliability data required for the calculation of the model's incident probabilities were assembled. This step proved to be rather difficult because no quantitative data on violations was readily available within the petrochemical industry. However, with the help of several research reports and especially the extensive data on violations that have been compiled in the aeronautical industry, a sufficiently accurate probability distribution could be defined.

In a final step, the quantitative data of the archetypal refinery, i.e., payoff parameters and an incident probability distribution, were entered into the PORT, and the following results could be observed.

The quantitative data yield a calculative/proactive safety culture for the archetypal refinery, which confirms that most modern petrochemical operations have arrived at this safety cultural stage. Furthermore, both M and W receive a positive payoff amounting to several million dollars and several hundred thousand dollars per year, respectively, at the current stage. Thus, the PORT confirms that an investment in safety actually delivers profitable results.

The most innovative aspect of the PORT is that, for the first time in the petrochemical industry, the effectiveness of different risk management strategies could be evaluated in a quantitative way. As an example, the strategies of increased punishment and increased management commitment were compared. For this purpose, the monetary payoff parameters were simply altered according to the requirements defined in Chapter 3. The subsequent calculation that was based on these altered payoff parameters indicated that increased management commitment is more effective than increased punishment because it yields a significantly improved monetary output. M's payoff increased by several hundred thousand dollars per year.

In a nutshell, the PORT offers a new tool for the evaluation of risk management strategies in the petrochemical industry. Due to its solid game theoretic foundation, the PORT further substantiates the findings of (Behm et al., 2004) and offers precise decision support to the managers in charge. Furthermore, the use of the PORT allows for a balanced and targeted allocation of resources that are often limited in a petrochemical operation.

5 Conclusion

The research that was conducted in this thesis sheds new light on the current risk management practices in the petrochemical industry. Game theoretic methods have been applied to risk management practices to render the complex human interactions in a petrochemical operation more accessible. This innovative approach, which is motivated by the extensive game theoretic literature on the effects of crime and punishment and, more specifically, by the models of (Hipel et al., 1995) and (Pradiptyo, 2007), allowed a considerable enrichment of the existing framework on HSE risk management.

The game theoretic model developed in this thesis integrates the concepts of behavioural economics discussed by (Battmann & Klumb, 1993) and the evolutionary safety culture discussed by (Westrum, 1993) and (Hudson, 2007). The model structures the "black box" of behavioural economics in an analytical manner by attributing cost and benefit parameters to the strategic decisions of the interacting parties, i.e., workforce and management. In addition, these parameters reflect the current stage of the organisational safety culture. Based on this model, an easily understandable graphical management decision-making tool, the Petrochemical Organisation Risk Triangle (PORT), was developed.

The PORT, which is considered the essential contribution of this thesis to petrochemical risk management research together with its underlying game model Γ_2, offers a new type of scientific systematisation. Not only does it integrate human interactions into the decision-making process, but it also enables the user to apply a quantitative comparison of different HSE risk management strategies and their effectiveness. To demonstrate the model's relevance to petrochemical applications, data sets on safety performance as well as on human reliability were assembled in the course of this research and were entered into the PORT. The results demonstrate that the PORT is a valid tool for improving the HSE performance and profitability of a petrochemical operation.

The main findings of the research conducted can be summarised as follows:

- Whether a rule will be violated depends strongly upon the type of safety culture that is in place in an organisation. In this respect, the present research further substantiates the empirical findings of (Fogarty & Shaw, 2010). Even more importantly, it could be demonstrated that the effectiveness of risk management strategies also depends upon the existing safety culture. For example, in a less advanced reactive safety culture, punishment is more effective than in a more advanced calculative/proactive safety culture. The debate on the effectiveness of punishment as a risk management strategy was enriched by further evidence indicating that increased punishment cannot be considered the "first best solution" – a proposition that is also supported by the recent empirical findings of (Rauhut, 2009). The argument by (Reason, 1997) that punishment and reward need to be fairly balanced and that a "just" safety culture needs to be created is thus fully supported by the game theoretic model developed in this thesis.
- Another central conclusion of this thesis is that risk management practices must be adapted to the local requirements and resource constraints of a petrochemical operation. The PORT offers a unique tool that enables the user to evaluate different risk management strategies in quantitative terms and to achieve exactly this adaptation by altering the right payoff parameters. Management can thus lead the way towards an improved safety culture based on a sound analytical foundation.
- In addition to these findings, it has been demonstrated that contractors are key players in the safety performance of a petrochemical operation. Although similar statements have been postulated by authors such as (Hudson, 1992, pp. 43-44), (Hudson, 2001), (Mayhew, Quinlan, & Ferris, 1997) and (Rebitzer, 1995), this thesis offers the first mathematical explanation for why contractors are likely to show inferior safety performance compared to companies' own staff members. Furthermore, the pivotal influencing factors for contractor safety were highlighted, and possible ways of improving the incentive structure, e.g., long-term performance-oriented contracts, were described.
- Finally, the game theoretic model provides further proof that the phenomenon that authors such as (Gonzalez & Sawicka, 2003) have described as the "erosion of compliance" in fact exists. The PORT clearly demonstrates that although incident probabilities drop due to technological progress, violation rates increase. Therefore,

it is crucial that the management of a petrochemical operation counteracts this phenomenon by improving the existing safety culture and by “pulling the right strings”. The PORT is capable of offering precise recommendations on which “strings to pull”.

By introducing game theory to risk management in the petrochemical industry, this thesis has opened up various areas of subsequent research.

- The first area of subsequent research could include conducting *game theoretic experiments* in a petrochemical environment. It would be very compelling to investigate how management, the workforce and contractors would react when faced with the strategic situations described in the developed game model. Such an experiment could test whether learning effects and bounded rationality, as described by (Cooper & Kagel, 2008), (Levitt & Miles, 2007), (Rauhut, 2009) and (Rauhut & Junker, 2009), affect the propositions of this thesis. The PORT could thus be put to a practical “stress test”.
- By far the largest area of subsequent research could be the development of further *game theoretic models*. Although this thesis only represents the first introduction of game theory into petrochemical risk management and several model simplifications were accepted, the PORT offers an excellent starting point for further model development.

  A first possibility for further model development would be relaxing the assumption of perfect detection. In reality, one might very well think of situations where the violator, i.e., the workforce, tries to deceive the inspector, i.e. the management, and conceal his actions. Game models featuring *imperfect detection* have been provided by (Brams & Kilgour, 1992) and (Rinderle, 1996, p. 53). In the same way, one could also imagine that the violator tries to bribe the inspector, and a corruption stage, according to (Friehe, 2008), could be introduced.

  A second interesting class of games is characterised by *inspector leadership*. Authors such as (Andreozzi, 2004), (Avenhaus, Okada, & Zamir, 1991), (Brams & Kilgour, 1992), (Franckx, 2001a) and (Rinderle, 1996) argue that rule violations can be reduced only if the inspector credibly announces his inspection strategy before the start of the game. In a petrochemical operation, such a scenario could easily be imagined when management announces that it will perform a certain number of inspections per year.

A third class of games could feature *repeated interaction* and *long-run inspectors*. Such games, which are used by (Andreozzi, 2004), (Andreozzi, 2010), (Franckx, 2001b) and (Rothenstein & Zamir, 2002), demonstrate that if a game is played repeatedly, violation mechanisms may change. Because the interaction between management and the workforce takes place on a continuous basis, such models appear to be very appealing. Furthermore, this class of games allows a conversion of the currently used exogenous incident probabilities into endogenous incident probabilities. In a repeated game, endogenous incident probabilities can be generated via Bayesian learning according to the methods described by (Gibbons, 1992) or (Jordan, 1995).

Finally, there is a class of games that completely alters the inspection strategy by introducing a *whistle-blowing* stage. These games include an impartial third player capable of retrieving private information from the violator. Authors such as (Berentsen, Brügger, & Lörtscher, 2008) and (Hipel, Kilgour, & Yin, 1994) argue that by implementing such a whistle-blowing scheme, rule violations can be drastically reduced and pareto-superior results compared with the original inspection game can be achieved. There are even a number of highly sophisticated game models, such as (Heyes & Kapur, 2007) or (Ting, 2008), that also take the organisational culture into account. Adopting the idea of whistle blowing within the petrochemical industry does not seem far-fetched, especially because there are already successful applications in the aeronautical industry, as described by (Hopkins, 2000). However, it must be considered that this class of games requires considerable mathematical expertise and might therefore be too complex for immediate industrial application.

- The third area of subsequent research could include further economic studies and data analyses on the costs and benefits of safety. It is acknowledged by authors such as (Tompa, Dolinschi, & de Oliveira, 2006) that the accuracy of the current cost studies could be improved by applying further economic expertise. One possible way of achieving this improvement would be to perform a specific analysis of the costs and benefits of safety incurred by a dedicated petrochemical operation. As an alternative, the sophisticated statistical analyses presented in (Meel et al., 2007) could be applied to the available petrochemical incident databases. Both approaches could be complemented with the cost structure described in (Health and Safety Executive, 1993) and could further substantiate the PORT.

