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HUMAN FACTORS IN ENGINEERING RISK

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Human factors in Engineering Risk

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Human factors in Engineering Risk

1. SUMMARY.

This paper investigates the human factors in Engineering Risk. It seeks to answer the questions; as safety equipment becomes more sophisticated and reliable, does human error assume increasing importance as a cause for loss and, if so, how can risk be managed and minimised.

An initial review of the IMIA Power Generation Database, which comprises mainly U.S. and German data, is conducted and this is compared and contrasted with an overview of sizeable losses recorded by U.K. contributors in 1998 and 1999. Due to the complexities which the human element imparts on a risk this review concluded that a quantitative analysis of the data, which was often incomplete from a technical perspective and rarely provided an investigation into the softer human contribution to the loss, would provide only limited insight into the human factor.

Through an analysis of several well-documented cases, where there had either been a loss or a perceived potential for a loss, the influence of the human element was often found to originate during formal risk assessment at the design stage. It then had an ongoing influence during the life of the risk, but it was found that the impact could be influenced through attention to systems, structures and local and national culture at multi-levels within an organisation. The degree of sophistication of safety equipment, which is plotted against the human element, was, in the cases investigated, an adjunct to good risk management but often secondary to this human element.

The human factors are subsequently applied to a risk map based on environment, financial, organisational and market risk and, through further investigation of the cases, it was seen that an organisation's risk profile is constantly shifting due to the internal and external factors which the mapping identifies. For risk minimisation, what emerges is a balanced risk map where attention to the 4 axis is appraised on a regular basis. It is suggested that Insurers may minimise their risk by active participation in Clients' risk management programmes. As a tool for identifying the effect of human elements within this overall map, and as a means for monitoring and improvement of human risk locally, the application of a human factor checklist in conjunction with a 3 dimensional intervention matrix is proposed. By this active attention to human factors it is shown that, by an appreciation of portfolio theory, a positive contribution to an Engineering Insurer's portfolio may be made by incorporating less than ideal risks within the portfolio.

2. INTRODUCTION.

In an attempt to compare loss data recorded by the U.K. contributors with that registered on the IMIA Power Generation database, as presented at the 1999 conference, a provisional analysis of U.K. registered losses for 1998 and 1999 in excess of £50k was undertaken. Overall some 375 such losses were identified for risks located in the U.K and overseas, the split between the broad categories of operational machinery breakdown (MB) & business interruption (BI), construction/erection and contractors plant being approximately 28%, 37% and 27% respectively (together with 8% other) as indicated in ***Figure 1***.

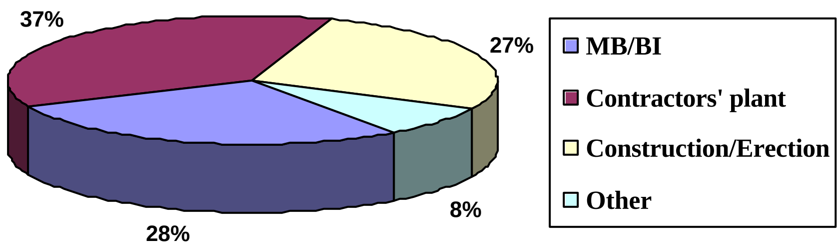

Figure 1. Illustration of categories for losses in excess of £50,000 recorded by U.K. contributors in 1998 and 1999.

For contractors' plant it was, in most cases, possible to identify the cause of the loss, many of which were due to arson or theft. For construction risks it was generally possible to identify the reason for the loss, be it due to external factors such as flood or machinery loss during testing and commissioning. However, when it comes to further analysis to determine the measures in place to prevent the loss, for example whether due account had been taken of earthquake or flood data, or to prevent a recurrence following the loss, the information available generally made this difficult to assess. For operational risks a similar lack of information is apparent and although a complete analysis was not undertaken, it was clear that the indicated cause followed a similar trend to the classifications (operation, maintenance, external etc.) registered on the IMIA Power Generation Database, information for which is largely derived from USA and German data (approximately 50% and 30% respectively as presented at the 1999 conference).

In the 1999 paper it was reported that in approximately 45% of cases recorded on the Power generation Database the age of equipment was unknown and in 55% of cases the actual failure cause was unknown, and this in an industry (power generation) where it may be expected that there would be a consistency in information availability. If global industry as a whole is considered it becomes increasingly more complex, as inferred in the 1999 paper and supported by U.K. information, to readily identify whether the root cause of losses was due to human failing or equipment sophistication, even when loss adjusters' reports are available.

Despite this, there is sufficient evidence to indicate that loss prevention can be influenced through human intervention during the life cycle of a risk. By the application of models to case studies it will be demonstrated how, by effective risk management, exposure to loss at an individual venture will be reduced, thereby reducing risk for the client and the insurer. It will be illustrated how this can have a consequential influence on the insurer's portfolio, thereby providing scope for more effective portfolio management.

3. REDUCING THE HUMAN EFFECT BY FORMAL RISK ASSESSMENT.

The paper 'Risk Based Management for Equipment Reliability' presented at the 1997 conference described in detail a range of risk management techniques. A number of these, such as fault tree analysis and event tree analysis are quantitative methods typically conducted at the design stage of a project. Others, such as Hazop (hazard and operability study) and FME(C)A (failure modes effect and criticality analysis) are more qualitative tending to use the expertise of a number of individuals to ascertain the acceptability of exposure, although with FME(C)A it is possible to extend an initial qualitative investigation to subsequent quantification if failure rate data is available and Hazop may be quantifiably analysed by Hazan as explained below.

However, the 'best practice' represented by these techniques often remains restricted to a number of industries such as nuclear and chemical where there is often a regulatory requirement to assess risk. Even here, as can be demonstrated for example in disasters such as Flixborough, reviewed in Section 5, subsequent modifications either to control systems or process equipment may be carried out without a reiteration of any initial assessment.

Hazard Identification

Both Hazop and FME(C)A are classified as *fundamental* methods of hazard identification based on a systematic consideration of deviations from the design intent. This is in contrast to *comparative* methods that use checklists based on experience, which may derive from Codes of Practice, or from studies on similar plant. These *comparative* methods may be adequate where plant designs are relatively standard and sufficient experience exists for the principal hazards to be well known (Skelton, 1997).

Hazop in particular is useful in identifying potential human effects and the guide words used will address (Skelton,1997):

- The equipment comprising a plant.
- The process materials which it contains.
- The means provided for measurement and control.
- The personnel interfaces responsible throughout the project and its operating life.

If however a Hazop study reveals an exposure that cannot be readily assessed by the experienced team conducting the study, possibly due to the complexity or novelty of the system, this will be itemised for action in a quantitative Hazan (hazard analysis). But, as the Hazop study itself is based on the skill of team members and their perceptions this will contribute significantly to the success of the qualitative analysis (Skelton, 1997). Here then is an early indication that human shortfalls may have an impact on the future risk. If, for example, due to inexperience of the Hazop team a safety feature such as reverse flow in ***Table 1*** were overlooked, perhaps leaving the integrity of the system totally reliant on one monitoring device, this could pose difficulties during the operational phase following failure of this monitoring device if the operator was inexperienced to cope with what would immediately be an emergency situation.

Hazop is traditionally used at the design stage of a project, the following example (***Table 1***) being an extract from a recently completed erection project at an oil refinery.

Ref	Deviation	Cause	Consequence	Safeguard	Recommendation
1.1	More flow	Upstream disturbance	Loss to flare	None	Install alarm
1.2	Reverse flow	Malfunctioning flare valve	Malfunctioning flare valve	None	Ensure check valve installed
1.3	Less flow	Upstream disturbance	Not a hazard		

Table 1. Extract of recent Hazop study of refinery new hydrogen plant.

The use of this form of 'best practice' can however be used during the life cycle of a plant, the scope for which is summarised in ***Table 2*** (Skelton, 1997).

Planning	Includes strategy, research & development and process selection.
Process design	Layout of installation and broad equipment specifications agreed.
Design engineering	Preparation of engineering drawings and detailed specifications for equipment fabrication, purchasing and operation.
Construction and commissioning	Erection, checking, testing and introducing feedstock.
Operations	Including periodic maintenance shutdown, modifications or for operational reasons.
Final shutdown	Operations terminated and plant dismantled.

Table 2. Application of Hazop study during the life cycle of an installation.

To maintain a fundamental integrity, and reduce the possibility of human effects to a minimum, it is imperative that Hazop studies, once conducted, are kept up to date with the original study forming an integral part of the plant and safety records to which reference is made when modifications are conducted (Skelton, 1997).

FME(C)A is primarily used to study material and equipment failure and can be applied to a wide range of technologies, generally at a relatively detailed level at or after the detailed design stage. It is a *bottom up* technique, that is it identifies a particular cause or failure mode within the system and traces forward the logical sequence to the final effect (Skelton, 1997).

All possible failure modes should be considered in such a study by asking what might fail, what effect this would have and what causes the failure, in circumstances such as:

- Premature operation.
- Failure to operate when required.
- Intermittent operation.
- Failure to cease operation when required.
- Loss of output or failure during operation.
- Degraded output.

From the human perspective failure modes such as cracked, distorted, fails to open/close, overheated (failure modes being listed in British Standard BS5760 Part 5) will have a cause and effect (Skelton, 1997), the Flixborough case (Section 5) providing graphic illustration. Analysis of the cause may again reveal exposure due to human factors.

4. A FOCUS ON CULTURE

What are human factors?

The U.K. Health and Safety Executive (HSE) definition is:

> *'Human factors refer to environmental, organisational and job factors, and human and individual characteristics which influence behaviour at work in a way which can affect health and safety'* (HSE, 1999).

The HSE split the human factors into three aspects: the job, the individual and the organisation, from a viewpoint of how these impact on people's health and safety related behaviour. Included within the categories are, for example:

- The job: task, workload, procedures, environment, ergonomics.
- The individual: competence, skills, risk perception, personality, attitudes.
- The organisation: culture, leadership, communication, work pattern, resources.

The HSE (1999) see as key ingredients of effective health and safety management to involve:

- Consideration of the job, individual and organisation.
- Addressing human factors in risk assessment, in design and procurement, during investigations and in day to day activities.
- Involving the workforce.
- Selecting from a range of control measures.

