HERIOT WATT UNIVERSITY

DELPHI ANALYSIS OF PROCESS INTENSIFICATION

All students on the FLAME MSc course at Heriot-Watt University, Edinburgh, study a module called 'Technology Futures', in which methodologies for predicting future trends in technological developments are explored. As FLAME is an energy course, most of the activities are energy-related, and Foresight-type projects are undertaken as part of the module. This report is the outcome of one such project, carried out by three students who had earlier studied process intensification.

The normal implementation of a Delphi analysis, used in this project, involves two or three 'rounds' of consultation with experts. Time precluded more than one round in this instance, but useful feedback was obtained from a wide range of companies and other organisations, (including many PIN members). The data received has been comprehensively analysed and are given below.

I and the authors, Dimitris Nikoleris, Rosa Arias and Mark O' Connor, hope that you find the report of interest, and thank the contributors for completing the questionnaires.

David Reay,
Module tutor,
21 October 2002.

FLAME
Flexible Learning Advanced Masters in Energy

Heriot-Watt University

Department of Mechanical and Chemical Engineering

MSc in Energy

Technology Futures Assignment

Title: ''Initial Delphi study on Process Intensification Technologies''

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Abstract

The paper is based on the findings of the initial round of a Delphi study conducted that focused on identifying the potential range of opportunities for Process Intensification technologies. A questionnaire was formulated and sent to a group of experts which were selectively chosen. The participants in the study were higher academic professionals and members of a variety of industrial sectors in the UK and Ireland.

An analytical review of the likely future scenarios in seven key areas –energy use, safety, plant size reduction, specific PI technologies, organisations' response and barriers to PI development- is outlined and commented. An additional strategic planning critique, based on the outcome of the respondents' views on the subject, is also included.

The study succeeded in identifying the potential future trends in the key areas of interest and recognised the merits of the principle barriers that obstruct the wide spread of PI technologies.

Contents

1. Summary of Results Achieved

A Delphi study was conducted over a period of three months on the subject of Process Intensification technologies and the identification of their potential future business opportunities. The study has been based on a qualitative research procedure that comprised of a questionnaire (See Appendix I), sent to a pre-selected group of experts in order to elicit and develop individual responses to the problems posed.

Out of a total of 206 experts contacted, 42 replies were received (20.4%), which could be claimed as a successful effort for such a task considering the time margins available. The range of organisations involved in the study included a number of different industrial sectors and academia (see table 1, Appendix II). An encouraging starting point for the study was the fact that 88% of the respondents are aware of PI concept (See Fig. 1, Appendix II). The results achieved from the study highlight a positive outlook for the future development of Process Intensification technology. The importance and need for PI is recognised as one of many tools needed to improve the way we live and work in order to combat the global environmental problem of climate change. Although some favourable prospects identified this technology as a realistic and viable option for increasing energy efficiency, the main barrier that obstructs its wider implementation is still conservatism. Perhaps PI is not mature enough to conquer the global role that the authors of this report believe it favours. All new technologies develop under competition. The Government must provide financial support for R&D in order to fully exploit PI's potential for energy efficiency, in combination with renewable energy sources. Under these conditions, both technologies will be able to compete with the conventional status quo and form the transition path to sustainability.

2. Introduction

Climate change and global warming is a reality that faces us all and will affect us all even more in the future. The overriding concern, however, is the impact of our activities on global warming, and the consequences of rises in temperature. Reducing CO_2 emissions by energy consumption reduction, improving energy efficiency in energy consuming products and processes and developing renewable energy supplies to replace the conventional fossil-fuelled based power stations are all seen to be necessary to counter this warming. The development of new process routes that consume less energy and lessen the amounts of gaseous or other effluents, comes from concern about climate change. There is a need for a cultural change to both mechanical chemical engineers and the role of the physicist in this task –e.g. co-operation/ technology transfer. Thus, energy efficiency is perhaps the major area that can be addressed by industry, and others, in helping to minimise global warming effects and possibly have the role of a lever in reducing the energy demand.

Process Intensification may be defined as "any engineering development that leads to a substantially smaller, cleaner, safer and more energy efficient technology". Growing global competition will necessitate major changes in the way plants are designed if we are to tackle the challenges ahead to combat climate change. Process Intensification brings many benefits to current design standards such as:

- Capital investment reduction
- Ever greater emphasis on improved safety
- Energy use reduction
- Better environmental performance
- Plant volume reduction
- Raw material cost reduction
- Increased process flexibility & inventory reduction

Better environmental performance, more efficient in the use of energy, increased safety and size reduction are characteristics necessary to tackle climate change, and as company competitiveness can benefit with its uptake, the concept of PI is now on the brink of becoming a widespread technology. There are psychological benefits in having very small process plant, as well as political, aesthetic and broader environmental and safety benefits. Such a trend may also be regarded as a good "public relations" exercise for a number of different sectors in industry. The productivity and flexibility of PI technologies, together with its potential to combine different disciplines, makes it an ideal ambassador for technology transfer across a wide range of industries.