In summary, the author recommends conducting game theoretic experiments and economic field research in a set of dedicated petrochemical operations before further developing the underlying game model. This recommendation can be explained by the fact that even sophisticated game models might not dramatically change the propositions of this thesis. (Rauhut, 2009) has already shown that a basic inspection game similar to the one used in this thesis can yield very compelling experimental results. It can thus be stated that the research conducted in this thesis has considerably advanced the debate on risk management in the petrochemical industry and has filled several research gaps highlighted in (Health and Safety Executive, 2009). Not only does this thesis provide a better understanding of the human interactions in HSE risk management, but it also leads the way towards the industrial application of game theoretic methods.

Appendix

A.1 Mixed strategy Nash equilibrium of game Γ_1

To find the corresponding equilibrium conditions and the players' optimum strategies, the expected payoffs π_i need to be calculated.

The payoff functions for W (Player 1) and M (Player 2) are defined as follows:

$$\pi_1(\alpha,\beta) = \alpha\beta a_{11} + \alpha(1-\beta)a_{12} + (1-\alpha)\beta a_{21} + (1-\alpha)(1-\beta)a_{22}, \quad (A.1)$$

$$\pi_2(\alpha,\beta) = \alpha\beta b_{11} + \alpha(1-\beta)b_{12} + (1-\alpha)\beta b_{21} + (1-\alpha)(1-\beta)b_{22}. \quad (A.2)$$

Rearranging delivers:

$$\pi_1(\alpha,\beta) = A_1 + B_1\alpha + C_1\beta + D_1\alpha\beta, \quad (A.3)$$

$$\pi_2(\alpha,\beta) = A_2 + B_2\alpha + C_2\beta + D_2\alpha\beta. \quad (A.4)$$

With the corresponding identities from Table 3.2,

$a_{11} = B_V - C_P$ $\quad\quad$ $b_{11} = B_E - C_E - C_H$

$a_{12} = B_V + B_C$ $\quad\quad$ $b_{12} = -B_S$

$a_{21} = B_D$ $\quad\quad$ $b_{21} = B_G - C_E$

$a_{22} = B_C$ $\quad\quad$ $b_{22} = B_G$,

one finds that:

$A_1 = a_{22} = B_C$ $\quad\quad$ $A_2 = b_{22} = B_G$

$B_1 = a_{12} - a_{22} = B_V$ $\quad\quad$ $B_2 = b_{12} - b_{22} = -(B_G + B_S)$

$C_1 = a_{21} - a_{22} = B_D - B_C$ $\quad\quad$ $C_2 = b_{21} - b_{22} = -C_E$

$D_1 = a_{11} + a_{22} - a_{12} - a_{21} = -(B_D + C_P)$ $\quad\quad$ $D_2 = b_{11} + b_{22} - b_{12} - b_{21} = B_E - C_H + B_S$.

The players' optimum equilibrium strategies α^* and β^* can be determined as follows:

$$\frac{\partial \pi_1(\alpha,\beta^*)}{\partial \alpha} = 0, \tag{A.5}$$

$$\frac{\partial \pi_2(\alpha^*,\beta)}{\partial \beta} = 0 \tag{A.6}$$
.

Rearranging delivers:

$$\alpha^* = -\frac{C_2}{D_2} = \frac{b_{22} - b_{21}}{b_{11} + b_{22} - b_{12} - b_{21}}, \tag{A.7}$$

$$\beta^* = -\frac{B_1}{D_1} = \frac{a_{22} - a_{12}}{a_{11} + a_{22} - a_{12} - a_{21}}. \tag{A.8}$$

Substituting the elements of (A.7) and (A.8) with the corresponding payoff identities from Table 3.2 finally leads to the following equations:

$$\alpha^* = \frac{C_E}{B_E + B_S - C_H} \quad \text{with} \quad \alpha^* \in (0,1), \tag{A.9}$$

$$\beta^* = \frac{B_V}{C_P + B_D} \quad \text{with} \quad \beta^* \in (0,1). \tag{A.10}$$

Due to the requirements of a single mixed strategy Nash equilibrium, i.e., $\alpha^* \in (0,1)$ and $\beta^* \in (0,1)$, the following payoff parameter conditions can be deduced:

$C_E > 0$,

$B_V > 0$,

$B_E + B_S > C_E + C_H$,

$C_P + B_D > B_V$.

If both players employ their equilibrium strategies, the corresponding payoffs are defined by:

$$\pi_1^* = \pi_1(\alpha^*,\beta^*) = A_1 + B_1\alpha^* + C_1\beta^* + D_1\alpha^*\beta^*, \tag{A.11}$$

$$\pi_2^* = \pi_2(\alpha^*,\beta^*) = A_2 + B_2\alpha^* + C_2\beta^* + D_2\alpha^*\beta^*. \tag{A.12}$$

Inserting (A.7) and (A.8) into (A.11) and (A.12), provides the following intermediate equations:

$$\pi_1^* = \frac{A_1 D_1 - B_1 C_1}{D_1} = A_1 - B_1 \frac{C_1}{D_1}, \tag{A.13}$$

$$\pi_2^* = \frac{A_2 D_2 - B_2 C_2}{D_2} = A_2 - B_2 \frac{C_2}{D_2}. \tag{A.14}$$

Finally, inserting the payoff identities from Table 3.2 into (A.13) and (A.14) delivers:

$$\pi_1^* = B_C + B_V \frac{B_D - B_C}{B_D + C_P}, \tag{A.15}$$

$$\pi_2^* = B_G - C_E \frac{B_G + B_S}{B_E - C_H + B_S}. \tag{A.16}$$

Both players' Nash equilibrium strategies and payoffs have thus been calculated.

A.2 Assumptions and algebraic inequalities of game Γ_2

With parameter identities from Table 3.14 and inequalities presented at the beginning of Chapter 3.3.1, the following conditions apply:

$a_{21} > a_{11}$: $B_D - B_V + C_P > 0$

$a_{23} > a_{13}$: $B_D - B_V + C_P > 0$

$a_{12} > a_{22}$: $B_V > B_C$

$a_{14} > a_{24}$: $B_V > 0$

$a_{13} > a_{11}$: $C_{I1} > 0$

$a_{23} > a_{21}$: $C_{I1} > 0$

$a_{14} > a_{12}$: $B_C + C_{I1} > 0$

$a_{24} > a_{22}$: $C_{I1} > 0$

$a_{12} > a_{11}$: $C_P > 0$

$a_{14} > a_{13}$: $B_C + C_P > 0$

$a_{21} > a_{22}$: $B_D > B_C$

$a_{23} > a_{24}$: $B_D > B_C$

$b_{11} > b_{21}$: $B_E - C_H > 0$

$b_{13} > b_{23}$: $B_E - C_H - B_G > 0$

$b_{22} > b_{12}$: $B_S > 0$

$b_{24} > b_{14}$: $B_G + B_S > 0$

$b_{13} > b_{11}$: $C_{I2} > 0$

$b_{23} > b_{21}$. $B_G + C_{I2} > 0$

$b_{14} > b_{12}$: $C_{I2} > 0$

$b_{24} > b_{22}$: $B_G + C_{I2} > 0$

$b_{11} > b_{12}$: $B_E - C_E - C_H + B_S > 0$

$b_{13} > b_{14}$: $B_E - C_E - C_H + B_S > 0$

$b_{22} > b_{21}$: $C_E > 0$

$b_{24} > b_{23}$: $C_E > 0$.

Since several conditions occur repeatedly, a reduction to the model's essential assumptions delivers:

$B_D - B_V + C_P > 0$

$B_V > B_C > 0$

$B_D > B_C$

$B_C + C_{I1} > 0$

$C_{I1} > 0$

$B_C + C_P > 0$

$C_P > 0$

$B_E - C_E - C_H + B_S > 0$

$B_E - C_H - B_G > 0$

$B_G + B_S > 0$

$B_S > 0$

$C_E > 0$

$B_G + C_{I2} > 0$

$C_{I2} > 0$.

A.3 Payoff parameters and equilibrium solution of game Γ_2

The players' optimum strategies and the corresponding Nash equilibria for game Γ_2 can be determined by analysing the expected payoffs π_i. The payoff functions for W (Player 1) and M (Player 2) are given by:

$$\begin{aligned}\pi_1(\alpha,\beta,\gamma) = {} & \alpha\beta r_v a_{11} + \alpha(1-\beta) r_v a_{12} + \alpha\gamma(1-r_v) a_{13} + \alpha(1-\gamma)(1-r_v) a_{14} + \\ & (1-\alpha)\beta r_{nv} a_{21} + (1-\alpha)(1-\beta) r_{nv} a_{22} + (1-\alpha)\gamma(1-r_{nv}) a_{23} + \\ & (1-\alpha)(1-\gamma)(1-r_{nv}) a_{24} \end{aligned}, \tag{A.17}$$

$$\begin{aligned}\pi_2(\alpha,\beta,\gamma) = {} & \alpha\beta r_v b_{11} + \alpha(1-\beta) r_v b_{12} + \alpha\gamma(1-r_v) b_{13} + \alpha(1-\gamma)(1-r_v) b_{14} + \\ & (1-\alpha)\beta r_{nv} b_{21} + (1-\alpha)(1-\beta) r_{nv} b_{22} + (1-\alpha)\gamma(1-r_{nv}) b_{23} + \\ & (1-\alpha)(1-\gamma)(1-r_{nv}) b_{24} \end{aligned}. \tag{A.18}$$

