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Safety, health or the environment—which comes first?

F.K. Crawley [a,b,*], D. Ashton [b]

[a] Department of Chemical and Process Engineering, University of Strathclyde, Glasgow G1 1XJ, UK
[b] W.S. Atkins Oil and Gas, Clifton House, Clifton Place, Glasgow G3 7LD, UK

Abstract

This paper describes the development and application of two integrated models which can be used for assessing the life cycle risk (to life) and environmental impact of a number of possible concept options for new offshore oil and gas developments. The two models can also be used for ranking the designs in terms of lowest human risk and environmental impact. The paper also gives values/criteria for both risks to safety, health and the environment by which the total safety, health and environmental assessment/impact may be balanced as a whole. The paper illustrates the use of the models and shows that the pragmatic or cosmetic improvement to safety, health or the environment may not be advantageous to the overall safety, health and environmental objectives.

While the models were developed originally for offshore installations, the basic framework can be readily adapted for use on onshore petrochemical processes. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

The concept of the *safety* of employees goes back to the start of the Industrial Revolution in Britain [1a,b]. However, with the scale-up of plant sizes in the 1950s and 1960s, new *safety* concerns were recognised; it was not only the slips, trips, falls and similar events but also the process events. So was developed the concept of Safety and Loss Prevention [2]. By the 1960s it was recognised that there were other more insidious hazards associated with process plants. These were hazards which affected the *health* of the employee [3]. Finally, in the 1960s and 1970s there was a clear recognition that industry could also adversely affect

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[*] Corresponding author. Present address: Department of Chemical and Process Engineering, University of Strathclyde, Glasgow G1 1XJ, UK.
E-mail address: frank.crawley@strath.ac.uk (F.K. Crawley).

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the *environment*, not only locally, but globally. Now many companies use the acronym SHE to describe those activities not as separate units but as one entity.

The principal of SHE is now well recognised but there is the conundrum:

> "How do I select the inherently safer and more environmentally benign design for development when the definition at the concept stage is poor?"

Put another way:

> "Is it better to develop the concept which 'looks' best and then add on safety and environmental features during the design?"

To achieve the inherently safer and more environmentally benign design, the concepts under consideration must be assessed as early in the project as possible by the use of quantified risk assessment (QRA).

QRA has tended to be applied to *safety* (or the catastrophic effects) and various criteria have been developed in the UK [4a,b], whereby the benefits, costs and residual risks can be assessed in a meaningful manner. (To date, the chronic effects on *health* have not been subject to such rigor.) However, the safety benefits inherent in one concept MAY equally have an adverse effect on the environment [5] and conversely the perceived benefit to the environment may have an adverse effect on the safety of personnel. Such a dilemma was recognised by one company [6] following the Piper Alpha Disaster [7]. In this case a holistic approach to criteria was used; one was national strategic benefit, another was net risk gain/loss and yet another was environmental. However, there is still a real risk that the well-intentioned attempt to enhance one aspect of SHE may have an adverse effect on another if the whole spectrum of SHE is not examined as a totality. This is because there is still a tendency for the three elements of SHE to be treated independently [5] and, as a result, the potential benefits in one area and the adverse effects in another are not analysed together.

The inevitable conclusion is that the answer to the question posed in the title is "It depends on where your first loyalty lies, *safety, health or environment*". The reason is that there is no absolute means of comparing the two in a meaningful manner.

2. Evolution of the models

Offshore developments, particularly those involving several fields, have many variables which must be accounted for at the concept stage. This includes platform type (steel, concrete, subsea, fixed, floating, etc.), the size and throughput, the drilling strategy, the hydrocarbon transport strategy, etc. It is possible that there could be of the order of three or four high level concepts with several variations within each of these, which need to be analysed in a meaningful and consistent manner. Unfortunately, there is a limit to the number of concepts that can be subject to a meaningful and detailed technical and commercial assessment. The dilemma is therefore: "Is the design taken too far before it is found to be too risky or is it possible that a concept which could demonstrate ALARP (risks as low as is reasonably practicable) was rejected because the data was incomplete?" This dilemma was overcome through the development of the concept risk assessment (CRA) model [8].

This model enabled risk parameters, such as risk to life and temporary refuge (TR), to be estimated with acceptable accuracy at the very earliest stages of concept definition. (The TR is the place where the occupants of the platform would assemble and wait until the emergency was controlled or from where they may start to abandon the platform.) It should be noted that tolerability criteria for the temporary refuge impairment frequency (TRIF) has been given in the offshore safety case regulations [9] pertaining to UK continental shelf (UKCS) exploration and production activities.