3. The Delphi Method

To develop a better understanding of the potential of a technology, it is useful to forecast what the prospects are for this technology being incorporated into daily routines across industry. Delphi is a widely used forecasting technique which consists of an exercise by group communication among a panel of geographically dispersed experts. It facilitates the formation of a group judgement without permitting a certain social interactive behaviour, as happens during a normal group discussion. It is essentially a method for achieving a structured anonymous interaction between carefully selected experts by means of a questionnaire with controlled feedback. The objective for the type of forecast where Delphi is commonly used is for creative exploration of ideas and suitable information for decision making, to identify factors influencing the future state of process intensification's development and to develop the time scale of differing aspects of the technology's realised potential. The views of the experts will give a good indication of what state the technology is in, the prospects and directions for its further development and its potential role in tackling climate change.

3.1 Basis of the Delphi Method

The Delphi method is based on a qualitative research procedure that comprises of a series of questionnaires, sent to pre-selected group of experts, designed to elicit and develop individual responses to the problems posed and to enable experts to refine their views as the group's work progresses in accordance with the assigned task. Controlled feedback and statistical response characterise Delphi. The outcome of a Delphi sequence is nothing but opinion and thus the results are only as valid as the opinions of the experts. Shortcomings do exist with the Delphi study and this needs to be remembered in the final decision making process based on the outcome of the Delphi study.

Concerns include:

- Discounting the future; one may have tendency to discount future events.
- Simplification urge; experts tend to judge future events in isolation from other developments.
- Illusory expertise; experts may be poor forecasters.
- Format Bias; format of questionnaire may be unsuitable to some potential societal participants.
- Manipulation of Delphi; responses can be altered by the monitors so as to achieve desired results.

3.2 Framework of Method

This study focused on anticipating the future trends of Process Intensification. The study made a special effort to analyse how experts prioritised the characteristics of PI, it considered specific areas of PI unit operations and their potential and also focused on how companies reacted to various market factors together with an assessment of whether it was considered that using PI can enhance company reactions to these market factors.

In this study, a team was formed to undertake and monitor the Delphi on the subject area of PI. Selection of experts followed and hence focus on developing the Delphi questionnaire took place. Testing of the questionnaire for proper and relevant wording took place for two rounds prior to transmission of the questionnaire to 206 experts geographically spread involving members of the industry and the academia. As it took a substantial time to receive back the completed questionnaires, it was decided to focus on one round only and statistically analyse these comprehensively prior to preparing this report.

4. Classification of Analysis

Our analysis was focused on seven specific areas whereby results of various questions could be applied to.

The areas of focus include:

- Energy use.
- Safety.
- Plant size reduction.
- Environmental improvement.
- Specific PI technologies.
- Organisation's response.
- Barriers to PI development.

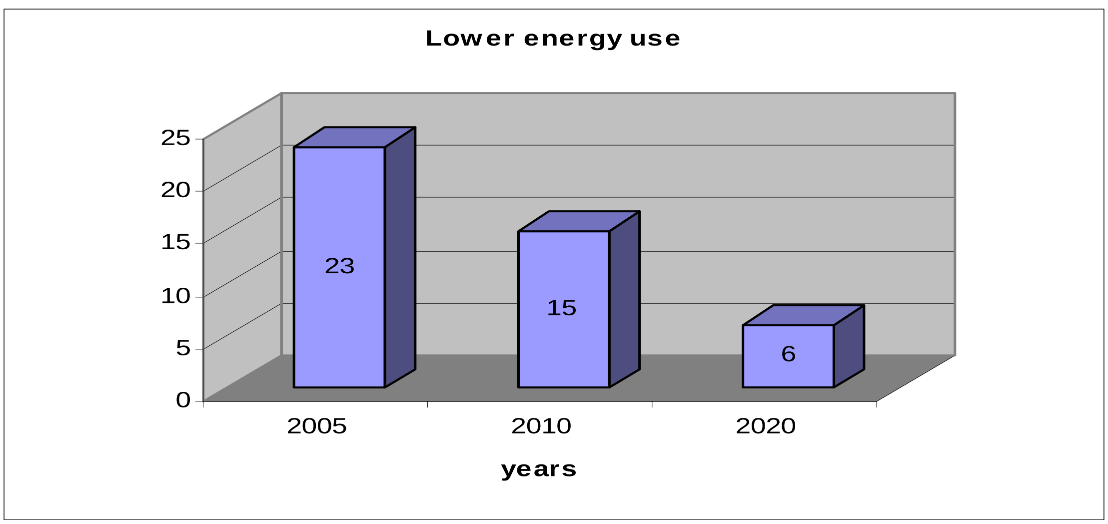
The structure used to formulate the questions targeting the above seven areas can be found in Appendix I.