These equations can be rearranged:

$$\pi_1(\alpha,\beta,\gamma) = A_1 + B_1\alpha + C_1\beta + D_1\gamma - E_1\alpha\beta + F_1\alpha\gamma, \tag{A.19}$$

$$\pi_2(\alpha,\beta,\gamma) = A_2 + B_2\alpha - C_2\beta - D_2\gamma + E_2\alpha\beta + F_2\alpha\gamma. \tag{A.20}$$

The corresponding parameter identities are defined by:

$$A_1 = a_{24} + r_{nv}(a_{22} - a_{24}) = B_C - r_{nv} C_{I1}, \tag{A.21}$$

$$B_1 = a_{14} - a_{24} + r_v(a_{12} - a_{14}) + r_{nv}(a_{24} - a_{22}) = B_V - r_v(B_C + C_{I1}) + r_{nv} C_{I1}, \tag{A.22}$$

$$C_1 = r_{nv}(a_{21} - a_{22}) = r_{nv}(B_D - B_C), \tag{A.23}$$

$$D_1 = (1-r_{nv})(a_{23} - a_{24}) = (1-r_{nv})(B_D - B_C), \tag{A.24}$$

$$E_1 = -\left(r_v(a_{11} - a_{12}) + r_{nv}(a_{22} - a_{21})\right) = r_v C_P + r_{nv}(B_D - B_C), \tag{A.25}$$

$$\begin{aligned} F_1 &= a_{13} + a_{24} - a_{14} - a_{23} + r_v(a_{14} - a_{13}) + r_{nv}(a_{23} - a_{24}) \\ &= r_v(B_C + C_P) + r_{nv}(B_D - B_C) - (B_D + C_P) \end{aligned}, \tag{A.26}$$

$$A_2 = b_{24} + r_{nv}(b_{22} - b_{24}) = B_G - r_{nv}(B_G + C_{I2}), \tag{A.27}$$

$$B_2 = b_{14} - b_{24} + r_v(b_{12} - b_{14}) + r_{nv}(b_{24} - b_{22}) = r_{nv}(B_G + C_{I2}) - r_v C_{I2} - (B_G + B_S) \tag{A.28}$$

$$C_2 = -\left(r_{nv}(b_{21} - b_{22})\right) = r_{nv} C_E, \tag{A.29}$$

$$D_2 = -\left((1-r_{nv})(b_{23} - b_{24})\right) = (1-r_{nv}) C_E, \tag{A.30}$$

$$E_2 = r_v(b_{11} - b_{12}) + r_{nv}(b_{22} - b_{21}) = r_v(B_E - C_E - C_H + B_S) + r_{nv}C_E, \tag{A.31}$$

$$\begin{aligned} F_2 &= b_{13} + b_{24} - b_{14} - b_{23} + r_v(b_{14} - b_{13}) + r_{nv}(b_{23} - b_{24}) \\ &= B_E - C_H + B_S - r_v(B_E - C_E - C_H + B_S) - r_{nv}C_E . \end{aligned} \tag{A.32}$$

In order to further facilitate equilibrium calculation and analysis let

$$\pi_2(\alpha,\beta,\gamma) = L_2 + M_2\beta + N_2\gamma, \tag{A.33}$$

with

$$\begin{aligned} L_2 &= A_2 + B_2\alpha \\ &= B_G - r_{nv}(B_G + C_{I2}) + \left(r_{nv}(B_G + C_{I2}) - r_v C_{I2} - (B_G + B_S)\right)\alpha, \end{aligned} \tag{A.34}$$

$$\begin{aligned} M_2 &= -C_2 + E_2\alpha \\ &= -r_{nv}C_E + \left(r_v(B_E - C_E - C_H + B_S) + r_{nv}C_E\right)\alpha, \end{aligned} \tag{A.35}$$

$$\begin{aligned} N_2 &= -D_2 + F_2\alpha \\ &= -(1 - r_{nv})C_E + \left(B_E - C_H + B_S - r_v(B_E - C_E - C_H + B_S) - r_{nv}C_E\right)\alpha . \end{aligned} \tag{A.36}$$

In addition, the following equilibrium parameters are introduced:

$$Q_2 = \frac{r_{nv}C_E}{r_{nv}C_E + r_v(B_E - C_E - C_H + B_S)}, \tag{A.37}$$

$$R_2 = \frac{(1 - r_{nv})C_E}{(1 - r_{nv})C_E + (1 - r_v)(B_E - C_E - C_H + B_S)} . \tag{A.38}$$

With the additional assumptions from (3.23), (3.24), (3.25) and $B_E - C_E - C_H + B_S > 0$ and $C_E > 0$ from Table 3.15, it becomes obvious that $0 \le Q_2 < 1$ and $0 \le R_2 < 1$.

Because $r_{nv} < r_v$, it follows that $Q_2 < R_2$ and one finally obtains:

$$0 \le Q_2 < R_2 < 1 . \tag{A.39}$$

By analysing equations (A.37) and (A.38), it follows that:

$$M_2 > 0 \Leftrightarrow Q_2 < \alpha,$$

$$M_2 = 0 \Leftrightarrow Q_2 = \alpha,$$

$$M_2 < 0 \Leftrightarrow Q_2 > \alpha,$$

$$N_2 > 0 \Leftrightarrow R_2 < \alpha,$$

$N_2 = 0 \Leftrightarrow R_2 = \alpha$,

$N_2 < 0 \Leftrightarrow R_2 > \alpha$.

Hence, there are nine possible combinations of the signs of M_2 and N_2 but due to the condition (A.39), only five cases can actually occur:

Case I: $M_2 > 0, N_2 > 0 \Leftrightarrow R_2 < \alpha$

Case II: $M_2 > 0, N_2 = 0 \Leftrightarrow R_2 = \alpha$

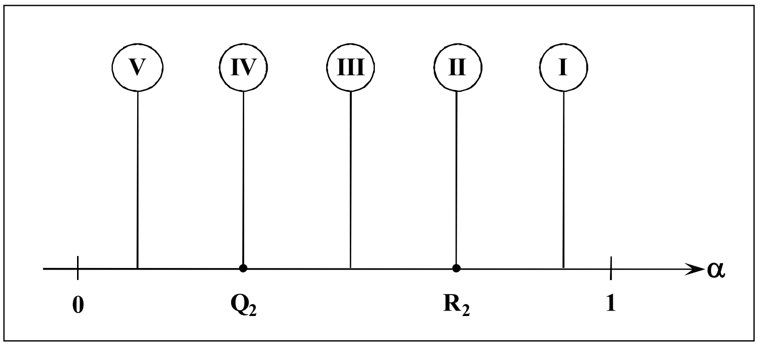
Case III: $M_2 > 0, N_2 < 0 \Leftrightarrow Q_2 < \alpha < R_2$

Case IV: $M_2 = 0, N_2 < 0 \Leftrightarrow Q_2 = \alpha$

Case V: $M_2 < 0, N_2 < 0 \Leftrightarrow Q_2 > \alpha$

These five cases will be the starting point for further equilibrium analysis and are represented graphically in Figure A.1.

Figure A.1: Equilibrium cases of game Γ_2 in function of Q_2, R_2 and α



Adapted from (Hipel et al., 1995, p. 241)

In a Nash equilibrium, both players maximize their expected payoff considering their opponent's "best move". Hence, an equilibrium calculation must be conducted for cases I to V by maximising π_1 and π_2. While equation (A.33) and the values of M_2 and N_2 reveal the maximum of π_2, locating the maximum of π_1 requires a more detailed analysis:

Case I: $M_2 > 0, N_2 > 0 \Leftrightarrow R_2 < \alpha$

Equation (A.39) shows that M chooses $\beta^* = 1$ and $\gamma^* = 1$ which results in:

$$\left.\frac{\partial \pi_1}{\partial \alpha}\right|_{\beta=1,\gamma=1} = B_1 - E_1 + F_1 \quad \text{(A.40)}$$

.

Because W's violation behaviour α^* is determined by the value of $\frac{\partial \pi_1}{\partial \alpha}$, which can be $\gtreqless 0$, three cases need to be distinguished:

(1) If $B_1 - E_1 + F_1 > 0$, then $\frac{\partial \pi_1}{\partial \alpha} > 0$ and consequently $\alpha^* = 1$. This forces $R_2 < 1$, which would be consistent with (A.39). But there is no equilibrium in this case, since $B_1 - E_1 + F_1 > 0$ requires:

$$r_v - r_{nv} < \frac{B_V - B_D - C_P}{C_{I1}}, \tag{A.41}$$

which is impossible considering assumptions (3.25) and $a_{23} > a_{13}$, i.e., $B_D - B_V + C_P > 0$.

(2) If $B_1 - E_1 + F_1 = 0$, then $\frac{\partial \pi_1}{\partial \alpha} = 0$ and consequently $\alpha^* \in [0,1]$. Although this would be consistent with (A.39), it is inconsistent with (3.25) since it would require $r_v < r_{nv}$. It follows that there is no equilibrium in this case.

(3) If $B_1 - E_1 + F_1 < 0$, then $\frac{\partial \pi_1}{\partial \alpha} < 0$ and consequently $\alpha^* = 0$. This forces $R_2 < 0$ which is inconsistent with (A.39) and, clearly, there can be no equilibrium.