The finer detail of the CRA model is not the basis of this paper. However, it must be recognised that with a significant number of concepts to be screened in the feasibility/concept stage of a project (typically about 30), time is very limited and decisions affecting the design selection frequently have to be made at short notice. With this in mind, it is often impracticable to subject more than a few concepts to a detailed assessment if the definition is poor and, if the definition is available, the assessment could take several man weeks for each concept.

The CRA model was developed on the premise that any piece of equipment can be characterised as a "*risk*" to life and the platform integrity and that the accuracy gained from a very detailed assessment could not be justified or supported by the level of definition available. The building block approach is based upon typical package breach frequencies (derived from numerous parts counts for North Sea platforms) and generic failure rate data from recognised sources [10a,b]. From this, it was possible to assess the leak spectrum per year and the ignited leak spectrum per year for each type of equipment and operating pressure. The equipment can therefore be defined as a fire size and frequency. An analysis of the error bands, which could result from this approach (called "pre-processed data"), shows that they are small. In reality this approach cannot assess the real risks as these will be affected by the culture of the operating company; however, the risks can be ranked in a meaningful manner. The risk to an employee then depends on, amongst other factors, whether the person is present, whether they can escape to the TR, whether TR integrity is threatened and, if so, whether personnel can escape from the platform and be rescued from the sea. The base risk derived from the sum of the equipment risks is then moderated by factors which reflect the design features of the installation. These include:

- The location and protection to escape routes.
- The design of the process modules for explosion overpressure minimisation and overpressure integrity.
- Fire mitigation supplied by fire protection, emergency shut down and de-pressuring and the emergency shut down design.

The TR impairment is moderated by factors which reflect the design features of the TR. These include:

- The location of the TR with respect to the main risk drivers of drilling.
- Production and the risers for fluid export.
- The design of the TR against the ingress of carbon monoxide from fires.
- The integrity of the TR under fire attack.

The escape impairment is moderated by the main factor:

- Escape craft integrity supplied by its design, location and ease of access from the TR.

The combination of events therefore examines first the initiating frequency. This in turn is modified by the ability of someone at or near the initiating event being able to reach the TR (not an immediate fatality). Having reached the TR the integrity is determined by the ability to control the initiating event and also the ability of the TR to supply protection to those inside (not a TR fatality). If evacuation is necessary, the design of and location of the escape craft is important (not an evacuation fatality). Success is the ability to escape the initial event, survive in the TR for at least 2 h and then escape to the sea and be rescued without injury. The model therefore examines three phases of the emergency, as it develops, and assesses the beneficial design features in turn. With knowledge of the personnel distribution the results of the analysis are in three areas:

- Immediate fatalities (those at or near the event).
- TR fatalities (those who died in the TR and could not be evacuated).
- Escape and rescue fatalities.

The results can also be given as individual risk per annum (IRPA), TRIF and potential loss of life (PLL).

It should also be noted that for an off shore oil and gas installation there are a number of specific risks not found in on shore process plants. There is the transport from the shore to the installation, the risk associated with shipping impact, the risks from structural collapse, the effects of weather and even seismic loading on the support structure and finally there is the risk from the production and drilling while asleep in the accommodation. All these factors are in addition to the normal “risks” during operations.

The CRA model, which has been calibrated and validated against a number of detailed installation QRAs, allows various options to be tested to determine the effects of changes in layout, location of structural fire protection, location of TR and other design features [11]. This allows fine-tuning of the design with the assurance that ALARP can be demonstrated. This is important, as there is then a clear demonstration to the regulator that the design was based on risk reduction/optimisation and there is a clear record of the decisions made and why they were made. That is, there is a clear record of management for safety in the design.

Increasingly the environmental impact of an installation is being recognised. Having the ability to rapidly compare the environmental impact of a range of options allows informed decisions to be made. The next model developed was the environmental impact model. Its aim is to determine the amount of each of the major pollutants (CO_2, NO_x, SO_x, VOCs and chemicals) produced from the range of options. Before any assessment can be carried out, it is first necessary to carry out an environmental impact identification (ENVID) study, against a set of guidewords. This identifies the major contributors for the specific options being considered. Generally, these consist of:

- Pollutants produced during power generation.
- Accidental release of hydrocarbon gas and liquid.
- Fugitive emission to atmosphere.
- Constant releases of hydrocarbons (e.g. oil in water).
- Emissions during fabrication and abandonment.