5. Analysis of Delphi Study Results.

5.1 Energy Sector

Lower energy use is a major issue for the globe. Energy efficiency and reduction of energy demand are key points for an initial approach to preserving the fragility of the planet. There is a statutory requirement for reducing energy consumption motivated by environmental considerations (climate change and conservation of natural resources), financial and legislative aspects. Industry has a central role on the energy use issue and should be part of the environmental solution. The 52% of the respondents surveyed revealed that an objective of lower energy use should be pursued in the short run (2005), whereas only 14% of those placed this objective as a longer-term strategy (2020, See Fig.2). The remaining 34% do not prioritise lower energy use as an immediate goal, but place it as a medium term strategy (2010).

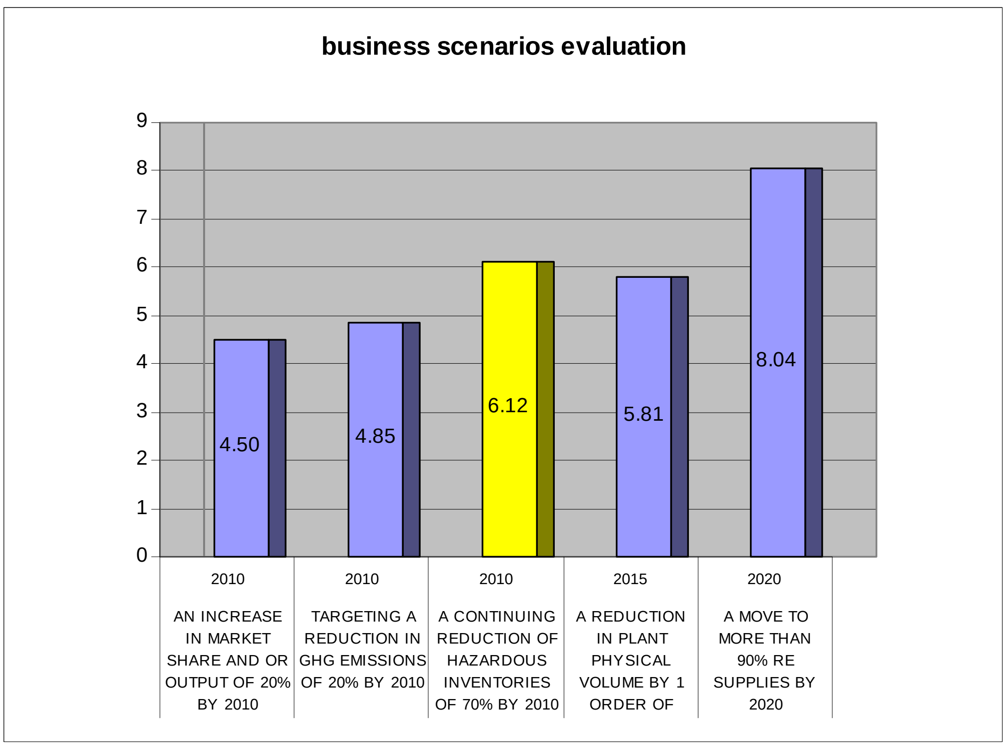
Fig. 2: Relevance of lower energy use in the future.



From this analysis it is revealed that lower energy use in the shorter term is a priority of the majority surveyed, but it is unclear as to what is the driving force that motivates their decision i.e. legislative enforcement or ethical reasons.