Case II: $M_2 > 0, N_2 = 0 \Leftrightarrow R_2 = \alpha$

It follows that $\beta^* = 1$ and $\gamma^* \in [0,1]$ leading to:

$$\left.\frac{\partial \pi_1}{\partial \alpha}\right|_{\beta=1} = B_1 - E_1 + F_1\gamma \tag{A.42}$$

.

(1) If $B_1 - E_1 + F_1\gamma > 0$, then $\frac{\partial \pi_1}{\partial \alpha} > 0$ and consequently $\alpha^* = 1$. This forces $R_2 = 1$ which is inconsistent with (A.39), i.e. $R_2 < 1$. Hence, there can be no equilibrium in this case.

(2) If $B_1 - E_1 + F_1\gamma = 0$, then $\frac{\partial \pi_1}{\partial \alpha} = 0$ and consequently $\alpha^* \in [0,1]$. This results in $R_2 = \alpha^*$ and the corresponding equilibrium:

$$(\alpha^*, \beta^*, \gamma^*) = (R_2, 1, \frac{E_1 - B_1}{F_1}) \tag{A.43}$$

This equilibrium exits among conditions $0 \le \frac{E_1 - B_1}{F_1} \le 1$ and $F_1 \neq 0$, or expressed in terms of r_V:

$$0 < r_v \le \frac{B_V - r_{nv}(B_D - B_C - C_{II})}{B_C + C_P + C_{II}} \tag{A.44}$$

(3) If $B_1 - E_1 + F_1\gamma < 0$, then $\frac{\partial \pi_1}{\partial \alpha} < 0$ and consequently $\alpha^* = 0$. This forces $R_2 < 0$, which is inconsistent with (A.39) and allows no equilibrium.

Case III: $M_2 > 0, N_2 < 0 \Leftrightarrow Q_2 < \alpha < R_2$

It follows that $\beta^* = 1$ and $\gamma^* = 0$ leading to:

$$\left.\frac{\partial \pi_1}{\partial \alpha}\right|_{\beta=1,\gamma=0} = B_1 - E_1 \tag{A.45}$$

(1) If $B_1 - E_1 > 0$, then $\frac{\partial \pi_1}{\partial \alpha} > 0$ and consequently $\alpha^* = 1$. This leads to $R_2 > 1$, which is inconsistent with (A.39), i.e. $R_2 < 1$ and there is no equilibrium in this case.

(2) If $B_1 - E_1 = 0$, then $\frac{\partial \pi_1}{\partial \alpha} = 0$ and consequently $\alpha^* \in [0,1]$. This results in the equilibrium:

$$(\alpha^*, 1, 0) \quad \text{with} \quad \alpha^* \in (Q_2, R_2). \tag{A.46}$$

The corresponding existence condition $B_1 = E_1$ can also be expressed in terms of r_v

$$r_v = \frac{B_V - r_{nv}(B_D - B_C - C_{II})}{B_C + C_P + C_{II}} \tag{A.47}$$

(3) If $B_1 - E_1 < 0$, then $\frac{\partial \pi_1}{\partial \alpha} < 0$ and consequently $\alpha^* = 0$. This forces $Q_2 < 0$ which is inconsistent with (A.39). Hence, there can be no equilibrium in this case.

Case IV: $M_2 = 0, N_2 < 0 \Leftrightarrow Q_2 = \alpha$

It follows that $\beta^* \in [0,1]$ and $\gamma^* = 0$ leading to:

$$\left.\frac{\partial \pi_1}{\partial \alpha}\right|_{\gamma=0} = B_1 - E_1\beta \qquad \text{(A.48)}$$

(1) If $B_1 - E_1\beta > 0$, then $\frac{\partial \pi_1}{\partial \alpha} > 0$ and consequently $\alpha^* = 1$. This leads to $Q_2 = 1$, which is inconsistent with (A.39). It follows that there can be no equilibrium in this case.

(2) If $B_1 - E_1\beta = 0$, then $\frac{\partial \pi_1}{\partial \alpha} = 0$ and consequently $\alpha^* \in [0,1]$. This results in $Q_2 = \alpha^*$ and the equilibrium:

$$(\alpha^*, \beta^*, \gamma^*) = (Q_2, \frac{B_1}{E_1}, 0) \qquad \text{(A.49)}$$

Together with the existence condition $0 \leq \frac{B_1}{E_1} \leq 1$ it follows that:

$$\frac{B_V - r_{nv}(B_D - B_C - C_{II})}{B_C + C_P + C_{II}} \leq r_v \leq \frac{B_V + r_{nv}C_{II}}{B_C + C_{II}} \qquad \text{(A.50)}$$

(3) If $B_1 - E_1\beta < 0$, then $\frac{\partial \pi_1}{\partial \alpha} < 0$ and consequently $\alpha^* = 0$. This forces $Q_2 = 0$ and leads to the following equilibrium:

$$(0, \beta^*, 0) \quad \text{with} \quad \beta^* \in (\frac{B_1}{E_1}, 1] \qquad \text{(A.51)}$$

In the light of $Q_2 = 0$, such an equilibrium is only possible if:

$$r_{nv} = 0 \qquad \text{(A.52)}$$

Case V: $M_2 < 0, N_2 < 0 \Leftrightarrow Q_2 > \alpha$

It follows that $\beta^* = 0$ and $\gamma^* = 0$ leading to:

$$\left.\frac{\partial \pi_1}{\partial \alpha}\right|_{\beta=0,\gamma=0} = B_1 \qquad \text{(A.53)}$$

(1) If $B_1 > 0$, then $\frac{\partial \pi_1}{\partial \alpha} > 0$ and consequently $\alpha^* = 1$. This leads to $Q_2 > 1$, which is inconsistent with (A.39). Hence, there is no equilibrium in this case.

(2) If $B_1 = 0$, then $\frac{\partial \pi_1}{\partial \alpha} = 0$ and consequently $\alpha^* \in [0,1]$. This leads to the following equilibrium:

$$(\alpha^*,0,0) \quad \text{with} \quad \alpha^* \in [0,Q_2) . \tag{A.54}$$

It follows that:

$$r_v = \frac{B_V + r_{nv} C_{I1}}{B_C + C_{I1}} . \tag{A.55}$$

(3) If $B_1 < 0$, then $\frac{\partial \pi_1}{\partial \alpha} < 0$ and consequently $\alpha^* = 0$. This forces $Q_2 = 0$ and leads to the following equilibrium:

$$(\alpha^*,\beta^*,\gamma^*) = (0,0,0) . \tag{A.56}$$

The corresponding existence conditions expressed in terms of r_v equals:

$$\frac{B_V + r_{nv} C_{I1}}{B_C + C_{I1}} < r_v < 1 . \tag{A.57}$$

In summary, there are six Nash equilibria with different existence conditions:

NE1: $(\alpha^*,\beta^*,\gamma^*) = (R_2, 1, \frac{E_1 - B_1}{F_1})$ when $0 < r_v \le \frac{B_V - r_{nv}(B_D - B_C - C_{I1})}{B_C + C_P + C_{I1}}$

NE2: $(\alpha^*,1,0)$ for $\alpha^* \in (Q_2, R_2)$ when $r_v = \frac{B_V - r_{nv}(B_D - B_C - C_{I1})}{B_C + C_P + C_{I1}}$

NE3: $(\alpha^*,\beta^*,\gamma^*) = (Q_2, \frac{B_1}{E_1}, 0)$ when $\frac{B_V - r_{nv}(B_D - B_C - C_{I1})}{B_C + C_P + C_{I1}} \le r_v \le \frac{B_V + r_{nv} C_{I1}}{B_C + C_{I1}}$

NE4: $(0,\beta^*,0)$ for $\beta^* \in (\frac{B_1}{E_1}, 1]$ when $r_{nv} = 0$

NE5: $(\alpha^*,0,0)$ for $\alpha^* \in [0, Q_2)$ when $r_v = \frac{B_V + r_{nv} C_{I1}}{B_C + C_{I1}}$

NE6: $(\alpha^*,\beta^*,\gamma^*) = (0,0,0)$ when $\frac{B_V + r_{nv} C_{I1}}{B_C + C_{I1}} < r_v < 1$

The only non-transitional Nash equilibria are NE1, NE3 and NE6.

A.4 Increased punishment in game Γ_2

In this chapter, the effects of an increased severity of punishment will be discussed for all three equilibrium cases of game Γ_2. Increasing the severity of punishment affects the payoffs parameters such that $\hat{C}_P > C_P$, $\hat{C}_H > C_H$ and $\hat{B}_E > B_E$. All further calculations will be based on the game model's assumptions already presented in Appendix A.2 and A.3.

1. Reactive Equilibrium: $(\hat{\alpha}^*, \hat{\beta}^*, \hat{\gamma}^*) = (\hat{R}_2, 1, \frac{\hat{E}_1 - B_1}{\hat{F}_1})$

   a) $\alpha^* \uparrow = \downarrow$, because $R_2 \uparrow = \downarrow$

   With $\hat{R}_2 = \frac{(1-r_{nv})C_E}{(1-r_{nv})C_E + (1-r_v)(\hat{B}_E - C_E - \hat{C}_H + B_S)}$,

   it can be demonstrated that:

   $\hat{\alpha}^* < \alpha^*$ if $\hat{R}_2 < R_2$, i.e. $(\hat{B}_E - \hat{C}_H) > (B_E - C_H)$,

   $\hat{\alpha}^* \geq \alpha^*$ if $\hat{R}_2 \geq R_2$, i.e. $(\hat{B}_E - \hat{C}_H) \leq (B_E - C_H)$.