At the concept stage the process flow diagram should give sufficient data to identify the main power consumers such as gas compressors, oil pumps, water injection pumps and the drilling unit. Even with this limited data on the process flows, it is possible to use standard physical equations and to reduce the power draws for these pieces of equipment to a set of "pre-processed" constants with a set of "pre-processed" variables to estimate the power required for the main consumers. Certain features can be simplified into a set of constants. These include:

- The universal gas constant.
- The density of sea water/oil.
- The suction temperature for gas compressors.
- The ratio of compressibility: molecular weight of the gas.
- The ratio of specific heats at constant pressure and volume.

The efficiency of a pump or compressor has to be reduced to a realistic value and cannot be assessed accurately until the designer/manufacturer is chosen. To the total load, an additional 30% is included to represent the second order power consumers such as lighting, heating, ventilation and minor process and utility pumps. (This value has been shown to be fairly constant across a variety of designs.)

The conversion of power to carbon dioxide equivalent is readily assessed for typical fuels and prime movers (diesel/gas turbine) such that for a given prime mover and fuel a carbon dioxide load per day can be assessed as a "pre-processed" value per megawatt. In addition, there is sufficient test bed data to convert power demand to an equivalence of NO_x and SO_x for different fuels and prime movers. In effect given a simple set of flows, pressures, fluid types and prime movers they can be quickly combined to determine the production rates of the following pollutants:

- CO_2 (t/unit time);
- SO_x (t/unit time);
- NO_x (t/unit time);
- particulates (t/unit time).

Likewise from the process risk model (CRA), which inherently contains leak profiles (rates and frequencies) and duration and a knowledge of the drains philosophy, it is possible to assess total accidental hydrocarbon losses (VOCs and oil). Fugitive emissions from each flange, valve, instrument tapping, etc. can also be assessed [11] from typical equipment counts for the major process vessels combined with detailed historical survey results for each type of fitting.

In this way each piece of equipment can be given an "environmental impact" value.

There are other losses that must be taken into account such as the losses of oil in produced water, losses of oil on drill cuttings, losses of gasses into flares and the resultant production of carbon dioxide. Offshore, these can be dealt with in different ways—the losses can either be accepted if they are within allowable limits, or the pollutant can be recovered by pumping (compressing) the materials into a "less polluting" location such as a reservoir. One of the major strengths of the model is its ability to compare the environmental impact of these different disposal options. This strategy involves balancing the carbon dioxide against VOCs/oil losses.

An example that is often investigated is the transport of oil, which can either be by pipeline or by tanker. Each option has a different set of impacts, which can be assessed from the rule sets. Possibly the most important feature of tanker transport is the higher VOC losses while filling offshore and breathage during transport while full or in ballast. These must be balanced against not only the power requirements during pumping, but also the energy required during fabrication and installation of the pipeline.

Both the safety and environmental impact modules have been tested and verified. The safety models have been tested against detailed QRAs which took possibly a hundred times as long [11] and the environmental model has been tested against platform data and environmental impact assessments. The models cannot stop at the operation phase as it is often required to assess the life cycle safety and environmental impacts. Safety is relatively simple as there should be a known set of hours for construction and abandonment. Fabrication also produces CO_2, NO_x, SO_x and particulates when ore is being mined, when it is being transported to the dock on the sea, back on the land and in the steel works. The same pollutants are produced when plate is rolled, welds are made and when the item is taken offshore. All of these can be assessed within the model. During abandonment, vessels have to sail offshore and uplift sections of the platform for final recycle on shore. This also produces pollutants which can be added into the environmental impact through the model. Once again there is a linkage to the mode of transport (land, road, rail, sea, the size of the bulk carrier) as well as the distance travelled, the type of fuel used (high/low sulphur diesel) and the quality of the prime mover, if it has, or has not, been fitted with pollution reduction features.

The two models therefore can produce both risks and pollutants collectively on a life cycle basis or during the three phases:

- fabrication and installation,
- operation,
- de-commissioning and abandonment.

It should be noted that the safety and environmental issues are dominated by the operational phase of the project.

The models are therefore:

- simple,
- quick to use,
- flexible,
- modelled on real installations,
- verified against more detailed time-consuming studies.

More importantly, they do allow an inherently better design to be developed as they can be applied early, before design changes become costly. An iterative process ensures that both safety and environmental issues influence the design.