Experience and culture.

The IMIA database categorises cause of failure as due to either external, operational, maintenance, application, repair, construction or design factors. It could be considered that to some extent all of these categories except perhaps for 'external', the effects of which may themselves be minimised at the design stage, are contributed to by a 'human element'. These may be as a direct consequence of poor operation, maintenance or repair, or more indirect as a result of poor design, risk assessment at the design stage as was earlier inferred, or very often due to a combination of these categories.

Jones (1999) extends the IMIA database categories to a ‘behavioural taxonomy’ which provides a framework in which the human effects may be measured. Together with ‘external’ and ‘sabotage’ the categories include:

- Equipment design.
- Design misapplication.
- Operation misapplication.
- Operator error or misuse.
- Fabrication/assemble.
- Installation/erection.
- Maintenance execution.
- Reliability planning.

In addition, within each of these taxonomies are various aspects of the human element. For example, an overlooked element within the previously discussed Hazop study at the equipment design/design application stage, could have been, using the HSE categories, due to the job (e.g. workload of Hazop team), individual (e.g. due to their risk perception) or organisation (e.g. provision of resources).

Best practice therefore does not rest solely with fundamental risk management techniques. As will be evident in the later case studies several of these human factors may combine to produce the loss, but equally human intervention at any of a number of these stages may have prevented the loss. For example, it could be considered that modern computerised design equipment would assist in preventing a failure, but this may only be as effective as the design engineer’s ability to interpret the data available. This may to a large extent be limited by his education and experience combining to form a ‘corporate memory’ to foresee possible difficulties from past events. Similarly, during operation, to minimise loss potential operators must be able to not only interpret vast amounts of data but to have an innate knowledge of the equipment in their charge. This requires not only knowledge of incidents and potential incidents at their own site, but a broader knowledge of events in similar circumstances elsewhere.

The following matrix, ***Figure 2***, will later be used to illustrate the degree of risk perceived at operational sites or projects under construction around the world with which the contributors have had first hand experience. Examples are used to illustrate the effect of the human element where they were operating satisfactorily, where there was perceived to be a risk or where there had been a loss.

To explain the matrix, where the sophistication of safety equipment is low and the human factor is low, the risk will be unacceptable. Low on the 'human factor' scale indicates that there is likely to be inattention to a number of behavioural taxonomy elements, including cultural factors (of job, individual and organisation) which may be limiting the degree of intervention that will be made, whether this be in an emergency situation or as a preventative measure. At the opposite extreme, where the sophistication of equipment is high and the human factor is high the potential for loss will be reduced to a minimum.

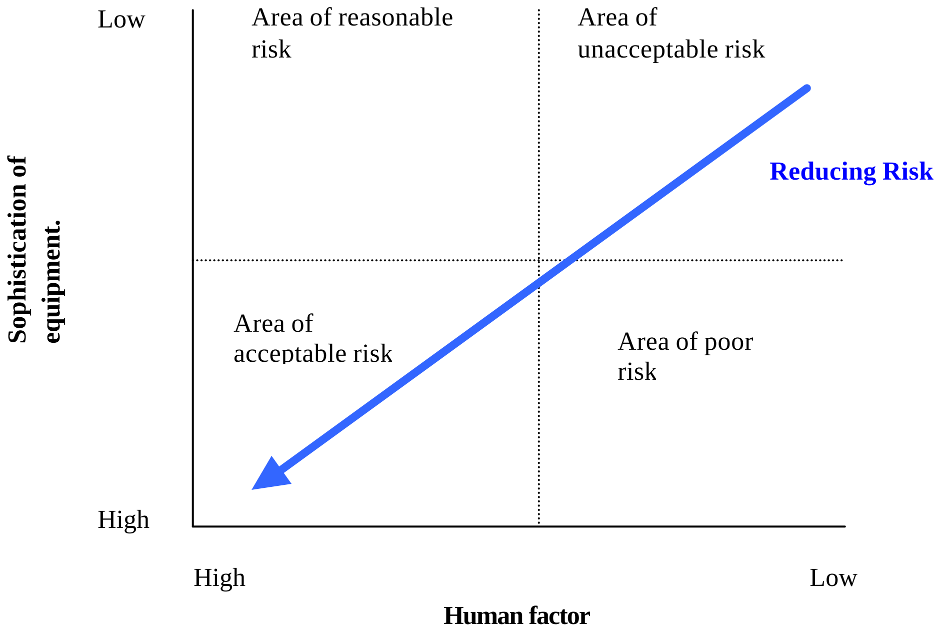

Figure 2. Matrix of sophistication of equipment and the human factors, attention to which will minimise loss potential.

The case studies in Section 5 provide examples of risks in each of the above quadrants. In these the degree of exposure is assessed and an indication is given where, by attention to training, culture and related aspects of climate, improvements may be made. There will of course be a residual risk due to sabotage or external factors, and there are instances where, despite high equipment sophistication and attention to human factors loss severity has been high.

Cultural levers to risk minimisation.

Whilst not always realising it, as risk control engineers gain experience they will increasingly utilise methodology in assessing risks and intervening by presenting recommendation for risk reduction based around the principles of 'Organisational Design'. In addition to assessing the physical aspects of the risk they will be analysing the complex inter-relationships at multi-levels within the organisation. Possibly at a sub-conscious level they will be attempting to overcome resistance to change, encouraging empowerment by persuading people at all levels within the organisation to change the system, if they deem the current system to be wanting. In short they will be combining their engineering knowledge with a further focus on the HSE job, individual and organisational human factors and their effects on the behavioural taxonomy.

Figure 3 provides an overview where and at what level intervention may be necessary when assessing a risk. During site assessment, the experienced Engineer will simultaneously be analysing the present state of the organisation by winning confidence, gathering data and thence gaining involvement in agreeing change requirements and setting targets for change.

It can be seen that by adopting this type of approach, balancing the softer elements of site management with the harder elements such as systems and procedures, that the risk reduction in ***Figure 2*** may be tackled by attention to the human elements. For example, whilst assessing a number of Scandinavian paper and pulp facilities it was apparent that those with the best loss ratio had a looser structure which seemed to benefit the working relationships in the more successful plants. By tackling the situation at the organisational level (as indicated in ***Figure 2***), key staff of the various plants conducted mirroring between the facilities and subsequently the structure was changed at the least successful plants. Here, the 'degree of intervention' at the organisational level was relatively low, the prime effect being a change of 'climate' which the senior management and individuals of the least successful plants who undertook mirroring were able to transfer to the group level. At the group level at these plants the minor structural changes required a slightly higher degree of intervention. Follow up indicated an improved risk. An explanation of the possible reason for this success is offered at the end of this section.

Hofstede (1983) conducted a study into these cultural effects at IBM plants in over 70 countries in an attempt to establish a systematic classification of national cultural differences. Measures were established on 4 dimensions and classified as follows:

Power distance. How far the culture encourages people to exert power.

Uncertainty avoidance. Degree in which a culture copes with novelty and encourages risk taking.

Individualism – collectivism. Degree to which a culture encourages individual as opposed to collectivist or group concerns.

'Masculinity – femininity'. Unfortunate stereotypical terminology, but assesses degree of task orientation, 'masculine' winning rather than losing with less regard of 'cost' of winning against the 'feminine' concern for the context and process whilst satisfying many participants' goals.

An indication of where national groups fit on a chart of power distance to uncertainty avoidance illustrates some interesting points (see ***Figure 4***).

OD INITIATIVE (Problem nature) LEVEL (of intervention)	BEHAVIOR *(What's happening now)*	STRUCTURE *(What is required system?)*	CONTEXT *(What is setting?)*
	DEGREE OF INTERVENTION →		
ORGANISATIONAL	**CLIMATE.** Poor moral, pressure, anxiety, lack of response to environmental change.	**SYSTEMS.** Poor/inappropriate goal definition. **STRATEGY.** Inappropriate or misunderstood. **STRUCTURE.** Inappropriate (degree of centralisation etc), inadequate environmental monitoring.	Geographical setting, market pressures, basic technology.
Area for action.	Survey, organisational mirroring.	Change structure.	Change strategy, physical set up, culture.
INTER – GROUP	**CO-ORDINATION** between groups poor, conflict & competition, different priorities.	**OPTIMISATION.** Of sub units. **INTEGRATION.** Lack of from task perspective. **INTERACTION.** Difficult to achieve.	Different values. Physical distance. Reduce psychological & physical distance.
Area for action.	Confrontation between groups with facilitation.	Responsibility redefinition. Reporting relationship change. Co-ordinating mechanism improvement.	Role exchange. Attachments & cross functional groups.
GROUP	**RELATIONSHIPS** Inappropriate – poor atmosphere. **GOAL ACCEPTANCE / AVOIDANCE .** **LEADERSHIP -** poor style, not trusted/respected, conflict.	**TASK.** Poorly defined **RELATIONSHIPS.** Unclear/inappropriate **REPORTING.** Procedures inappropriate.	Resources insufficient. Group composition inappropriate.
Area for action.	Process improvement & team building.	Self-directed work groups, redesign relationships.	Change technology, group composition.
INDIVIDUAL	**NEEDS.** Not considered. **CHANGE.** Unwillingness to accept. **LEARNING /DEVELOPMENT.** Little chance.	**JOB DEFINITION** poor **TASK.** Too easy/hard.	Individual/job mismatch. Lack of selection/promotion. Inadequate training/recognition.
Area for action.	Counsel, role profile, career advice.	Enrichment, agreement on competences.	Realign objectives with status and reward. Improve training opportunity

Figure 3. Areas to target for change – deciding on change initiatives (Developed from Pugh Organisational Development matrix).