   Given the level of enforcement and safety commitment remain unchanged, the same dependencies already known from game Γ_1 apply. Hence, as long as the net benefit of the increased punishment $\hat{B}_E - \hat{C}_H$ is greater than its original value, W's violation probability decreases. Otherwise, it remains unchanged or decreases.

   b) $\beta^* =$, since $\beta^* = 1$

   With $\hat{\beta}^* = \beta^*$, it obvious that M's enforcement probability remains unchanged and safety procedures are thus always enforced in case of an incident.

   c) $\gamma^* \downarrow$, because $\frac{E_1 - B_1}{F_1} \downarrow$

$$\frac{\hat{E}_1 - B_1}{\hat{F}_1} = \frac{r_v(B_C + C_{II} + \hat{C}_P) + r_{nv}(B_D - B_C - C_{II}) - B_V}{r_v(B_C + \hat{C}_P) + r_{nv}(B_D - B_C) - (B_D + \hat{C}_P)}.$$

By comparing this expression with its initial value and by substituting $\hat{C}_P = C_P + \Delta C_P$, where $\Delta C_P \in R^+$, it can be demonstrated that $\hat{\gamma}^* < \gamma^*$.

Proof:

$$\frac{\hat{E}_1 - B_1}{\hat{F}_1} < \frac{E_1 - B_1}{F_1}, \quad \text{because} \quad -(r_v a + (1-r_v) b \Delta C_P) < 0,$$

$$\text{with} \quad \begin{aligned} a &= (1-r_{nv})(B_D - B_C) + (1+r_v)C_{II} \\ b &= B_V - r_{nv}(B_D - B_C - C_{II}) \end{aligned}.$$

The expression $r_v a + (1-r_v)b$ cannot become negative since

$$r_v a + (1-r_v)b =$$
$$(r_v - r_{nv})(B_D - B_C) + (r_v^2 + r_v r_{nv} + r_v - r_{nv})C_{II} + (1-r_v)B_V > 0,$$

where $B_D > B_C$, $B_V > 0$, $C_{II} > 0$ as well as $r_v > r_{nv}$.

This implies that, in a reactive environment, a more severe punishment reduces M's enforcement probability in case of no incident with certainty.

2. Calculative/Proactive Equilibrium: $(\hat{\alpha}^*, \hat{\beta}^*, \hat{\gamma}^*) = (\hat{Q}_2, \frac{B_1}{\hat{E}_1}, 0)$

   a) $\alpha^* \uparrow = \downarrow$, because $Q_2 \uparrow = \downarrow$

   With $\hat{Q}_2 = \dfrac{r_{nv} C_E}{r_{nv} C_E + r_v(\hat{B}_E - C_E - \hat{C}_H + B_S)}$,

   it follows that:

   $\hat{\alpha}^* < \alpha^*$ if $\hat{Q}_2 < Q_2$, i.e. $(\hat{B}_E - \hat{C}_H) > (B_E - C_H)$,

   $\hat{\alpha}^* \geq \alpha^*$ if $\hat{Q}_2 \geq Q_2$, i.e. $(\hat{B}_E - \hat{C}_H) \leq (B_E - C_H)$.

   Identical to the results of the reactive equilibrium, W's violation probability increases, decreases or remains unchanged depending on the effectiveness of the new punishment.

   b) $\beta^* \downarrow$, because $\dfrac{B_1}{E_1} \downarrow$

   With $\hat{E}_1 = r_v \hat{C}_P + r_{nv}(B_D - B_C)$,

   it can easily be demonstrated that:

$\hat{\beta}^* < \beta^*$, because $\frac{B_1}{\hat{E}_1} < \frac{B_1}{E_1}$.

As a consequence, increased punishment leads to a reduced enforcement probability in case of an incident.

c) γ^* =, because $\gamma^* = 0$

With $\hat{\gamma}^* = \gamma^*$, it follows that M's enforcement probability in case of no incident remains unchanged.

3. Generative Equilibrium: $(\hat{\alpha}^*, \hat{\beta}^*, \hat{\gamma}^*) = (0,0,0)$

In a generative environment, the changes in payoff parameters caused by an increased severity of punishment have no effect on the equilibrium values which results in $\hat{\alpha}^* = \alpha^*$, $\hat{\beta}^* = \beta^*$ and $\hat{\gamma}^* = \gamma^*$.

4. Equilibrium Thresholds:

Since the equilibrium thresholds generally apply to all equilibrium cases, only a single comparative statics analysis needs to be conducted.

a) $X \downarrow$

With $\hat{X} = \frac{B_V - r_{nv}(B_D - B_C - C_{I1})}{B_C + \hat{C}_P + C_{I1}}$, one obviously finds that $\hat{X} < X$.

The described change of the RET results in a decreased surface area of the reactive equilibrium's existence region since the RET line moves further to the left.

b) $Y =$

With $\hat{Y} = \frac{B_V + r_{nv} C_{I1}}{B_C + C_{I1}}$, one finds that $\hat{Y} = Y$.

The GET remains unaffected by an increase in the severity of punishment.

A.5 Increased management commitment in game Γ_2

The effects of an increased management commitment will be discussed for all three equilibrium cases of game Γ_2. The conditions $\widetilde{B}_C > B_C$, $\widetilde{B}_D > B_D$, $\widetilde{B}_E > B_E$, $\widetilde{B}_G > B_G$, $\widetilde{B}_S > B_S$ and $\widetilde{B}_V < B_V$ as well as the model's essential assumptions from Appendix A.2 and A.3 apply. However, one important simplification is introduced. It is argued that increased management commitment causes the benefits for having a clean safety record B_C and for having a documented clean safety record B_D to rise at least equally or slightly in favour of B_D which delivers $\widetilde{B}_D - \widetilde{B}_C \geq B_D - B_C$.

1. Reactive Equilibrium: $(\widetilde{\alpha}^*, \widetilde{\beta}^*, \widetilde{\gamma}^*) = (\widetilde{R}_2, 1, \frac{\widetilde{E}_1 - \widetilde{B}_1}{\widetilde{F}_1})$

   a) $\alpha^* \downarrow$, because $R_2 \downarrow$

   With $$\widetilde{R}_2 = \frac{(1-r_{nv})C_E}{(1-r_{nv})C_E + (1-r_v)(\widetilde{B}_E - C_E - C_H + \widetilde{B}_S)},$$

   it follows that:

   $\widetilde{\alpha}^* < \alpha^*$, because $\widetilde{R}_2 < R_2$, due to $\widetilde{B}_E + \widetilde{B}_S > B_E + B_S$.

   The new level of management commitment causes W's violation probability to decrease.

   b) $\beta^* =$, since $\beta^* = 1$

   M's enforcement probability remains unchanged, i.e. $\widetilde{\beta}^* = \beta^*$ and M always enforces in case of an incident.

   c) $\gamma^* \uparrow=\downarrow$, because $\left(\frac{E_1 - B_1}{F_1}\right) \uparrow=\downarrow$

   $$\frac{\widetilde{E}_1 - \widetilde{B}_1}{\widetilde{F}_1} = \frac{r_v(\widetilde{B}_C + C_{I1} + C_P) + r_{nv}(\widetilde{B}_D - \widetilde{B}_C - C_{I1}) - \widetilde{B}_V}{r_v(\widetilde{B}_C + C_P) + r_{nv}(\widetilde{B}_D - \widetilde{B}_C) - (\widetilde{B}_D + C_P)}.$$

   By substituting $\widetilde{B}_C = B_C + \Delta B_C$, $\widetilde{B}_D = B_D + \Delta B_D$ and $\widetilde{B}_V = B_V - \Delta B_V$, while ΔB_C, ΔB_D, $\Delta B_V \in R^+$, the above expression can be compared to its original value. This comparison delivers the following equations:

$\tilde{\gamma}^* < \gamma^*$ if $\frac{\tilde{E}_1 - \tilde{B}_1}{\tilde{F}_1} < \frac{E_1 - B_1}{F_1}$, i.e. $-\left(\frac{a}{c}\Delta B_C + \frac{b}{c}\Delta B_D\right) < \Delta B_V$,

with

$$a = \left(r_v^2 - r_{nv}^2 + 2r_v r_{nv}\right)C_{I1} - r_v\left(B_D - B_V + C_P\right) + r_{nv}\left(C_P - B_V\right)$$
$$b = \left(r_{nv}^2 - r_v r_{nv}\right)C_{I1} + r_v\left(B_C + C_P + C_{I1}\right) - r_{nv}\left(C_P + C_{I1} - B_V\right) - B_V$$
$$c = r_v\left(B_C + C_P\right) + r_{nv}\left(B_D - B_C\right) - \left(B_D + C_P\right)$$

The described inequality holds since $c < 0$.

$\tilde{\gamma}^* \geq \gamma^*$ if $\frac{\tilde{E}_1 - \tilde{B}_1}{\tilde{F}_1} \geq \frac{E_1 - B_1}{F_1}$, i.e., $-\left(\frac{a}{c}\Delta B_C + \frac{b}{c}\Delta B_D\right) \geq \Delta B_V$.