The simplicity comes from the characterisation of each piece of equipment as a series of “risks” or “pollutant loads” which require minimal manipulation other than addition. The flexibility comes from the characterisation of each mitigation which is then summed and used to condition the base risk or load, the effects of each can then be tested to find the optimum. The reality is drawn from extensive databases for failure rates and the characteristics of major process equipment items from detailed quantitative assessments. The two models can be run in parallel to assess the impact of a design change and to test the sensitivity of a safety change on the environmental impact and an environmental change on safety. The two models can therefore be used constructively to reach the most acceptable values of ALARP and best practicable environmental option (BPEO). However, what happens when a beneficial change to one has an adverse change on the other?

3. What is ALARP and what is BPEO?

The criteria for demonstrating and reconciling ALARP and BPEO are not clear when the development of any offshore installation has the potential for impact on an international scale. Even before the installation is installed and commissioned, there are likely to be many potential sources of pollution and risk to personnel associated with the construction phase outside the host country. Safety standards and environmental standards are not uniform throughout the world. The two are subject to different regulations, standards and perceptions in different countries. With regard to personnel risk, this can be demonstrated by statistics taken from the HSE in the UK [12] which shows that even within Europe there are considerable variations in safety standards. Tables 1 and 2 show this clearly.

Likewise, the level of pollutants will vary and depend on the adoption or not of cleaner processing. In simple terms there are several routes to producing electricity; the nature of the pollution will change but is it less polluting?

- Nuclear power produces nuclear waste.
- Most hydroelectric power produces visual pollution and relies upon other (off-peak) power sources for regeneration of pumped storage.
- Fossil fuels produce carbon dioxide.

Table 1
All industry risks for selected member states of EU and USA [12]

Rank order	Nation	All industry risks per 10^5 employee years
1	GB	1.2
2	Anonymous	1.7
5	USA	3.2
10	EU AVE	3.9
15	Anonymous	5.5
16	Anonymous	5.7

Table 2
Construction risk for selected member states of EU [12]

Nation	Construction risk per 10^5 employee years
UK	6.9
Anonymous	7.9
Anonymous	17.6
Anonymous	19.3

Factors which can cloud the environmental issue include:

- Some of the pollutants may be given a higher or lower weighting such that environmental criteria may be subjective and not real.
- Evaluation of environmental impact may be complicated where raw materials are extracted, processed, fabricated and transported involving different countries at different stages.

The global pollution will be influenced by the transport routes and the different operating standards of the many different nations with different needs and priorities. One simple example of base line pollution is taken from the British Medical Journal [13] which shows the way the concentration varies around a pollution source and eventually reaches a background level. The isopleths are quoted for 1985 and of course will be different for the year 2001. This shows that while the effects on the environment and health may be local, global averaging can be used to assess the effects on health of those more local to the source of the release.

It is concluded that national standards, costs, convenience and speed of delivery may influence ALARP and BPEO. They also have different meanings in different member states of the European Union. In other words the ALARP and BPEO are variables and are not fixed.

4. Unifying “SHE” criteria

The common factor which unites the project in consideration of safety and the environment is finance. The project is justified on a rate of return and therefore it is logical to reduce the safety, health and environmental criteria to a set of financial values. In this way if the total cost of capital, safety, health and environment is excessive, the financial criteria will not be met and the project will not be sanctioned. There is a trade-off between the four costs, which suggests that if the risk to life is too high, it might be better to reduce that cost (risk) by increasing passive safety features but also the capital costs. The values that should be ascribed to safety and the environment are therefore the values that a company would consider worth spending to prevent that “risk”. These values can derive by examining the costs to society as a whole and then adding a company-specific humanitarian factor.

In Europe there is a general acceptance that the catastrophic or fatal accidents are the true measure of safety. To a degree this is correct, as fatality has a clear and unambiguous definition and may have to be matched or bettered [9] by some industrial or national criteria, such as offshore. (As this paper was written in the United Kingdom the Pound Sterling will be used as the unit of currency.) In Britain the courts are beginning to award punitive damages for “loss of quality of life”; yet the value of a statistical life [14] was valued at £902,000 in 1998. The compensation awarded by courts in the UK for loss of quality of life and following litigation may be significantly higher, perhaps by a factor of 2 or more. The value that society would be required to bear to prevent a loss of one life is therefore higher than the “statistical cost of one life”. Is this value relevant everywhere in the world?