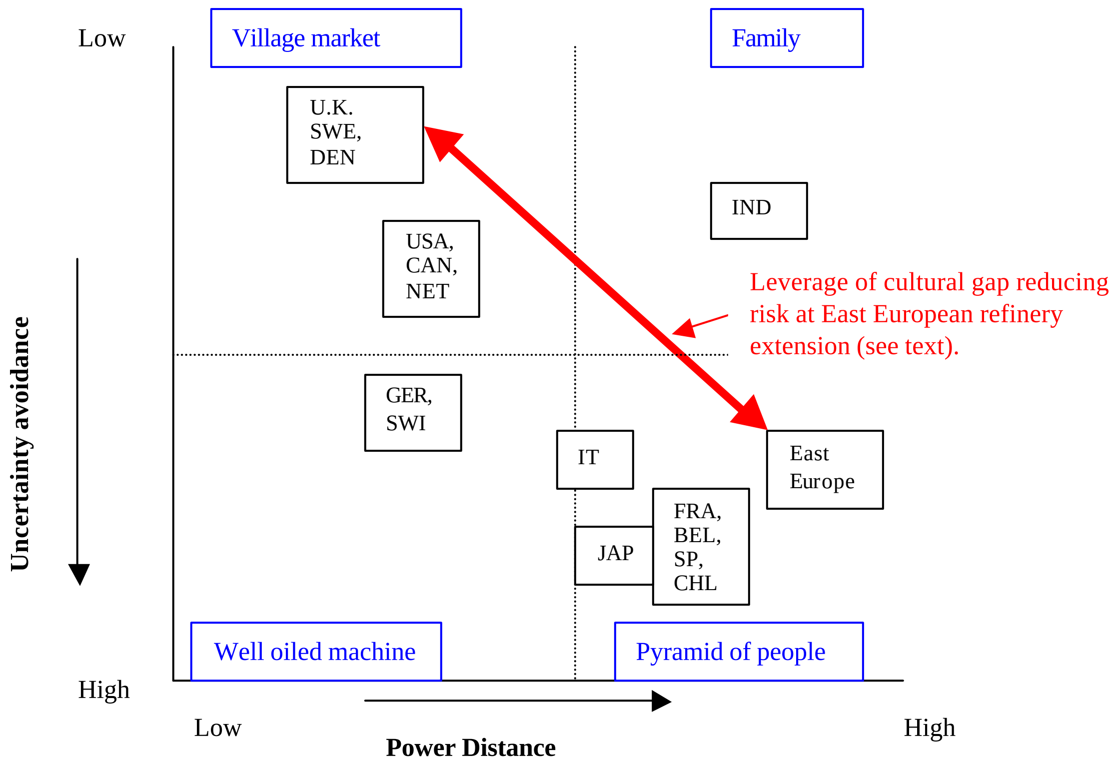

Figure 4. Illustration of different 'uncertainty avoidance' and 'power distance' aspects in different national culture (developed from Hofstede 1983).

Of course caution must be used when applying this model. The study was carried out at plants owned by a single company within a single industry. It does not predict the effects of extreme situations such as those which may occur in 3rd world countries, where the labour force may be casual and large numbers of the population may be dispossessed by intimidation, famine or disease. The model does however provide an insight of the differences in basic national culture, an invaluable tool in reducing the human element of risk.

An example of how a potentially unacceptable situation was tackled by an appreciation of these cultural aspects at an Eastern European oil refinery extension is where the excellent Western project management team (U.S., British and Dutch personnel) were having severe difficulties implementing acceptable safety and engineering standards. During the construction phase problems encountered included the flouting by local contractors of, for example, access rules and permit to work systems, together with the implementation of the required welding procedures and an inspection regime for cranes.

It was apparent that if the situation persisted losses would inevitably arise. If matters were not resolved prior to commissioning, due to further interface difficulties between local employees and largely Western main contractors (equipment suppliers), the potential for a serious situation was seen as unacceptable, particularly considering the high degree of automation being installed as part of the upgrade. Facilitating between the refinery and project managers the Insurer's engineer instigated the appointment of a Polish speaking safety officer (British) as part of the project management team. This appointment was seen to have an immediate effect on site safety, this individual being able to ensure that the necessary regulations were enforced whilst translating the benefits of these requirements to terms more acceptable to the local workforce to ensure more active compliance. In effect, the immediate problem of bridging the cultural gap was achieved as illustrated by the arrow in ***Figure 4.***

In the previous Scandinavian paper and pulp plant example the Hofstede models indicate that whilst the Scandinavian group is similar to some other Western Europe and Northern American countries in power distance, uncertainty avoidance and individualism, there was a distinct difference in that the Scandinavian group indicated high 'femininity'. There was a definite concern for the community in that experiences were readily transferred successfully between plants. The best practices established as a result of the organisational mirroring, which included structural change at the least successful plants to ones to facilitate more interaction, appear to reflect this aspect. Case study 4 provides a further example of group foresight in Scandinavia. So, using the HSE categories, there had been a local improvement in organisation that translated to a clearer focus on the job and individual. From this there ensued a benefit to the maintenance execution within the behavioural taxonomy.

Reduction of Risk through legislation and inspection.

The above examples illustrate that, whilst formal risk assessment techniques may be mandatory for some process industries, risk reduction by attention to the human element is essential. It is often the case however that dramatic reduction in risk is often made by forcing compliance, the mandatory requirements of which will assist in reducing the human effect.

An example of how legislation with its associated requirement for stringent inspection and training (an enforced focus on the organisation, job and individual) has contributed to reduced risk for operatives is illustrated for power presses in the U.K. ***Figure 5*** shows the number of investigated accidents at tools and power presses in the U.K. from 1943 to 1998.

Following a report by a committee established by H.M. Inspectors of Factories in 1945 entitled 'Safety at Power Presses' a sharp decline in the number of accidents ensued. A Joint Standing Committee was established at that time and issued its 'First Report' in 1950 the contents of which included:

- New presses and new types of safety devices.
- Existing guarding and interlocking with a view to improving performance and reliability.
- The use of fluid assistance in the operation of presses and guards.

A second report was issued in 1952 making further recommendations to manufacturers and encouraging for the first time training of power press setters. By the end of 1954 over 1,600 setters had attended relevant training at the Birmingham (U.K.) RoSPA (Royal Society for Prevention of Accidents) centre.

Incidents however remained at an unacceptable level, and in the 3rd and 4th Reports of the Joint Sub-committee issued in 1957 and 1959 respectively, emphasis was further placed on the requirements for standards of maintenance and guarding together with the necessity for electrical control systems and interlocking. It was not until 1965 though that the 'Power Press Regulations' were introduced, enforcing what were previously recommendations. These included, for the first time, the requirements for power presses to be inspected. A sharp decline in incidents followed. Further legislative requirements were introduced in 1972, which required the reporting of defects that were a danger to employed persons to H.M. Factories Inspectorate by a Competent Person. As a result, a further drastic reduction in incidents to 49 was recorded for 1979.

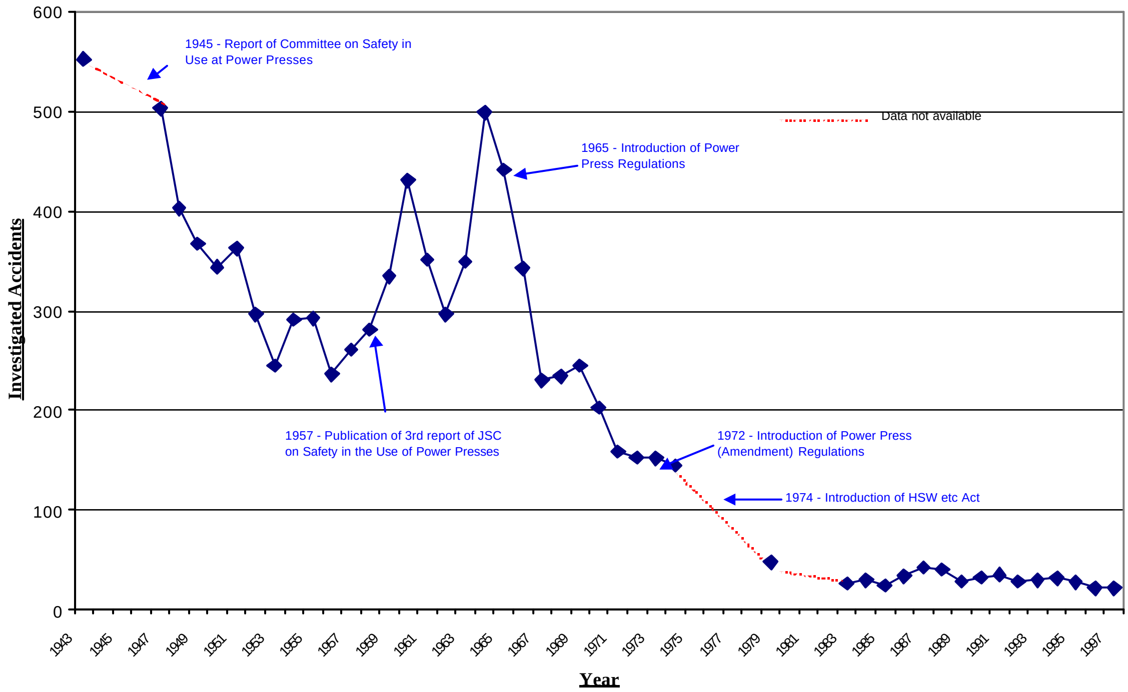

Figure 5. Investigated Accidents at Tools and Power Presses in U.K. 1943 to 1998.

Since that time the number of Power Presses in the U.K. has reduced by at least 60% and in 1998 the Power Press Regulations (of 1965 and 1972) were revoked and replaced by the risk based regulations 'PUWER' (Provision and Use of Work Equipment Regulations). A further requirement of these regulations is, based on the risk identified, the inspection of electric wiring, control circuits and other defects that have been established for causing about a quarter of the 20 to 30 accidents reported in recent years.

However, despite the legislation and the associated requirements for maintenance control systems and inspection it is apparent that the human element is a direct factor in a significant number of the remaining accidents. Health and Safety Executive data itemised for 1997/98 that 'failure of guard due to human element' resulted in 4 accidents and 'guards not provided or used' a further 5, a total of 22 accidents being reported for the period.

It could be that with consideration of particularly the uncertainty avoidance parameter illustrated in ***Figure 4*** for the U.K. that it is inevitable that individuals in this culture will take risks. Zurich Engineering's Power Press expert's recent experiences in Japan appear to reflect this hypothesis, the legislative requirements for safety devices being less stringent than in the U.K and, although statistics are not readily available, there is industry knowledge that accidents are rare.