Hence, whether M's enforcement probability decreases, increases or remains unchanged is not evident. Nevertheless, above equations allow concluding that M's enforcement probability is bound to decrease as long as the reduction in the benefits of violation dominates the weighted increase in the benefits of compliance.

2. Calculative/Proactive Equilibrium: $(\tilde{\alpha}^*, \tilde{\beta}^*, \tilde{\gamma}^*) = (\tilde{Q}_2, \frac{\tilde{B}_1}{\tilde{E}_1}, 0)$

a) $\alpha^* \downarrow$, because $Q_2 \downarrow$

With $\tilde{Q}_2 = \frac{r_{nv} C_E}{r_{nv} C_E + r_v(\tilde{B}_E - C_E - C_H + \tilde{B}_S)}$,

it follows that:

$\tilde{\alpha}^* < \alpha^*$, because $\tilde{Q}_2 < Q_2$, due to $\tilde{B}_E + \tilde{B}_S > B_E + B_S$.

Hence, W's violation probability decreases in case of increased management commitment.

b) $\beta^* \downarrow$, because $\frac{B_1}{E_1} \downarrow$

$$\frac{\tilde{B}_1}{\tilde{E}_1} = \frac{\tilde{B}_V - r_v(\tilde{B}_C + C_{I1}) + r_{nv} C_{I1}}{r_v C_P + r_{nv}(\tilde{B}_D - \tilde{B}_C)}.$$

By substituting $\tilde{B}_C = B_C + \Delta B_C$, $\tilde{B}_D = B_D + \Delta B_D$ and $\tilde{B}_V = B_V - \Delta B_V$, while ΔB_C, ΔB_D, $\Delta B_V \in R^+$ the above expression can be compared to its original value and it can be demonstrated that $\tilde{\beta}^* < \beta^*$.

Proof:

$\frac{\tilde{B}_1}{\tilde{E}_1} < \frac{B_1}{E_1}$, because $a\Delta B_C + b\Delta B_D + c\Delta B_V < 0$, with

$$\begin{aligned} a &= r_{nv}^2 C_{II} - r_v^2 C_P - r_v r_{nv}(B_D + C_{II}) + r_{nv} B_V \\ b &= r_v r_{nv}(B_C + C_{II}) - r_{nv}^2 C_{II} - r_{nv} B_V \\ c &= r_{nv}(B_C - B_D) - r_v C_P \end{aligned}.$$

Considering $\Delta B_D \geq \Delta B_C$, the inequality $a\Delta B_C + b\Delta B_D + c\Delta B_V < 0$ holds, since $a + b < 0$ due to $-r_v^2 C_P - r_v r_{nv}(B_D - B_C) < 0$ and $c < 0$ due to $B_C < B_D$.

Thus, M's enforcement probability decreases in case of an incident.

c) γ^* =, because $\gamma^* = 0$

Thus, $\tilde{\gamma}^* = \gamma^*$ and M's enforcement probability remains unchanged.

3. Generative Equilibrium: $(\tilde{\alpha}^*, \tilde{\beta}^*, \tilde{\gamma}^*) = (0,0,0)$

In a generative environment, the changes in parameters caused by an increased management commitment towards safety have no effect on the equilibrium, i.e. $\tilde{\alpha}^* = \alpha^*$, $\tilde{\beta}^* = \beta^*$ and $\tilde{\gamma}^* = \gamma^*$.

4. Equilibrium Thresholds:

a) $X \downarrow$

With $\tilde{X} = \frac{\tilde{B}_V - r_{nv}(\tilde{B}_D - \tilde{B}_C - C_{II})}{\tilde{B}_C + C_P + C_{II}}$, one finds that $\tilde{X} < X$.

Proof:

$\frac{\tilde{B}_V - r_{nv}(\tilde{B}_D - \tilde{B}_C - C_{II})}{\tilde{B}_C + C_P + C_{II}} < \frac{B_V - r_{nv}(B_D - B_C - C_{II})}{B_C + C_P + C_{II}}$, because

$a\Delta B_C - b\Delta B_D - c\Delta B_V < 0$, with

$$
\begin{aligned}
a &= r_{nv}\left(B_D + C_P\right) - B_V \\
b &= r_{nv}\left(B_C + C_P + C_{I1}\right) \\
c &= B_C + C_P + C_{I1}
\end{aligned}
.
$$

Considering $\Delta B_D \geq \Delta B_C$, the inequality $a\Delta B_C - b\Delta B_D - c\Delta B_V < 0$ holds, because $a - b < 0$ due to $r_{nv}\left(B_D - B_C - C_{I1}\right) - B_V < 0$ and $c > 0$.

The described change in the RET results in a decreased surface area of the reactive equilibrium's existence region. Hence, supposing that the incident probability remains unchanged, a calculative organisation moves further away from a reactive stage.

b) $Y \downarrow$

With $\tilde{Y} = \dfrac{\tilde{B}_V + r_{nv} C_{I1}}{\tilde{B}_C + C_{I1}}$, one finds that $\tilde{Y} < Y$, because $\dfrac{\tilde{B}_V}{\tilde{B}_C} < \dfrac{B_V}{B_C}$.

The described change in the GET results in a decreased surface area of the calculative/proactive equilibrium's existence region. Hence, supposing that the incident probability remains constant, a calculative organisation moves towards a generative safety culture.

A.6 Contractor safety in game Γ_2

The effects of contractor safety will be discussed for all three equilibrium cases of game Γ_2. The conditions $\breve{B}_C < B_C$, $\breve{B}_D < B_D$, $\breve{B}_E < B_E$, $\breve{C}_H < C_H$ and $\breve{C}_P < C_P$ as well as the model's essential assumptions from Appendix A.2 and A.3 apply. However, in comparison to the original game Γ_1, an important simplification is introduced. Contractor safety causes the benefits for having a clean safety record B_C and for having a documented clean safety record B_D to decrease at least equally or slightly in favour of B_D, which results in $\breve{B}_D - \breve{B}_C \leq B_D - B_C$.

1. Reactive Equilibrium: $(\breve{\alpha}^*, \breve{\beta}^*, \breve{\gamma}^*) = (\breve{R}_2, 1, \frac{\breve{E}_1 - \breve{B}_1}{\breve{F}_1})$

   a) $\alpha^* \downarrow = \uparrow$, because $R_2 \downarrow = \uparrow$

   With $\breve{R}_2 = \dfrac{(1-r_{nv})C_E}{(1-r_{nv})C_E + (1-r_v)(\breve{B}_E - C_E - \breve{C}_H + B_S)}$,

   the following results can be imagined:

   $\breve{\alpha}^* < \alpha^*$ if $\breve{R}_2 < R_2$, i.e., $\breve{B}_E - \breve{C}_H > B_E - C_H$,

   $\breve{\alpha}^* \geq \alpha^*$ if $\breve{R}_2 \geq R_2$, i.e., $\breve{B}_E - \breve{C}_H \leq B_E - C_H$.

   Hence, whether the violation probability decreases, increases or remains unchanged is not evident.

   Nevertheless it can be concluded that, as long as the net benefits of the enforcement are smaller with C than they are with S, C will violate more often. This proposition is supported by the following consideration. Inserting $\breve{B}_E = B_E - \Delta B_E$ and $\breve{C}_H = C_H - \Delta C_H$, with $\Delta B_E, \Delta C_H \in R^+$, into above equation delivers $\Delta C_H - \Delta B_E \gtreqless 0$. Considering that M also needs a contractor management programme with significant handling costs, it is realistic to assume that ΔC_H will be small and $\Delta C_H < \Delta B_E$. As a consequence, $\Delta C_H - \Delta B_E < 0$, i.e., $\breve{\alpha}^* > \alpha^*$.

   It is thus very likely that contractors violate more often than staff members although it cannot be determined with certainty.

b) $\beta^* =$, since $\beta^* = 1$

M's enforcement probability remains unchanged, i.e. $\breve{\beta}^* = \beta^*$.

c) $\gamma^* \downarrow = \uparrow$, because $\left(\frac{E_1 - B_1}{F_1}\right) \downarrow = \uparrow$

$$\frac{\breve{E}_1 - \breve{B}_1}{\breve{F}_1} = \frac{r_v\left(\breve{B}_C + C_{II} + \breve{C}_P\right) + r_{nv}\left(\breve{B}_D - \breve{B}_C - C_{II}\right) - B_V}{r_v(\breve{B}_C + \breve{C}_P) + r_{nv}(\breve{B}_D - \breve{B}_C) - (\breve{B}_D + \breve{C}_P)}.$$

By substituting $\breve{B}_C = B_C - \Delta B_C$, $\breve{B}_D = B_D - \Delta B_D$ and $\breve{C}_P = C_P - \Delta C_P$, with ΔB_C, ΔB_D, $\Delta C_P \in R^+$, the above expression can be compared to its original value. This comparison delivers:

$\breve{\gamma}^* < \gamma^*$ if $\frac{\breve{E}_1 - \breve{B}_1}{\breve{F}_1} < \frac{E_1 - B_1}{F_1}$, i.e., $-\left(\frac{a}{c}\Delta B_C + \frac{b}{c}\Delta B_D\right) > \Delta C_P$ with,

$$\begin{aligned} a &= \left(r_v^2 - 2r_v r_{nv} + r_{nv}^2\right)C_{II} + \left(r_v - r_{nv}\right)\left(B_D + C_P - B_V\right) \\ b &= \left(r_v r_{nv} - r_{nv}^2\right)C_{II} + \left(r_{nv} - r_v\right)\left(B_C + C_P + C_{II}\right) + \left(1 - r_{nv}\right)B_V \\ c &= \left(r_v^2 - r_v r_{nv}\right)C_{II} + \left(r_v - r_{nv}\right)\left(B_D - B_C - C_{II}\right) - r_v\left(B_V + C_P\right) + B_V, \end{aligned}$$

$\breve{\gamma}^* \geq \gamma^*$ if $\frac{\breve{E}_1 - \breve{B}_1}{\breve{F}_1} \geq \frac{E_1 - B_1}{F_1}$, i.e., $-\left(\frac{a}{c}\Delta B_C + \frac{b}{c}\Delta B_D\right) \leq \Delta C_P$.