Global warming is probably occurring. As yet it is not totally clear if it is only due to “greenhouse gases” or if it is due to a number of variables, some of which might not yet have been identified. The approach to taxes on carbon dioxide vary within companies [15a,b]

Table 3
Additional deaths in London due to SMOGs [17]

Deaths	Date
4700	December 1952
300–800	December 1957
340–700	December 1962
100–180	December 1991

and between member states of Europe [16]. In Britain, carbon dioxide is taxed at about £5 per tonne but can be as low as £1 after allowances are set against employment taxes. If there is not uniformity on an international basis, the environmental cost of the unit will vary depending on where it is produced. BPEO may therefore be a perception and not a reality as already indicated.

Finally, it is necessary to assess the chronic health aspects of pollutants and the cost to the nation in the form of demands on medical resources, poor health itself, and the impact of loss of productivity and ultimately of premature deaths. Table 3 shows four fatal SMOG pollution events in London alone.

The same reference gives some insight into the impact of pollutants on health: "... there is evidence that pollution can affect the frequency and severity of (asthma) attacks in those who suffer form asthma ..."; it is not believed to be causative. It also states that there is uncertainty as to whether pollution related death is directly caused or rather precipitated in those where it may have occurred in the near future, that is, there must be a pre-existing cardio-respiratory disease. Ref. [18] uses the term "deaths brought forward". Sulphur dioxide does not only lead to death due to bronchitis, pneumonia and lung diseases but it can severely damage health through asthma, allergic sensitisation and eye damage; it can also produce congenital defects [13]. Perhaps equally important from an economic standpoint is the increase in lost working days for those who may not be recorded as medical cases but who feel unable to work.

The picture is complicated by the debate on the parameter for particulates. At present it is PM_{10} (10 μm), but others argue it is total soot and some others it is $PM_{2.5}$ or even PM_1. There is justification for believing it is the smaller particulates which cause the most damage. The question is "Are we measuring the correct parameter?"

The quantification of the effects of air pollutants [18] gives data whereby it is possible to quantify the benefits of reducing air pollution. However, it is necessary to examine three conditions:

- local (say within 10 km);
- regional (say within 1000 km);
- global.

The local pollution exists close to the polluter but regional pollution may spread further [13]. Ultimately, the dispersion reaches a global threshold. The concentration of CO_2 trends, generally, upward, whilst for SO_2 the trend is downward. On the other hand, the concentrations of PM_{10} and NO_2 is generally constant. In 1 year Britain produces 250,000 t of particulates [19] of which 20% comes from diesel engines and 2,200,000 t of NO_2 of which

Table 4
Cost of pollutants [18] in hospitalisation/health impairment

Pollutant	Cost per tonne (£)
SO_2	1.5
NO_2	1.5
Particulates	2.5
Ozone	2.0

20% comes from diesel engines and 29% from petrol engines [20]. Clearly, the dominant contributions come from an area outwith the control of any one industry.

For Britain the quoted annual deaths brought forward are 15,800, and the additional hospital admissions over and above this are 23,200 [18]. Whilst the adverse impact of pollution in the form of hospital admissions can be assessed in terms of cost, the overall financial impact of precipitated deaths could be misrepresented if no account is taken of a reduction in costly medical care. The data quoted in [18] allows an assessment of the true cost to society. The following is an assessment of the cost of hospital care and also the hidden cost of impaired health for those not admitted to hospital and lost productivity through absenteeism.

Unfortunately, it is not possible to ascribe absolute values to the cost of damage to the fabric of buildings and the repair/replacement costs. The values in Table 4 have been inflated in order to take this into account.

In a similar manner the cost of carcinogens can be assessed. From [18] it is possible to assess the cost of releases of benzene (in a similar manner to Table 4). This is £400 per tonne when a humanitarian factor is added. Given this as an assessment point it should be possible to ratio this value for other carcinogens through the individual maximum exposure levels.

In the case of the oil industry, there is a cost for oil as a pollutant which is significantly higher than its value as a fuel. The cost of the discharge is a function of among other things its density, volatility, chemical composition and the location of the leak. The costs of clean-up of pollution can be assessed from databases or insurance costs [21]. For the lighter crude oils produced in the UK and Europe, the pollutant value is about £2000 per tonne. The majority of the costs are associated with the "clean-up" so the heavier oils will cost more. Further, losses near sensitive areas such as fishing grounds will incur an additional cost. The final remedial cost of spilt heavy oil can rise to over £20,000 per tonne and if there is litigation it could rise by an additional order of magnitude. If the oil is sufficiently dispersed at a concentration of about 10–20 ppm (w/w), there is no clear evidence of damage to flora and fauna in the sea. The same problem arises with the release of process chemicals, already discussed. In some cases the effects can be identified locally, but the far-reaching effects of the diluted pollutant is less clear. For some of the more toxic chemical's some companies have self-imposed penalties of the order of one million pounds per tonne [22].