The U.K. Health and Safety Executive appear to recognise this power distance aspect. The requirements, for example, of dual hand control for power presses being more onerous in the U.K. than elsewhere in Europe.

5. CASE STUDIES – COULD IT HAVE BEEN PREVENTED?

Case 1. Design and modification.

The 1974 Flixborough incident in the U.K demonstrates clearly where, if a Hazop study had been conducted, the disaster may well have been averted. With reference to Lancaster (1996), oxidation of hazardous cyclohexane took place in a train of 6 reactors with interconnecting pipework and a bellows between each. In March 1974 cyclohexane was found to be leaking from the 5^{th} reactor. This was removed for examination and reactors 4 and 6 connected by means of a fabricated dog-leg length of pipe, as the reactors were on different levels, which was inserted between the existing two bellows.

The failure occurred 2 months later. It was primarily due to forces acting on the assembly tending to turn it in a clockwise direction together with a bending moment acting on the pipe. Whatever the reason for this, and there has been much discussion subsequent to the enquiry centred around the possibility of an internal event caused by a process disturbance, it is evident that a Hazop study utilising guide words such as 'more pressure' or 'higher temperature' would have highlighted the deficiencies of the temporary arrangement.

Whilst such Hazop studies are often confined to the chemical and petro-chemical sectors, the methodology may be usefully employed throughout industry. Similarities can be seen with the Flixborough case in a more recent loss that occurred at a relatively small combined cycle plant where steam generated by gas turbine waste heat was used to drive a turbo generator. At the inlet to the steam turbine was a bellows designed by a major contractor, but once again 'corporate memory' seems to have been lost. It had not been considered that the steam turbine, the inlet to which the bellows was directly connected, would expand in a vertical direction as well as longitudinally for which it was designed. After some two years of operation the bellows failed at night in an unmanned boiler house. The repaired item, which was never reinstated, is shown in ***Figure 6.*** A more conventional pipe loop was subsequently used.

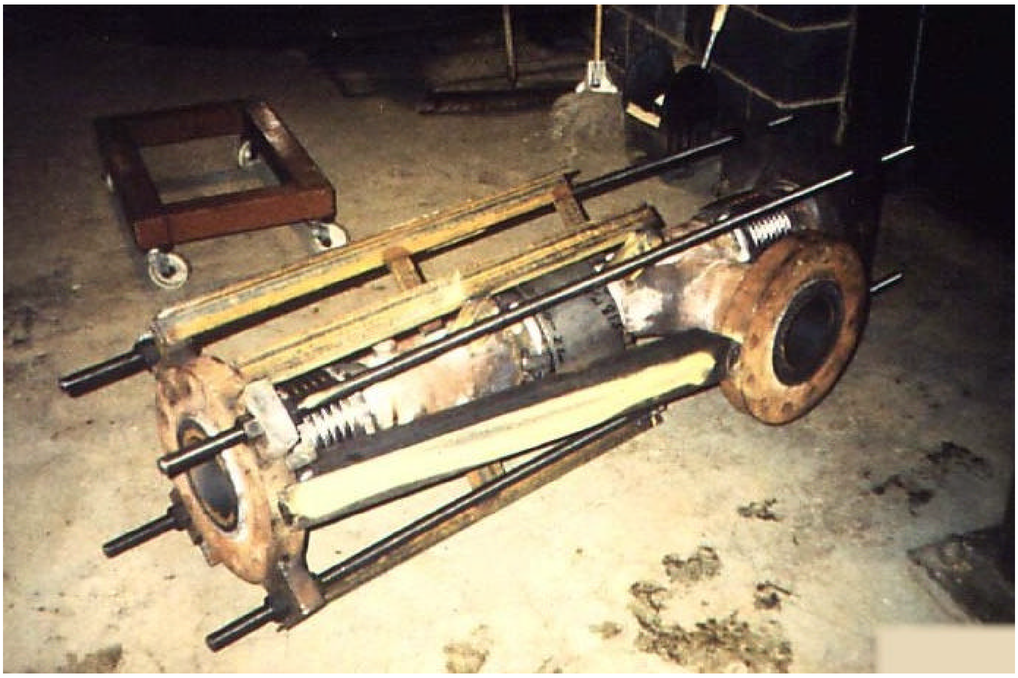

Figure 6. Repaired bellows with connection to steam turbine left, steam inlet centre and bellows attached to wall right.

Case 2. Design and operator inadequacies.

A further example illustrating corporate memory loss concerns the blading of a Kaplan hydro-electric turbine. In the paper 'Trends in Technology of Hydro Plant', Agenda 5 of the 1998 conference, Dr Grein presented an illustration of crack propagation in such blades as reproduced in ***Figure 7***.

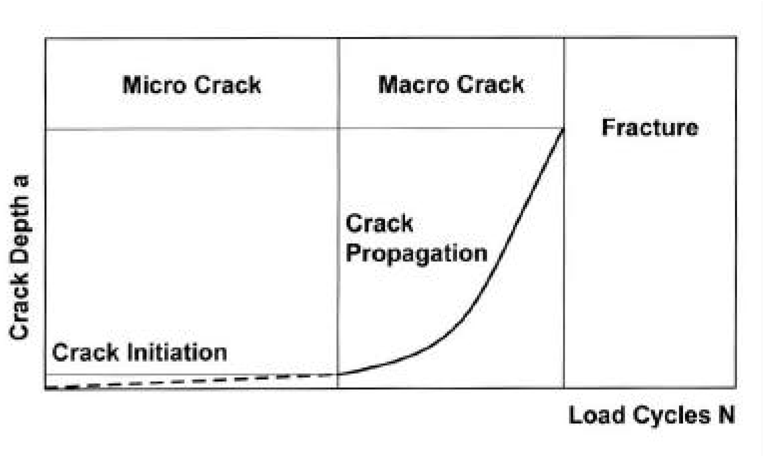

Figure 7. Illustration of crack propagation in hydro-electric turbine blading (Grein, 1998).

Figure 8 shows a blade of a Kaplan type turbine close to the fracture stage.

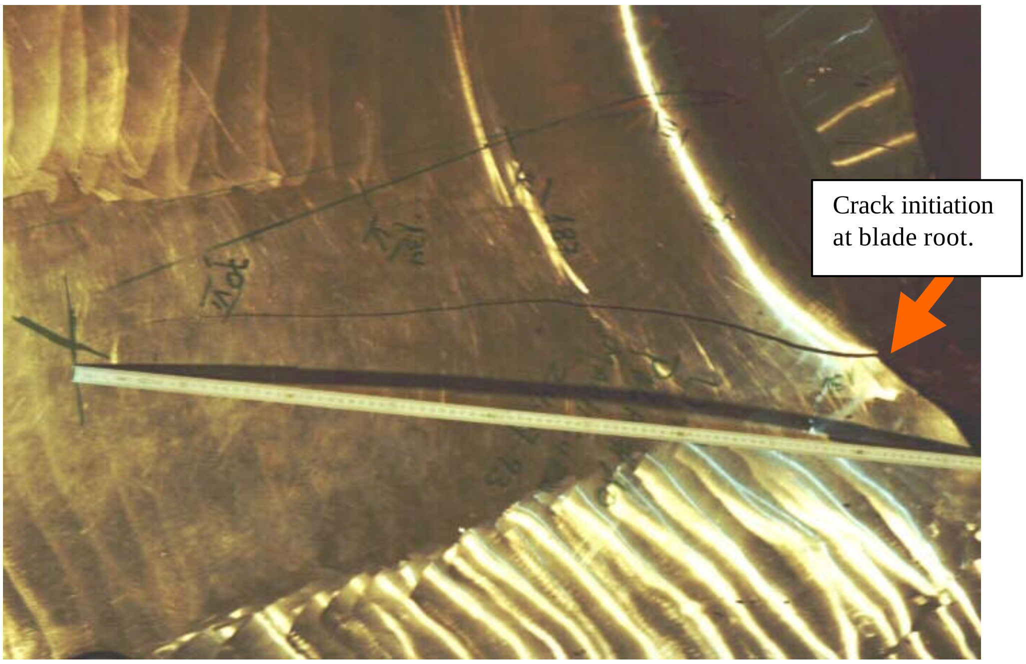

Figure 8. Macro crack of a Kaplan hydro-electric turbine blade with crack initiation point visible at root.

The prime cause of the failure was inadequate radiusing at the blade root from where the crack propagated as seen in the photograph (a substantially increased radius was made on replacement blades). The turbine had permanent vibration equipment fitted to the highest standard incorporating data collection and trend analysis. Indeed, on investigation, the increase in vibration could be clearly seen several months prior to the discovery of the damaged blade and action had been taken, albeit that this was entirely inappropriate.

The monitoring equipment had indicated a far greater increase in vibration at the upper generator bearing and the maker's representative had, following investigation and discovery of no fault with the generator electrically, balanced the generator unit as a whole. At this stage, and until several days of operation later when the vibration levels continued to increase, no attempt was made to examine the turbine (a relatively easy task requiring only the removal of an inspection cover). Even following the discovery of the failure the question had not been asked by the client - why didn't we discover the fault with all our sophisticated equipment?

Here, it is clear that there were design and operational aspects to the loss and, in attempting to analyse from a cultural perspective, the picture becomes more complicated. Manufacturers and the service engineer were German and the machine was located in South America where in each case there should have been a high level of uncertainty avoidance. It would have been expected therefore that precautions against loss would have been taken at the design stage and through to the investigation of all possibilities for the cause of vibration by the maker's service engineer. It would also be assumed that the site would have invested in thorough training.

A complete explanation is not always possible, the site seemed quite well managed and the overall climate was good, but with consideration of the context in which the operators were operating in ***Figure 3***, it became immediately apparent that the individuals had not received sufficient training. What's more they seemed aware of this but had not tackled their superiors – perhaps a reflection of the power distance continuum. It was here then that the focus for improvement was made.

Case 3. Poor maintenance and operation.

Occasionally a loss appears to have so many contributory factors that it is difficult to ascertain immediately when the problems actually arose. One such event occurred at a boiler located in a South African pulp and paper mill which was fired with 'black liquor' (a combination of lignin and chemical salts in liquid form). The co-axial tubes of the boiler were severely damaged as a result of continued firing on low water level.