Examining these equations in more detail reveals that even if M were able to reach the same level of compliance benefits with C than with W, i.e., $\Delta B_C = \Delta B_D = 0$, it would still need to enforce more often. This result is due to the fact that, per definition, $\Delta C_P > 0$. Consequently, only $\breve{\gamma}^* > \gamma^*$ remains as the possible equilibrium strategy.

2. Calculative/Proactive Equilibrium: $(\breve{\alpha}^*, \breve{\beta}^*, \breve{\gamma}^*) = (\breve{Q}_2, \frac{\breve{B}_1}{\breve{E}_1}, 0)$

a) $\alpha^* \downarrow = \uparrow$, because $Q_2 \downarrow = \uparrow$

With $\breve{Q}_2 = \frac{r_{nv} C_E}{r_{nv} C_E + r_v(\breve{B}_E - C_E - \breve{C}_H + B_S)}$,

the following results can be imagined:

$\breve{\alpha}^* < \alpha^*$ if $\breve{Q}_2 < Q_2$, i.e., $\breve{B}_E - \breve{C}_H > B_E - C_H$,

$\breve{\alpha}^* \geq \alpha^*$ if $\breve{Q}_2 \geq Q_2$, i.e., $\breve{B}_E - \breve{C}_H \leq B_E - C_H$.

Hence, as long as the net benefits of the enforcement are smaller with C than they are with S, C will violate more often. This proposition is once again supported by the high likelihood of $\Delta C_H < \Delta B_E$ and consequently $\breve{\alpha}^* > \alpha^*$.

b) $\beta^* \uparrow$, because $\frac{B_1}{E_1} \uparrow$

With $\frac{\breve{B}_1}{\breve{E}_1} = \frac{B_V - r_v(\breve{B}_C + C_{II}) + r_{nv}C_{II}}{r_v\breve{C}_P + r_{nv}(\breve{B}_D - \breve{B}_C)}$,

it can easily be demonstrated that:

$\breve{\beta}^* > \beta^*$ because $\frac{\breve{B}_1}{\breve{E}_1} > \frac{B_1}{E_1}$.

Proof:

$$B_V - r_v(\breve{B}_C + C_{II}) + r_{nv}C_{II} > B_V - r_v(B_C + C_{II}) + r_{nv}C_{II},$$

because $\Delta B_C > 0$, which delivers $\breve{B}_1 > B_1$.

$$r_v\breve{C}_P + r_{nv}(\breve{B}_D - \breve{B}_C) < r_v C_P + r_{nv}(B_D - B_C),$$

because $-\left(r_v \Delta C_P + r_{nv}(\Delta B_D - \Delta B_C)\right) < 0$, which delivers $\breve{E}_1 < E_1$.

It can thus be concluded that M's enforcement probability in case of no incident increases.

c) $\gamma^* =$, because $\gamma^* = 0$

M's enforcement probability remains unchanged, i.e. $\breve{\gamma}^* = \gamma^*$.

3. Generative Equilibrium: $(\breve{\alpha}^*, \breve{\beta}^*, \breve{\gamma}^*) = (0,0,0)$

In a generative environment, there is no difference between contractor and staff member safety with $\breve{\alpha}^* = \alpha^*$, $\breve{\beta}^* = \beta^*$ and $\breve{\gamma}^* = \gamma^*$.

4. Equilibrium Thresholds:

a) $X \uparrow$

With $\breve{X} = \frac{B_V - r_{nv}(\breve{B}_D - \breve{B}_C - C_{II})}{\breve{B}_C + \breve{C}_P + C_{II}}$, one finds that $\breve{X} > X$.

Proof:

$$B_V - r_{nv}(\breve{B}_D - \breve{B}_C - C_{I1}) > B_V - r_{nv}(B_D - B_C - C_{I1})$$

since $(\Delta B_D - \Delta B_C) \geq 0$.

Furthermore, $\breve{B}_C + \breve{C}_P + C_{I1} < B_C + C_P + C_{I1}$ since $-(\Delta B_C + \Delta C_P) < 0$.

The described change in the RET results in an increased surface area of the reactive equilibrium's existence region. Hence, supposing that the incident probability remains constant, a calculative organisation moves further towards a reactive stage.

b) $Y \uparrow$

With $\breve{Y} = \dfrac{B_V + r_{nv} C_{I1}}{\breve{B}_C + C_{I1}}$, one finds that $\breve{Y} > Y$, because $\breve{B}_C < B_C$.

The described change in the GET results in an increased surface area of the calculative/proactive equilibrium's existence region. Hence, supposing that the incident probability remains constant, a calculative organisation moves further away from a generative safety culture.

A.7 Improved safety standard in game Γ_2

An improvement in safety standard is equivalent to a reduction of the game's risk level, which is determined by incident *probability*, i.e., r_v and r_{nv}, and *consequences*, i.e. C_{I1} and C_{I2}. In a first part, the effects of reduced incident probabilities as a consequence of technological progress will be investigated, i.e., $\hat{r}_{nv} < r_{nv}$ and $\hat{r}_v < r_v$. In a second part, the effects of reduced incident costs as a consequence of organisational effectiveness will be investigated with $\hat{C}_{I1} < C_{I1}$ and $\hat{C}_{I2} < C_{I2}$.

Technological progress:

1. Reactive Equilibrium: $(\hat{\alpha}^*, \hat{\beta}^*, \hat{\gamma}^*) = (\hat{R}_2, 1, \frac{\hat{E}_1 - \hat{B}_1}{\hat{F}_1})$

   a) $\alpha^* \downarrow = \uparrow$, because $R_2 \downarrow = \uparrow$

   $$\hat{R}_2 = \frac{(1-\hat{r}_{nv})C_E}{(1-\hat{r}_{nv})C_E + (1-\hat{r}_v)(B_E - C_E - C_H + B_S)}.$$

   Comparing the expression with its original value by substituting $\hat{r}_{nv} = r_{nv} - \Delta r_{nv}$ and $\hat{r}_v = r_v - \Delta r_v$ where $\Delta r_v, \Delta r_{nv} \in R^+$ yields the following results:

   $\hat{\alpha}^* < \alpha^*$ if $\hat{R}_2 < R_2$, i.e., $\Delta r_v > \left(\frac{1-r_v}{1-r_{nv}}\right)\Delta r_{nv}$,

   $\hat{\alpha}^* \geq \alpha^*$ if $\hat{R}_2 \geq R_2$, i.e., $\Delta r_v \leq \left(\frac{1-r_v}{1-r_{nv}}\right)\Delta r_{nv}$.

   In a reactive environment, the violation probability either increases, decreases or remains unchanged depending on the variation of both incident probabilities. However, if one assumes that both incident probabilities decrease by the same amount, i.e., $\Delta r_v = \Delta r_{nv}$, it follows that $\hat{\alpha}^* < \alpha^*$.

   b) $\beta^* =$, since $\beta^* = 1$

   M's enforcement probability remains unchanged, i.e. $\hat{\beta}^* = \beta^*$. Thus, M enforces every time an incident happens.

c) $\gamma^* \downarrow = \uparrow$, because $\left(\frac{E_1 - B_1}{F_1}\right) \downarrow = \uparrow$

$$\frac{\hat{E}_1 - \hat{B}_1}{\hat{F}_1} = \frac{\hat{r}_v(B_C + C_{II} + C_P) + \hat{r}_{nv}(B_D - B_C - C_{II}) - B_V}{\hat{r}_v(B_C + C_P) + \hat{r}_{nv}(B_D - B_C) - (B_D + C_P)}.$$

By substituting $\hat{r}_{nv} = r_{nv} - \Delta r_{nv}$ and $\hat{r}_v = r_v - \Delta r_v$, where $\Delta r_v, \Delta r_{nv} \in R^+$, the above expression can be compared with its original value. This comparison delivers:

$$\hat{\gamma}^* < \gamma^* \quad \text{if} \quad \frac{\hat{E}_1 - \hat{B}_1}{\hat{F}_1} < \frac{E_1 - B_1}{F_1}, \quad \text{i.e.,} \quad \Delta r_v < -\frac{\left(\frac{c}{a} + r_v\right)}{\left(\frac{b}{a} - r_{nv}\right)} \Delta r_{nv},$$

for $\frac{b}{a} - r_{nv} \neq 0$ with

$$a = C_{II}(B_D + C_P)$$
$$b = (B_C + C_{II} + C_P)(B_D + C_P) - B_V(B_C + C_P)$$
$$c = (B_D - B_C - C_{II})(B_D + C_P) - B_V(B_D - B_C),$$

$$\hat{\gamma}^* \geq \gamma^* \quad \text{if} \quad \frac{\hat{E}_1 - \hat{B}_1}{\hat{F}_1} \geq \frac{E_1 - B_1}{F_1}, \quad \text{i.e.,} \quad \Delta r_v \geq -\frac{\left(\frac{c}{a} + r_v\right)}{\left(\frac{b}{a} - r_{nv}\right)} \Delta r_{nv},$$

for $\frac{b}{a} - r_{nv} \neq 0$.