It is therefore apparent that safety criteria are comparatively well established whereas health and environmental criteria have much more uncertainty and are more pragmatic. Before any optimised solution can be arrived at, the various criteria must be assessed in a clear and measurable way such that one criterion can be fairly balanced against the

Table 5
Value of risks and pollutants or notional price worth spending to reduce risks or pollutants

Element	Value (£)
1 life	5000000[a]
1 t of benzene	400[b]
1 t of oil	5000[c]
1 t CO_2	2–10[a]
1 t of NO_2	3.0[d]
1 t SO_2	3.0[d]
1 t of particulates	5.0[d]
1 t of ozone	4.0[d]
1 t of VOC (CO_2 equivalent)	3–20

[a] Country dependant.

[b] Can be used as a reference for other carcinogens.

[c] Location dependant.

[d] Can be used as references for other health risks.

other. This will require convergence of the safety, health and environmental lobbies, both nationally and internationally, and a clear understanding of the impacts and interaction of one on the other. At the end of the day it is the company shareholders that must decide. Are they satisfied with profit at any cost or are the perceived risks to life and the environment a significant factor? Do they want lower risks and a lower dividend, and if the drive for the ethical high ground becomes excessive, can that company trade and cover its costs? The public will in the end dictate the price of the product.

For most offshore developments, it would be expected that project and national safety and environmental criteria or goals would be set and striven towards. The use of the two models allows those development options which are inherently safer and environmentally responsible to be identified. However, there is a high likelihood that one design option may score highly from a safety standpoint but suffer from adverse environmental impact. The optimal option can now be assessed by weighing up the costs, benefits and dis-benefits of all of the design options in a consistent manner using the values in Table 5 with an appropriate multiplier. In this way, safety and environmental issues can be given equal weighting with less scope for bias or subjective and inconsistent assessment.

The safety costs are the loss of life plus the PLL from carcinomas. The health costs are those associated with hospitalisation and the deaths brought forward and loss of productivity. The environmental costs are those associated with the pollutant and its effect on society, global warming, algae blooms or fabric damage. Each has a value which can then be put into the overall project costs. Should a company feel that it wishes to have a higher safety, health or environment profile, the values given can be raised (but *not* reduced).

5. Example

As a means to illustrate the significance of this analysis and the title of this paper, the models have been run in parallel and the result derived. One example which is worth discussion is that of the abandonment of the Brent spar offshore storage facility. The original

Table 6
Weight of pollutant producing equivalent steel in spar from ore

Pollutant	Tonnes
CO_2	60000
SO_2	100
NO_2	600

costs of dumping in deep water was of the order of 19 million pounds; the final costs rose by about an additional 40 million pounds [23]. This reference also notes the production of benzene (a known carcinogen) and significantly more man hours used in recycling spar. This would increase the human risk but it would be less than one statistical life. The energy consumed in the safety and environmental controls was equivalent to about 60,000 t of carbon dioxide and some hundreds of tonnes of nitrogen and sulphur oxides. These values should be compared with Table 6 which gives the pollution produced by making the quay from raw materials.

In reality the oil residues were only a few hundred tonnes and if the dumping option was not acceptable, the BPEO may have been to cut the spar into sections and then to re-cycle the sections through a steel works with a minimum of cleaning so as to produce a quay for reconstituted steel.

Using the data in Table 7 the true social and environmental costs were as follows:

- Option 1: dump
  (a) 500 t residual oil: £21,500,000;
  (b) 5000 t residual oil: £44,500,000.
- Option 2: re-cycle to a new quay
  (a) with aborted abandonment: £64,000,000;
  (b) without aborted abandonment: £44,000,000.

In simple terms the method of abandonment adopted produced almost as much pollutant as the original construction and it cost significantly more. Taken all together the final abandonment of Brent spar by recycling the steel into a quay was:

- cost negative,
- risk negative,
- pollution neutral,

and did not satisfy the principles of ALARP and BPEO.