Fortunately no tubes failed, if they had the consequences could have been catastrophic due to the effect of water on the sodium salts. However, it was necessary to retube the entire furnace.

Some of the contributory factors to the loss were identified as a severe lack of maintenance of the boiler controls. This included:

- The prime safety device, the water gauge glass, was completely obscure and had not been repaired even although there had been a recent outage.
- A secondary water level cut out device had been disconnected (apparently for some time).
- The connections to the differential pressure devices from the boiler were fitted using inappropriate techniques (including PTFE tape and screwed connections).

Due to the poorly maintained gauge glass and disconnected secondary level control device, the entire water level control of the boiler was dependent on 3 comparators, the computer monitoring the level being programmed to recognise the best 2 of the 3 signals. Unfortunately the arrangement of the 3 comparators (essentially differential pressure transmitters) providing these signals was such that 2 of them were connected to a common pressure leg. When the pressure leg connected to the 2 devices developed a leak due to the inappropriate connection described above, the computer was taking this incorrect signal to be correct. Even at this stage it would have been possible for the operator to take action. The one correctly reading indicator, connected to the pressure leg which did not develop a leak, could have been viewed on the display screens but was not, and, during the later stages, it was reported that the boiler was making some rather unusual noises.

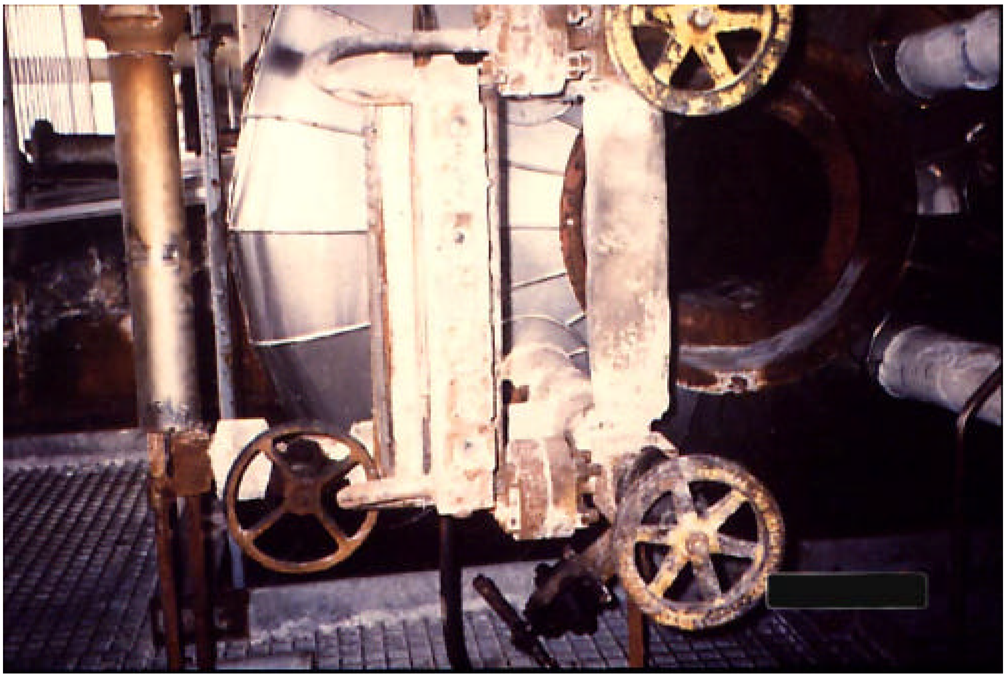

Figure 9. Obscure gauge glass and, to left the disconnected secondary water level control device.

On the ***Figure 2*** matrix this risk was clearly in the unacceptable quadrant. Control equipment was virtually non existent and there had been a failure to intervene at multi levels in the human area. Even so, by appreciation of cultural differences and perhaps more importantly to assist local managers in tackling what may be extreme local cultural variations, it is possible to tackle the situation. In this type of case intervention is required at the highest levels of ***Figure 3.*** Contextually, consideration of the geographical setting was required and there was an immediate need to upgrade the basic technology. Simultaneously the structure required significant change, including the need to establish thorough training of personnel at all levels, providing an appreciation of the hazards of the process, and there was an overwhelming need to change the climate from one of apparent oppression. The changes had to be appropriate, with an appreciation of the cultural variations. For example workers at the lower levels may be illiterate, they may understand little of the dominant language, and in any case the spoken word may have more meaning than written procedures.

Case 4. Excellent human factor, low sophistication of equipment.

Few cases are available for analysis where there are losses when few gaps can be identified in the Organisational Development matrix of ***Figure 3*** and where there is a reasonable alignment with the national cultural features of Hofstede. When they do occur site personnel seem to experience a genuine shock, and to many the loss really does appear sudden and unexpected, but very soon they are utilising significant creative skills to repair the damage. When the human factor in ***Figure 2*** is 'high' there is still room for improvement by utilising more sophisticated equipment, although this could be considered more to be a tool to compliment skills rather than something on which to rely.

A Scandinavian paper mill suffered a catastrophic failure of a guide roll, one of a number the purpose of which is to guide the 'felt' over which the paper is laid over some 50 steam drying cylinders. These drying cylinders are pressure vessels operating at a pressure of approximately 3.5 bar. ***Figure 10*** shows the result. The failed guide roll destroyed 5 of the steam cylinders and a number of other guide rolls.

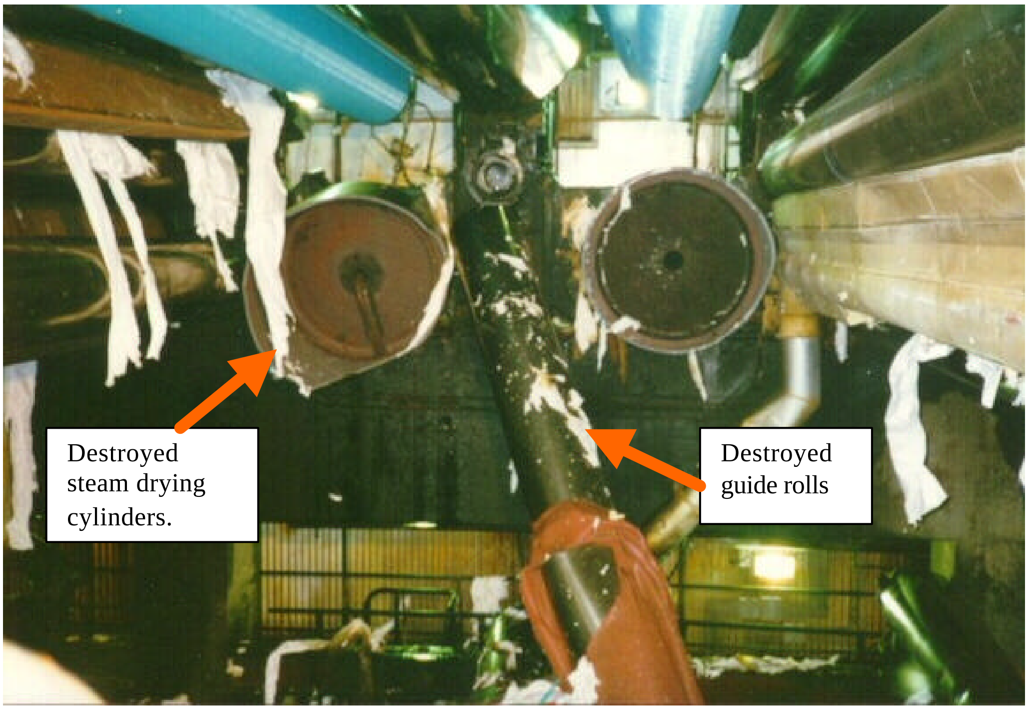

Figure 10. Catastrophic failure of part of a large paper machine's drying section.

The machine could operate without 1 or 2 drying cylinders, but with 5 out of use the paper could not be dried to the required degree. No spares were immediately available, but within 5 days the plant was back in operation despite a replacement time for new rolls expected to be 6 to 9 months. Although there were no definitive contingency plans for such an event the whereabouts of spares was known, and as an excellent example of the Scandinavian 'femininity' combined with 'collectivism' on the Hofstede scales the industry had a system of assistance to deal with such eventualities.

Such failures were unknown locally. The cause was established as a fatigue crack originating at an internal strengthening arrangement fixed to the roll during manufacture prior to it being welded in 2 sections circumferentially.

Since the failure further vibration analysis and non-destructive testing has been implemented. Previously the larger rolls in the press section of the paper machine had permanent vibration monitoring, extension of this system to the drying section would provide early warning of imbalance which the failed roll may have exhibited prior to the failure. Non-destructive testing to the welded sections of not only the type of roll that failed but also rolls elsewhere in the machine would provide indication of a number of incipient defects. In effect a FMECA study has been conducted, although perhaps not as prescriptively as laid down in Standards, but the results of the investigations conducted internally have identified where more sophistication in both maintenance and operational equipment would clearly enhance the risk.

Case 5. A complete turnaround.

Insurers' involvement as facilitating engineers at a German oil refinery started some 10 years ago. At the time the risk was clearly in the area of unacceptable risk with frequent losses. A few of the problems were poor maintenance practice, Operations dictated to Maintenance, there were virtually no records of mechanical maintenance and the control equipment had not been upgraded in many areas for decades. Attention at all levels of ***Figure 3*** would be required to turn this risk around.

It is difficult to illustrate with photographs how such a transformation occurred, it is more akin to painting a picture. Once the main areas for attention were identified to senior management a five-year plan was drawn up detailing changes, this plan itself taking almost a year to develop. But once implementation started it was rapid. Key staff were replaced, over the period and during 3 shutdowns the instrumentation and safety shut down systems were renewed. Younger more enthusiastic engineers were brought in to be guided by a German with extensive experience at U.S. refineries and over the period 'best practice' has been established in both maintenance and operation.

So at organisational level Directors provided the structures and systems in which the change could be made. At inter-group level attachments between departments developed a broader appreciation, at group level technology was enhanced and the group composition changed, and at individual level there was a focus on individual skills, needs and competences. Intervention had focused on the context at each of these levels, whilst simultaneously appreciating the need for structural and behaviour change. All in all an alignment was being developed with the German 'well-oiled machine' definition of Hofstede.