Thus, M's enforcement probability either increases, decreases or remains unchanged depending on the variation of both incident probabilities. Considering that both incident probabilities are likely decrease at the same amount, it can be concluded that $b + c + a(r_v - r_{nv}) > 0$ and consequently $\hat{\gamma}^* > \gamma^*$.

2. Calculative/Proactive Equilibrium: $(\hat{\alpha}^*, \hat{\beta}^*, \hat{\gamma}^*) = (\hat{Q}_2, \frac{\hat{B}_1}{\hat{E}_1}, 0)$

a) $\alpha^* \downarrow = \uparrow$, because $Q_2 \downarrow = \uparrow$

$$\hat{Q}_2 = \frac{\hat{r}_{nv} C_E}{\hat{r}_{nv} C_E + \hat{r}_v (B_E - C_E - C_H + B_S)}.$$

Comparing the expression with its original value by substituting $\hat{r}_{nv} = r_{nv} - \Delta r_{nv}$ and $\hat{r}_v = r_v - \Delta r_v$, where $\Delta r_v, \Delta r_{nv} \in R^+$, yields the following results:

$$\hat{\alpha}^* < \alpha^* \quad \text{if} \quad \hat{Q}_2 < Q_2, \quad \text{i.e.,} \quad \Delta r_v < \frac{r_v}{r_{nv}} \Delta r_{nv} \quad \text{for} \quad r_{nv} \neq 0,$$

$$\hat{\alpha}^* \geq \alpha^* \quad \text{if} \quad \hat{Q}_2 \geq Q_2, \quad \text{i.e.,} \quad \Delta r_v \geq \frac{r_v}{r_{nv}} \Delta r_{nv} \quad \text{for} \quad r_{nv} \neq 0.$$

In a calculative environment, the violation probability either increases, decreases or remains unchanged depending on the variation of both incident probabilities. Once again, by assuming that both incident probabilities decrease by the same amount, i.e. $\Delta r_v = \Delta r_{nv}$, it can be demonstrated that $\hat{\alpha}^* < \alpha^*$.

b) $\beta^* \downarrow = \uparrow$, because $\frac{B_1}{E_1} \downarrow = \uparrow$

$$\frac{\hat{B}_1}{\hat{E}_1} = \frac{B_V - \hat{r}_v (B_C + C_{I1}) + \hat{r}_{nv} C_{I1}}{\hat{r}_v C_P + \hat{r}_{nv} (B_D - B_C)}.$$

By substituting $\hat{r}_{nv} = r_{nv} - \Delta r_{nv}$ and $\hat{r}_v = r_v - \Delta r_v$, where $\Delta r_v, \Delta r_{nv} \in R^+$, the above expression can be compared with its original value. This comparison delivers:

$$\hat{\beta}^* < \hat{\beta} \quad \text{if} \quad \frac{\hat{B}_1}{\hat{E}_1} < \frac{B_1}{E_1}, \text{ i.e., } \Delta r_v < \frac{\left(r_v - \frac{c}{a}\right)}{\left(r_{nv} + \frac{b}{a}\right)} \Delta r_{nv} \quad \text{for} \quad r_{nv} + \frac{b}{a} \neq 0,$$

$$\text{with} \quad \begin{aligned} a &= C_{I1} C_P + (B_C + C_{I1})(B_D - B_C) \\ b &= B_V C_P \\ c &= B_V (B_D - B_C) \end{aligned},$$

$$\hat{\beta}^* \geq \hat{\beta} \quad \text{if} \quad \frac{\hat{B}_1}{\hat{E}_1} \geq \frac{B_1}{E_1}, \text{ i.e., } \Delta r_v \geq \frac{\left(r_v - \frac{c}{a}\right)}{\left(r_{nv} + \frac{b}{a}\right)} \Delta r_{nv} \quad \text{for} \quad r_{nv} + \frac{b}{a} \neq 0.$$

In a calculative environment, the enforcement probability either increases, decreases or remains unchanged depending on the variation of both incident probabilities. Once again, by assuming that both incident probabilities decrease by the same amount, i.e., $\Delta r_v = \Delta r_{nv}$, it can be concluded that $b + c - a(r_v - r_{nv}) > 0$, because $r_v - r_{nv} < 1$ and thus $\hat{\beta}^* > \beta^*$.

c) γ^* =, because $\gamma^* = 0$

M's enforcement probability remains unchanged, i.e. $\hat{\gamma}^* = \gamma^*$.

3. Generative Equilibrium: $(\hat{\alpha}^*, \hat{\beta}^*, \hat{\gamma}^*) = (0,0,0)$

In a generative environment, a change in incident probabilities has no effect on the equilibrium strategies, i.e., $\hat{\alpha}^* = \alpha^*$, $\hat{\beta}^* = \beta^*$ and $\hat{\gamma}^* = \gamma^*$.

4. Equilibrium Thresholds:

Since incident probabilities are set to be exogenous and constant during one round of play, a change of incident probabilities does not affect the equilibrium thresholds.

Organisational effectiveness:

1. Reactive Equilibrium: $(\hat{\alpha}^*, \hat{\beta}^*, \hat{\gamma}^*) = (R_2, 1, \frac{E_1 - \hat{B}_1}{F_1})$

a) α^* =, because $\hat{\alpha}^* = R_2$

Interestingly, a reduction in incident costs has no effect on W's violation behaviour, i.e., $\hat{\alpha}^* = \alpha^*$.

b) β^* =, since $\hat{\beta}^* = 1$

M's enforcement probability also remains unchanged, i.e., $\hat{\beta}^* = \beta^*$.

c) $\gamma^* \uparrow$, because $\left(\frac{E_1 - \hat{B}_1}{F_1}\right) \uparrow$

$\hat{\gamma}^* > \gamma^*$ because $E_1 - \hat{B}_1 > E_1 - B_1$, due to $(r_v - r_{nv})\hat{C}_{I1} < (r_v - r_{nv})C_{I1}$.

It can be concluded that a reduction in incident costs leads to an increased enforcement probability for M.

2. Calculative/Proactive Equilibrium: $(\hat{\alpha}^*, \hat{\beta}^*, \hat{\gamma}^*) = (Q_2, \frac{\hat{B}_1}{E_1}, 0)$

a) α^* =, because $\hat{\alpha}^* = Q_2$

Once again, a reduction in incident costs has no effect on W's violation behaviour, i.e., $\widehat{\alpha}^* = \alpha^*$.

b) $\beta^* \uparrow$, because $\frac{\widehat{B}_1}{E_1} \uparrow$

$\widehat{\beta}^* > \beta^*$ because $\widehat{B}_1 > B_1$, due to $(r_{nv} - r_v)\widehat{C}_{II} < (r_{nv} - r_v)C_{II}$.

In a calculative environment, a reduction in incident costs thus leads to an increased enforcement probability for M when there is an incident.

c) $\gamma^* =$, because $\gamma^* = 0$

M's enforcement probability remains unchanged with $\widehat{\gamma}^* = \gamma^*$.

3. Generative Equilibrium: $(\widehat{\alpha}^*, \widehat{\beta}^*, \widehat{\gamma}^*) = (0,0,0)$

A change in incident costs does obviously not affect the players' strategies, resulting in $\widehat{\alpha}^* = \alpha^*$, $\widehat{\beta}^* = \beta^*$ and $\widehat{\gamma}^* = \gamma^*$.

4. Equilibrium Thresholds:

a) $X \uparrow$

With $\widehat{X} = \frac{B_V - r_{nv}(B_D - B_C - \widehat{C}_{II})}{B_C + C_P + \widehat{C}_{II}}$, one finds that $\widehat{X} > X$, as long as

$a\Delta C_{II} > 0$, with $a = B_V - r_{nv}(B_D + C_P)$.

Although this condition cannot always be guaranteed (e.g., if r_{nv} becomes large), the described change in the RET will always result in an increased surface area of the reactive equilibrium's existence region. The reason being that the RET's x-axis intercept increases with certainty due to

$$\frac{B_V}{B_C + C_P + \widehat{C}_{II}} > \frac{B_V}{B_C + C_P + C_{II}}.$$

Hence, supposing that the incident probability remains constant, a calculative organisation moves further towards a reactive culture.

b) $Y \uparrow$

With $\widehat{Y} = \frac{B_V + r_{nv}\widehat{C}_{II}}{B_C + \widehat{C}_{II}}$, one finds that $\widehat{Y} > Y$,

because $a\Delta C_{II} > 0$ with $a = B_V - r_{nv}B_C$.

Due to $B_V > B_C$, the described change in the GET always results in an increased surface area of the calculative/proactive equilibrium's existence region. Thus, supposing that the incident probability remains constant, a calculative organisation moves further away from a generative safety culture.

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