Table 7
Human risk and environmental costs for three design options

Option	Cost (£ million)
Subsea	3.7
Jacket	9.1
FPSO	9.1

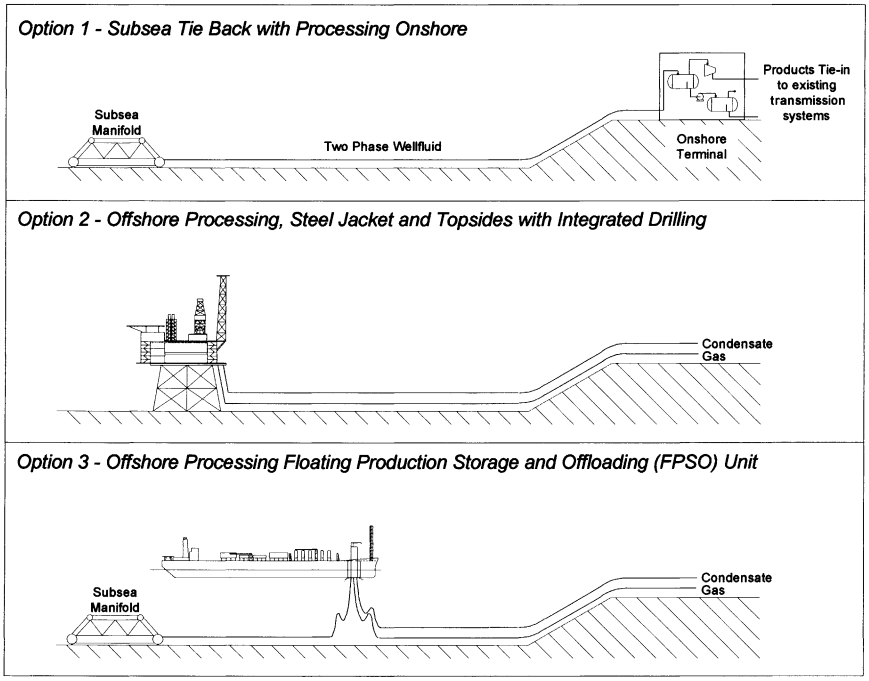

Fig. 1. Diagram of options considered within case study.

6. Case study

Indications of the variety of design concepts that can be considered are shown in Fig. 1. As space does not permit a full detailed example to be presented here, only the life cycle CO_2 emissions predicted by the model and the PLL for these three options are presented in Figs. 2 and 3. Full listings of NO_x, SO_x, particulates, routine releases and potential accidental losses as well as other risk measures such as individual risk and TRIF are also available broken down by operational phase.

For each option the production phase is the most significant contributor to CO_2 emissions and PLL, due to the length of this phase. The long subsea tieback has a lower contribution during this phase as there is no offshore accommodation that requires servicing. The integrated platform has the highest contribution during construction due to the amount of steel and energy required for fabrication. In this example, the FPSO is assumed to be a conversion from a tanker rather than a new build, hence the construction emissions and risks are those associated with fabrication and installation of a new topsides only. It is seen that the integrated drilling facilities lead to some benefit during the drilling and workover phases, as there is no requirement for servicing the accommodation on a third party drilling rig or any mobilisation requirements. The FPSO option has a higher risk during the production phase, as although the individual risks for the FPSO and integrated platform are similar, additional personnel are required to maintain the marine facilities of the converted tanker.

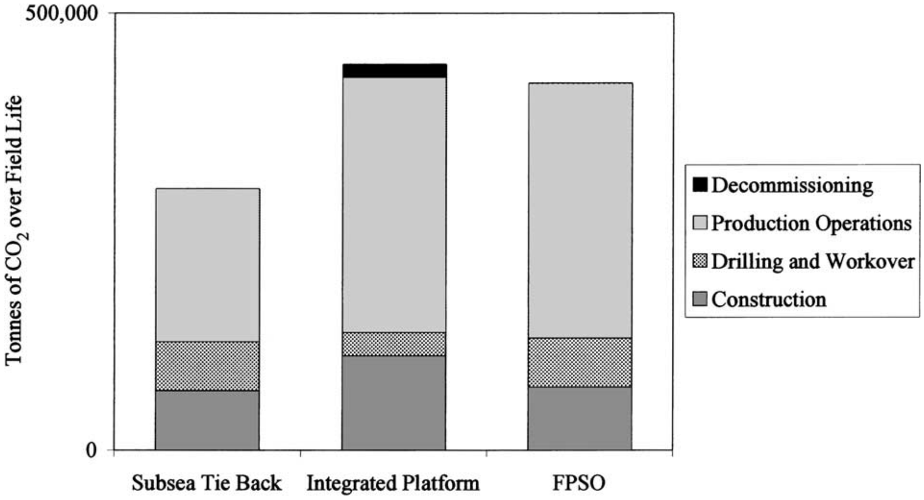

Fig. 2. Life cycle CO_2 production.