The sophistication of the safety equipment installed at the plants described in the case studies is plotted against the human element in ***Figure 11*** below.

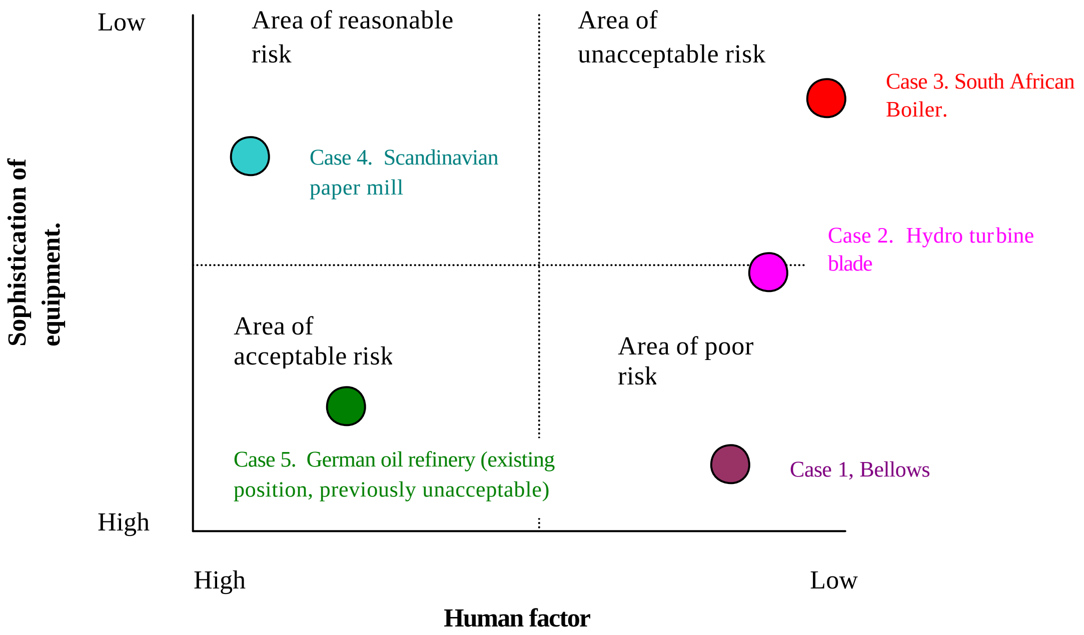

Figure 11. Indication of individual cases on the Matrix of sophistication of equipment and human factors. ***Distance from intersection of axis indicates degree of intervention required to reduce risk to a minimum.***

6. HUMAN CONTRIBUTION TO RISK MINIMISATION.

What 'Risk' are we seeking to minimise?

In the 1999 Conference paper 'Managing Risk in the Construction Industry' (Werner, 1999), an emphasis is placed on the development of partnerships with all parties involved in a project. We suggest that this argument can be readily transferred to operational risks, but that in any case the partnership will only be successful if attention to detail on what is presenting the risk can be established.

Some useful guidance is presented in the 1999 Conference paper 'Safety in the Nuclear Industry' (Moroni, 1999). Here a link between the following was seen as important:

- Technological risk controlled by compliance with basic safety and policy requirements.
- Risks inherent to human and socio-organisational factors prevented by quality of actions, organisations and decision-making processes.
- Risk of internal and external disunity (social aspect) prevented by maintaining a climate of trust, co-operation, social relations and quality of management.

It can be seen that these risk areas fit favourably with our previous models, and it is possible to see the inference of a desirability for a balance between various aspects of the risk package. In an excellent paper entitled 'Rebuilding behavioural context: turn engineering into people rejuvenation' Bartlett & Ghoshal (1995) describe the importance of this balance on four axis', linking discipline with stretch (for example balancing safety policy with new technology) whilst providing an atmosphere of trust balanced by a strong element of support.

To investigate where attention to the human contribution can minimise risk through this rejuvenation it is useful to break down the three risk categories above into further constituent parts in the form of a risk map as shown in ***Figure 12*** (Open University, 1998).

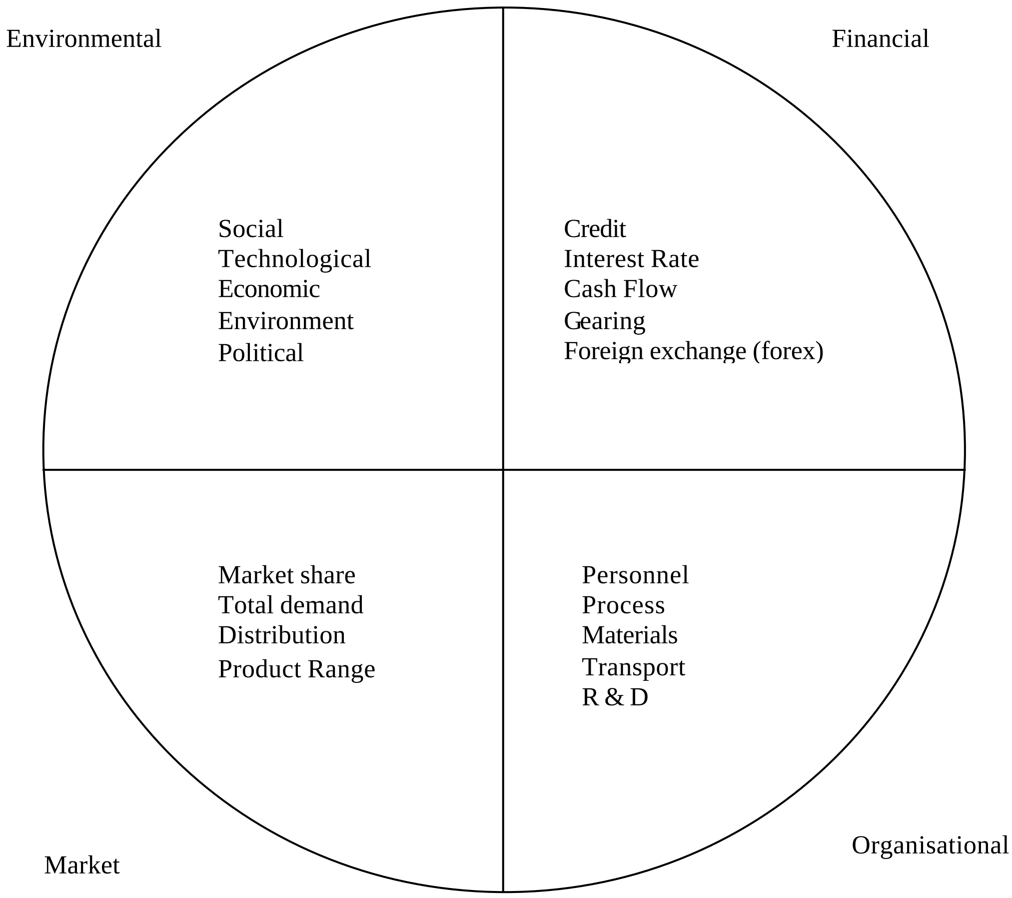

Figure 12. Basic Risk Mapping Categories.

It is beyond the scope of this paper to analyse in detail the constituent parts of this map. A financial risk map, for example, of any particular client will be complex. To assist in an analysis of these financial aspects Swann and Precious (1996) propose the use of a template where the 'contributions, limitations and expectations' of nine stakeholder types are measured against five risk elements, namely forex, interest rate, commodity price, equity and funding and company specific factors. Within the 'company specific factors' are included the company structure and management, again a direct link into human factors from this financial perspective.

Similarly, the risk map will be constantly changing. A change of management may alter the social climate within the environmental segment, as may a change in macro political environment. For example, the Standard and Poor's sovereign credit rating for Taiwan is rated AA+ with a stable outlook, but the October 1999 review notes that this is constrained by the 'political, social and economic vulnerabilities posed by Taiwan's relationship with the Peoples Republic of China'. There is a strong inference that if instability is introduced into such economies the interactions between the elements of the risk map will alter over a short time scale. With reference to ***Figure 2*** a risk, which was seen as acceptable with high human factors and sophistication of equipment, may consequently revert to an area of poor risk.

We suggest however that it is possible to use the ***Figure 12*** model to good effect at several levels, and it may be that a general qualitative profile developed from Engineering and Underwriting experience presents a good approximation to a map which has been quantified at each level for each particular risk. The earlier example of the German refinery will be used to demonstrate.

Prior to the involvement of facilitating Engineers the Company's *financial* risk was seen to be acceptable. The *market* risk was relatively stable although there was an increasing demand for more highly refined products (which would in turn provide the company with greater profit for investment). *Organisational* risk was seen as weak with some key personnel not performing and R & D as far as identifying the need for appropriate maintenance techniques was poor. From an *environmental* risk perspective there were political pressures to reduce emissions and socially there was an air of inattention to individual need.

Over a period of several years the construction of new plant reduced the *market* risk and to an extent the *environmental* risk with the installation of improved safety equipment, which was further enhanced by attention to individuals. The employment of more dedicated personnel improved the *organisational* risk and with a reasonably stable economy this combined with the *financial* risk which was further improved. The profiles of the previous and current situations are illustrated in ***figure 13***.

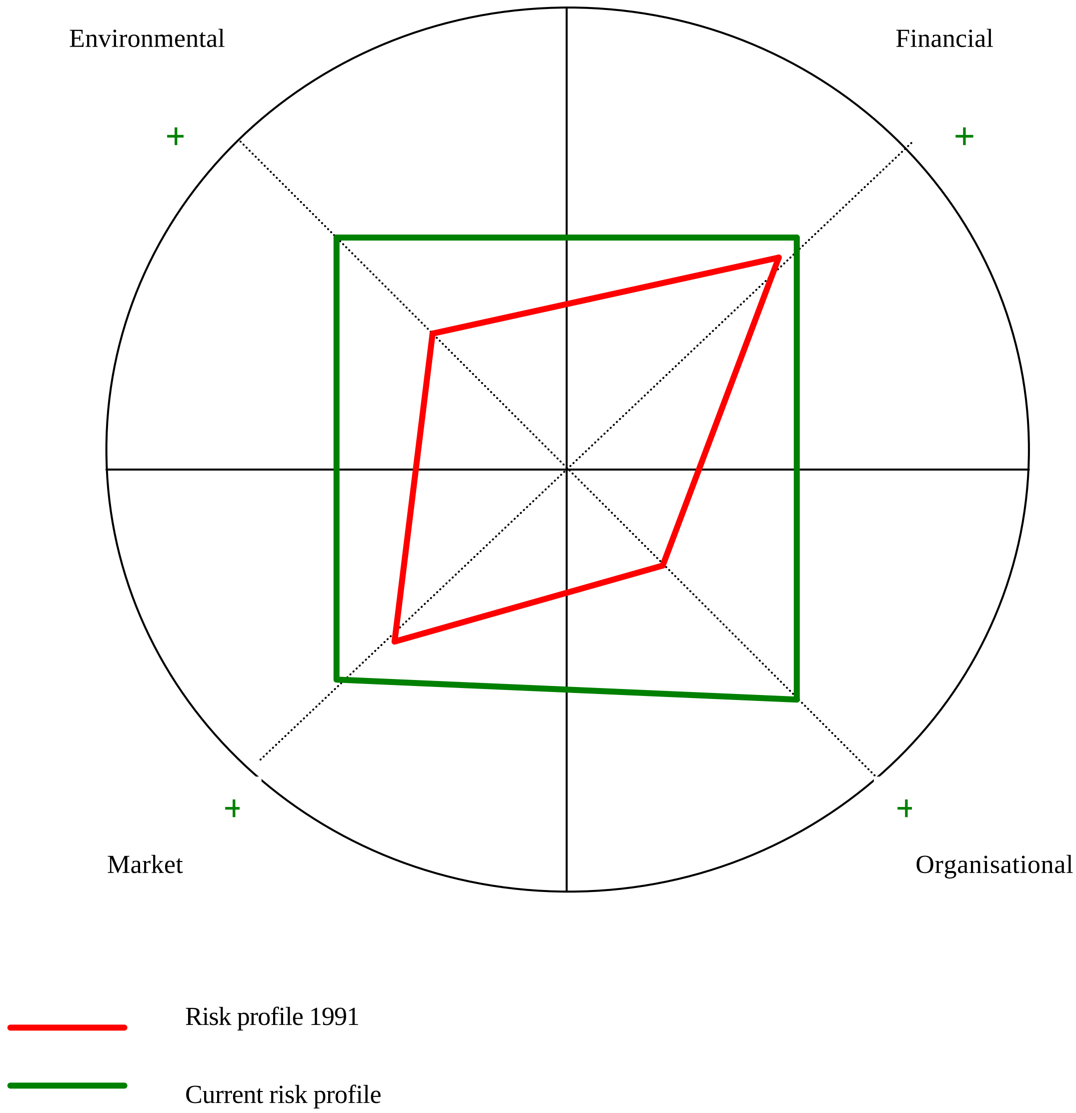

Figure 13. Improved risk through particular attention to the human elements of *Organisational* and *Environmental* risk. (Risk improving as it moves towards periphery of circle.)

A portfolio of risks.

What is also evident in ***Figure 13*** is that a more balanced risk profile has emerged in that attention to the organisational and environmental aspects is now as positive as the financial and market aspects. In addition the correlation effect, as described below, has had a beneficial influence on the financial and market aspects. There is a clear benefit here to both the company and insurers.

Swiss Re (Sigma 2/99) sees that the various risks to which a company is exposed as themselves a portfolio of risks where the volatility of the entire portfolio is usually less than the aggregate volatility of individual risks. This is due to the correlation effect between the constituent parts of the risk portfolio. So, even for an individual company, a diversification effect has therefore been established due to these correlation differences between the constituent parts (environmental, finance, market and organisational) of the company's risk profile.

Portfolio theory was originally developed for portfolios of shares (Markowitz won the 1990 Nobel Prize for Economics for quantifying the risk and return of equity portfolios in a financial model). There seems a strong analogy on the underlying principles of portfolio theory for these financial investors and insurers. In the following the terms 'investor' and share' used in the theory may be readily substituted by 'insurer' and 'risk'. In answering Markowitz's question, 'how should investors (insurers) combine shares (risks) into a portfolio to offer the best return' the assumptions are (following Open University, 1998 and Markowitz, 1952):

- Investors (insurers) make decisions in single period frameworks.
- Investors (insurers) prefer more money to less money.
- Investors (insurers) are risk averse (requiring extra return for extra risk).
- Investors (insurers) judge the attraction of shares (risks) solely in terms of expected returns and standard deviation of the shares (risks) (measuring how likely it is that expected returns will be achieved).

Portfolio theory then (as intended for investors), demonstrates how optimal portfolios can be achieved by concentrating only on returns, risk and correlation coefficients. (Open University, 1998). We suggest that this will be equally valid for insurers and that the human factor will influence all 3 aspects.

For a portfolio of shares it is possible to calculate the correlation coefficient mathematically by a knowledge of expected returns and standard deviation of returns. For insurance purposes though it may be more appropriate to estimate the coefficient initially giving due regard to the knowledge of the risk and the overall perception of the risk map derived from ***Figure 12***. This may then be compared to a portfolio of risks already held. ***Figure 14*** illustrates a simple example of how risk and return of a portfolio comprising different weightings of two risks will combine where there is a positive correlation between them.

What ***Figure 14*** shows is that it is possible to benefit from holding risks which are somewhat less than ideal. By carefully choosing a portfolio of risks it is possible to improve risk without reducing return, or reduce risk without sacrificing return.

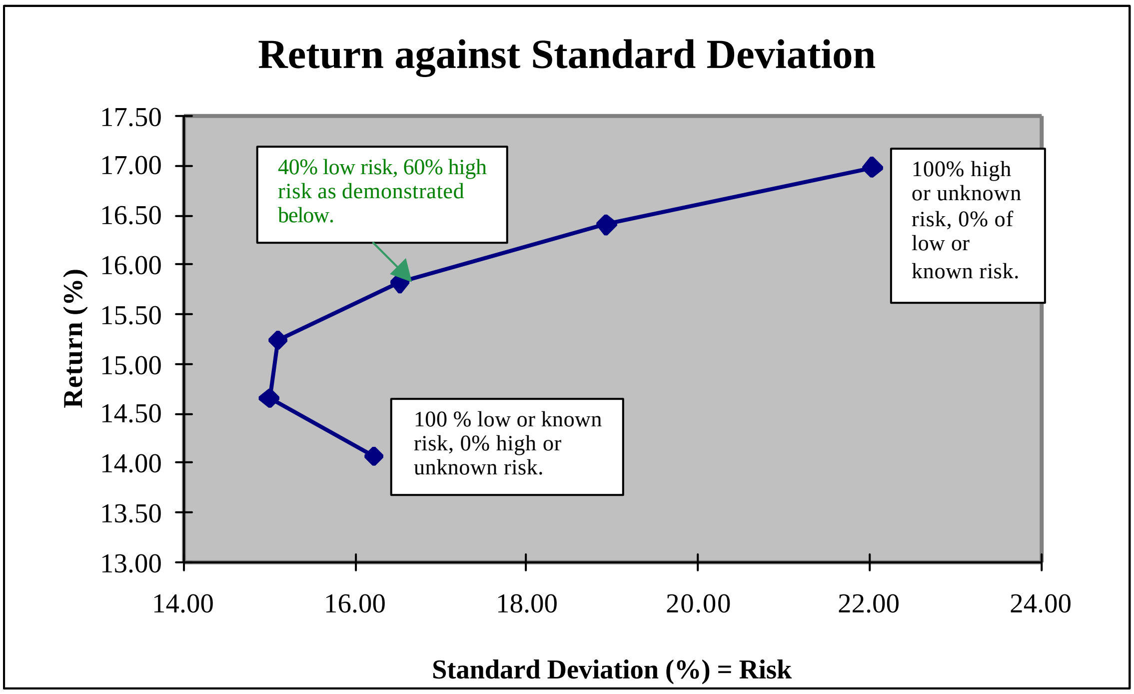

Figure 14. Illustration of return for a portfolio of 2 shares positively correlated.

Note: The above example is based on the estimated return of two shares (based on historic data) and an estimated correlation coefficient. The standard deviation for individual shares are based on differences between the market rate and risk free rate over a period of time – the figures used (22.04 and 16.23 for shares 1 and 2 respectively) are based on an actual case of two UK blue chip companies. Share 1 has an expected return of 14.06% and share 2 an expected return of 16.99%. The estimated correlation coefficient is 0.33. So, for example, for a holding of 40% share 1 (the ‘low’ risk) and 60% share 2 (the ‘high’ risk) the following may be calculated:

Expected return of portfolio = (0.6 x 16.99) + (0.4 x 14.06) = 15.82%

$S_p^2 = W_1^2 S_1^2 + W_2^2 S_2^2 + 2 W_1 W_2 S_1 S_2 Corr_{12}$

$S_p^2 = (0.6^2 \times 22.04^2) + (0.4^2\ 16.23^2) + (2 \times 0.6 \times 0.4 \times 22.04 \times 16.23 \times 0.33) = 273.6$

$S_p = 16.23\%$

Where S is the standard deviation of the portfolio of shares 1 and 2 and W is the weight of shares 1 and 2 invested in value terms.

An evolving opportunity set of portfolios.

For any insurer it is likely that the portfolio of risks held and the correlation coefficients of the risks will be constantly evolving. Unlike the holding of shares it is not often that we can choose which risks to insure or at what price to buy or sell. But this could be to our advantage. By building loyalty and trust with the client and assisting them to reduce their risk profile, poor risks will improve, and to rebalance the portfolio for the future it will again be feasible to choose further less than ideal opportunities.

Consider the 'efficient frontier' of ***Figure 15*** to be an ideal portfolio of risks to hold where the combination offers the maximum return per unit of risk or minimum risk per unit of expected return. It is unlikely that many risks with which we are presented will be on this frontier, but somewhere in the shaded area beneath it. It is possible however that over time the risk would reach the frontier. Returning to the German refinery, this has undoubtedly moved from A to B as safety equipment has become more effective and with an increasing focus on the human element. Also, although there has been some reduction in premium, return has increased due to the reduced loss ratio. Similarly, the South American hydro-electric plant moved closer towards the efficient frontier by a particular focus on training.