The final issue raised here is that of decommissioning. While the onshore facility can be readily decommissioned and the FPSO can be re-used, the integrated platform must be returned to shore for dismantling and recycling, which is an energy intensive activity.

Once again reverting to Table 5 it is possible to put a value to the human risk and to the environmental impact.

It will be noted that the balance of costs for the jacket and the FPSO options are the same, the lower environmental costs off setting the slightly higher human risks. The question now is which should be chosen?

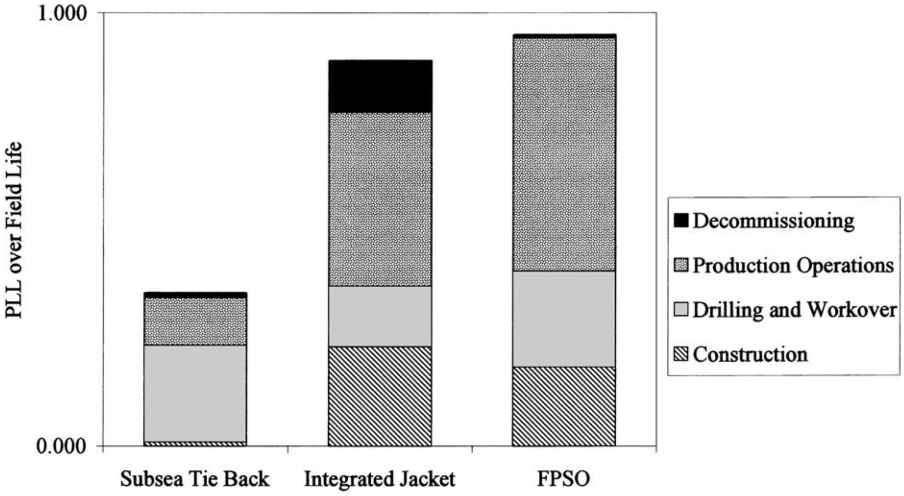

Fig. 3. Life cycle PLL.

These options have not been costed accurately but the rank order is: subsea tieback:FPSO: integrated jacket.

The subsea tieback can only operate within about 25–50 km of the shore due to the high-pressure drop of two-phase flow. If the development was close to the shore this would be the first option. If the development was over 50 km from the shore, the choice would now be between the jacket and the FPSO. The summed cost of capital, human risk and environmental impact favour the FPSO.

Efforts should still be made to reduce the SHE impact for the FPSO but the scope will be somewhat limited.

The power of the model is thus to identify the major issues at the very earliest stages of facility development. Sensible design solutions can then be identified to allow fine-tuning of the design at the concept stage. This process then allows a solid demonstration that the BPEO principles have been applied.

7. Future work

The work to date has focused on the off shore issues. However, the issues of biological and chemical oxygen demand as well as the cost of nitrate and phosphate run off from sites can be assessed from the remedial cost with a humanitarian factor. There are other factors which can be added by the rule of “ratio and proportion” once the key fixed points are assessed. The groundwork has been established and the research should not take long to complete.

The “pre-processing” approach can equally be applied to any other on shore processes. The initial leak spectrum can be assessed in a similar manner to that already described. Factors can then be ascribed for design features, which describe the effects, be they fire, explosion or toxins. The mitigating design features can also be described by a set of factors which describe the plant features. One factor would describe those features which might increase the potential for/of a vapour cloud explosion and another might describe the isolation standards and the leak duration. With a simplification to the dispersion effects it would also be possible to assess the toxic risks. In this manner the IRPA and also the total PLL for employees and the risk to the public could be assessed.

8. Conclusions

Risk and environmental models have been developed which allow the optimisation of the design of offshore oil and gas installations.

The capability has been developed to convert safety, health and environmental risks into financial terms, which allows the total cost impact of a development to be estimated.

There are significant differences in safety standards and the approach to pollutants between the member states of the EU.

The major contribution to the environmental impact of an offshore installation is the operation phase and not the construction and abandonment phases.

The tendency to treat safety and environmental issues in isolation has resulted in sub-optimal designs.

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