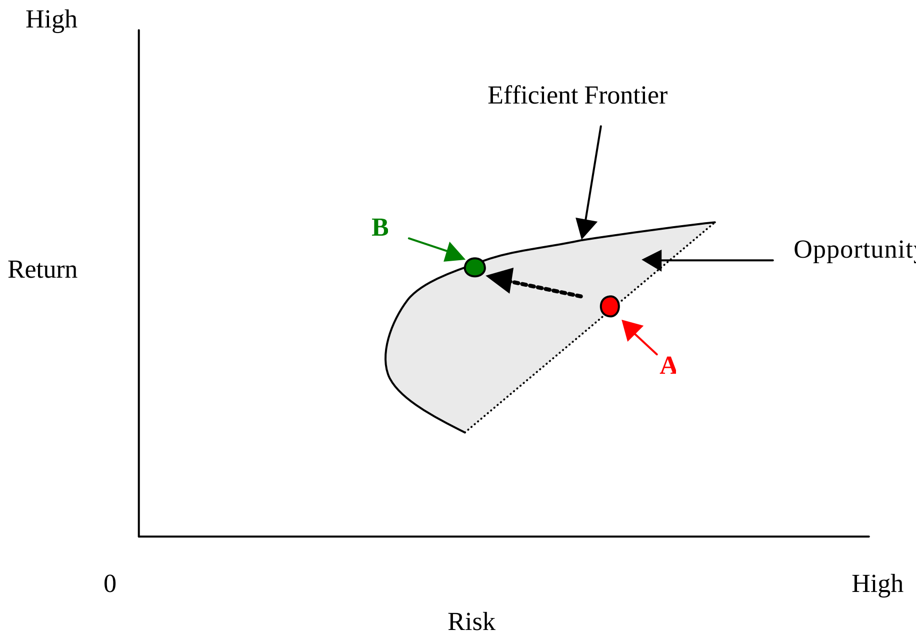

Figure 15. Improvement of risk within the 'Opportunity Set'

This model therefore provides further scope for risk identification and selection. Not all risks can be improved, and situations also arise where risks that were previously acceptable will revert, or perhaps give indication that they will revert, from a position on the efficient frontier to elsewhere within the opportunity set. Identification of positive or negative movement may be made by regular scanning of the risk map. In some circumstances it may be possible to take corrective or preventive action, but in others minimisation of insurers' exposure will also depend on identifying the point on the risk map when the risk deteriorates to a point where it is seen that it will become unacceptable.

7. CONCLUSIONS AND THE WAY AHEAD.

The scope of this paper has been necessarily broad – it has been shown that human factors are complex, and on a global basis cultural differences often require different solutions or degree of intervention when considering the relationship between equipment sophistication and human error.

Conclusions are presented as inter-related topics for further debate.

Formal risk assessment.

Formal risk assessment, such as Hazop and FMECA, has been shown to have a clear benefit in reducing risk in the particular industries in which they are traditionally applied. The use of these techniques may be readily transferred to industries where they are not normally applied, the outcome of the studies linking directly to the installation of enhanced safety equipment where necessary, whilst having a secondary influence on improving the human element as teams identify shortcomings.

Risk based inspection.

Statistics indicate a dramatic fall in U.K. power press incidents following the introduction of an enforceable inspection and testing regime. Obligations in the U.K. have now shifted to risk based inspection with the introduction of regulations such as PUWER (Provision and use of Work Equipment Regulations) and LOLER (Lifting Operations and Lifting Equipment Regulations) which focus both on safety equipment and human effects. These provide an excellent basis for adapting elsewhere, subject to consideration of cultural differences discussed in the paper.

Human factors checklist

As a means of identifying, monitoring and improving human factors in the workplace introduce a categorised checklist based on the job, the individual and the organisation. The following is a development of that proposed by the HSE (1999) to recognise possible cultural influences. Results may be either positive or negative or graded, for example on a 1 to 10 scale.

The job.

Have the following been addressed with regard to the job:

- Identification and analysis of critical tasks.
- Evaluation of employees' decision-making needs.
- Optimum balance between human and automatic systems.
- Provision of ultimate safety device.
- Ergonomic design of equipment and process information displays.
- Appropriate procedures and instructions, with consideration of literacy of operatives.
- Environmental considerations – noise, lighting, heat, access for maintenance etc.
- Provision of correct tools and equipment.
- Shift scheduling to minimise stress and health and safety effects.
- Effective communication, including considerations for shift hand over.
- Liaison between sections, contractors and OEM (original equipment manufacturer).

1. The individual

Have the following been addressed with regard to the individual:

- Job specifications considering skills, qualifications, aptitude, personality, intelligence, literacy and physique.
- Matching of skills and aptitudes to job requirements.
- Selection policies to select appropriate individuals.

- Implementation of effective training system.
- Monitoring of personal performance on safety critical issues.
- Counselling in support of ill health, stress or in conjunction with practical training.
- Recognition of the needs of the individual.

The organisation.

Have the following been addressed with regard to the organisation:

- Implementation of effective health and safety system.
- Promotion of a positive safety climate and culture.
- Visible health and safety leadership.
- Systems to set, monitor and improve standards.
- Appropriate supervision.
- Incident reporting, analysis and prevention.
- Appropriate structures throughout.
- Adequate staffing policy with suitable work patterns.
- Effective communication systems and practices throughout.
- Provision of appropriate employee benefit (e.g. basic/enhanced medical insurance, recognition of family, perks).
- Corporate governance (e.g. social responsibility, ethics, environmental consideration).
- Facilities for the retention of experience (corporate/industrial).

Intervention Matrix.

As a method for identifying where, and to what degree, intervention is required for the reduction of losses by attention to the human element, apply the following model (***figure 16)*** developed from the Behavioural Taxonomy (Jones, 1999) and the Organisational Development matrix (***figure 3***). As discussed in the text, when deciding on the level and degree of intervention, consideration of national and local culture is paramount – but the process need not be lengthy, the experience of the risk facilitator being the key to the decision process. The results of the human factor checklist in 3 above could contribute to the input.

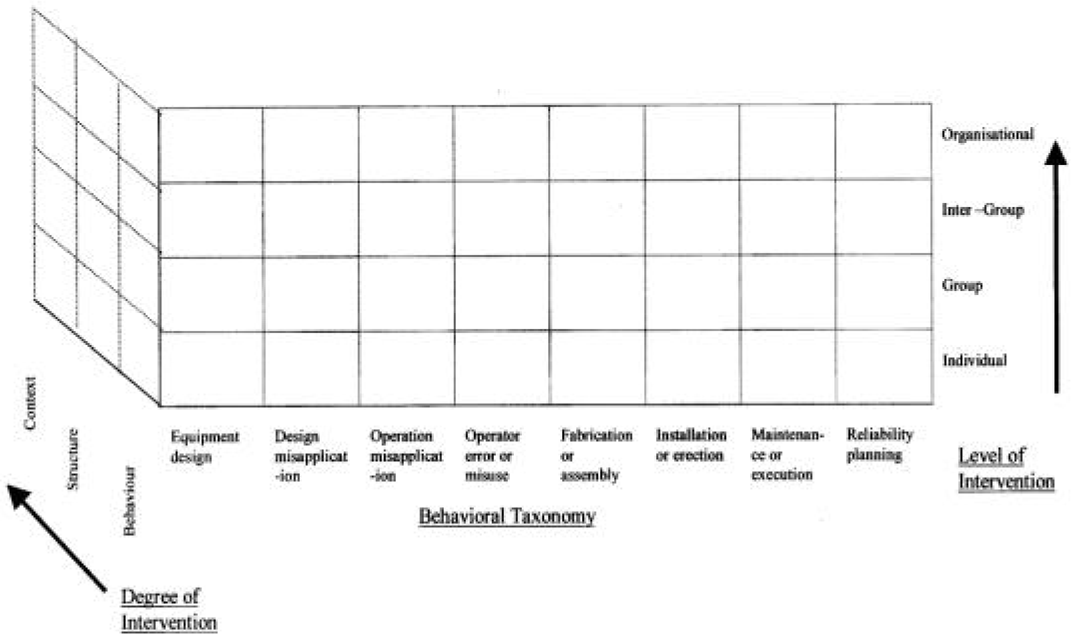

Figure 16. Intervention Matrix for the reduction of human error.

Risk mapping.

This paper has made some provisional suggestions on risk mapping, utilising the results of the resulting profile in portfolio theory. Use of this method will assist engineering insurers in determining their desired exposure. From an initial estimate of correlation coefficient and expected return it will be possible to adjust the risk profile, and estimate potential change (positive or negative), of specific cases following input of the results of the Intervention Matrix.

Further consideration is required in determining the constituents of the correlation coefficient. External elements of the risk map, for example industry, country, political and economic stability may be suitable components.

Further considerations of human factors in engineering risk management.

Case studies have suggested that the correlation between the sophistication of safety equipment and human error depend on complex issues surrounding individual cases. As engineering insurers we are in a privileged position in being able to assess the status of a risk first hand. The conclusions have suggested areas where this direct input may be enhanced, but the success will depend on appropriate intervention and the ability of the engineering facilitator to win the trust of the client. Good risk management is therefore closely aligned with trust.

Insurers' Underwriters and Engineers' skills may be further developed and risk minimised by closer attention to the human element throughout the life cycle of a risk. Often this may demand a more direct intervention, ensuring that sufficiently experienced personnel are available from as early as possible in the venture, through the operational phase to eventual decommissioning, or following a loss, when a shift in the risk profile may be occurring.

This intervention aligns closely with trust. Whilst, on the 4 dimensions of rejuvenation studied by Bartlett & Ghoshal (1995) as discussed in Section 6, the link between the underlying 'discipline' and the associated 'stretch' with which clients will inevitably be aspiring to maintain competitive advantage will be assessed, the closer presence will be providing the associated 'support'. 'Trust' is linked directly with this support, but for this to be maintained the 'rejuvenation' requires an openness to learning and willingness to commit. If these relationships can be developed and enhanced, this and the ongoing review of the risk map, will provide the sound basis for risk minimisation; a move towards the efficient frontier.

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