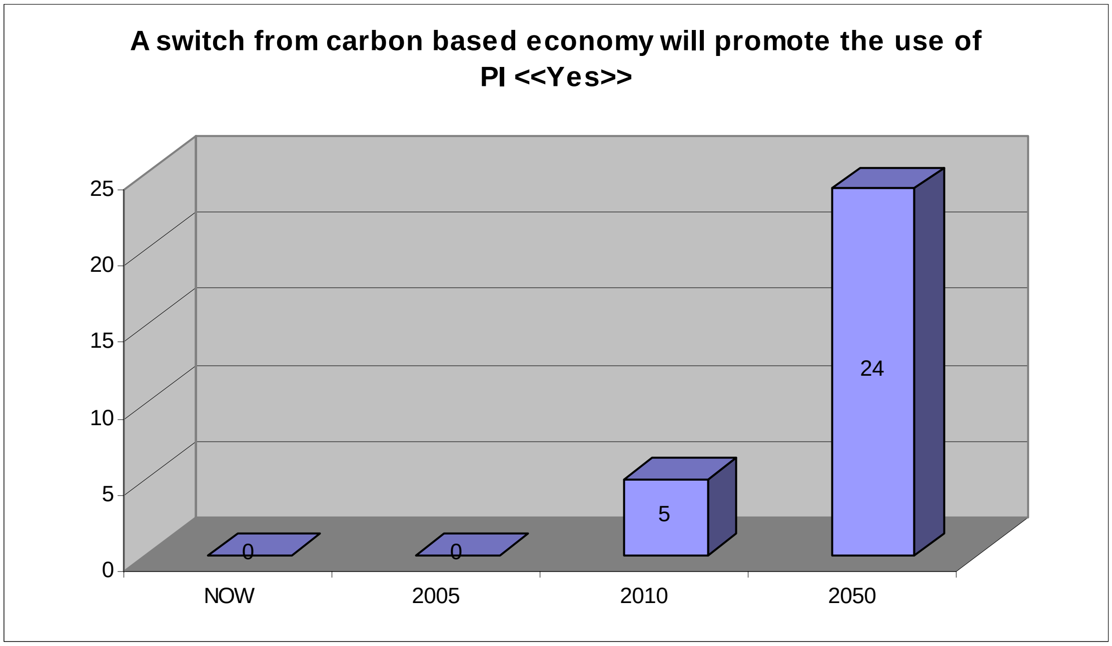
Related to the above issue of energy use, it has been ascertained that an energy source switch is a desirable goal for industry, as revealed from the graph below. From Fig. 3, it can be seen that a move to more than 90% of renewable energy supplies achieved the greatest attention (from a scale of 1-10, a score of 8.04/10 average was achieved from a total of 44 surveyed). However, the benefits of process intensification, namely; improved safety, inventory reduction, a reduction in greenhouse gases and plant physical size reduction has received substantial approval as can be seen from below. Bridging process intensification and renewable technology has a significant role to play in tackling the present and future environmental issues. This also comes in line with the recent British government's Performance and Innovation Unit Energy Review, which has recommended a combination of low carbon energy efficient and renewable technologies to form the basis of a sustainable future energy policy.

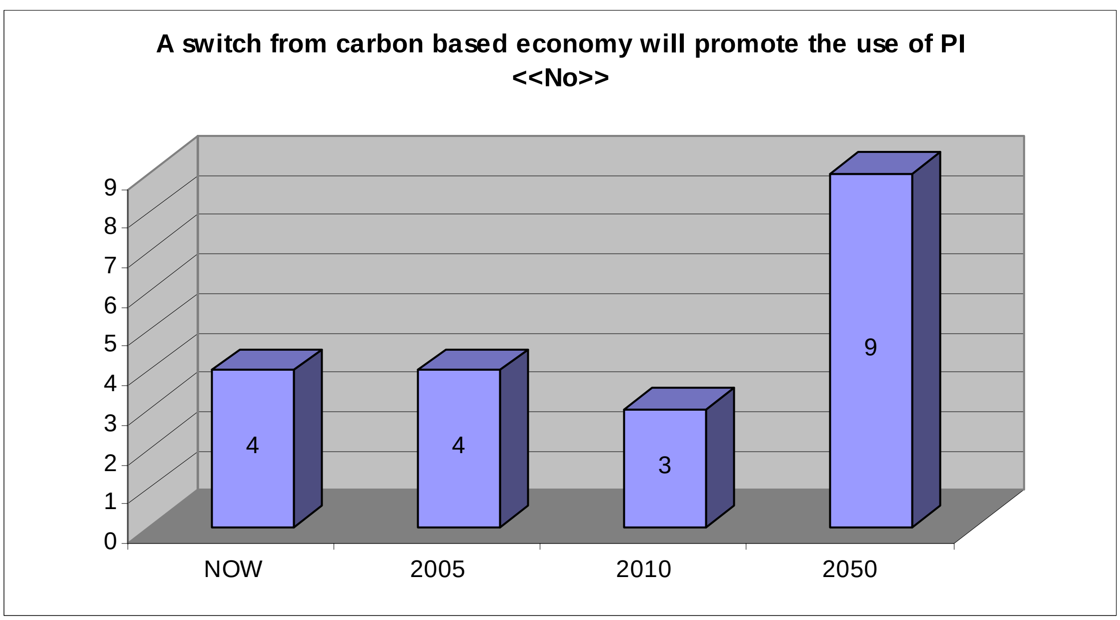
Fig. 3: Likely future business scenarios



Evident from the survey results (59.2%) is the favourable role that a switch from a carbon based economy to an alternative energy source (i.e. Hydrogen/Ethanol) will play in promoting the utilisation of process intensification technologies in the long term (2050), as can be seen in Fig. 4. However, 40.8% of those surveyed feel that a fuel switch will have no benefit on the uptake of PI technologies. Possible reasons for this may relate to the perceived outlook on whether Hydrogen can be adopted successfully on a global market scale to be an energy provider. While no doubt denying the Hydrogen will assist PI uptake, it may not be the only reason why PI can develop further as other technological and market related barriers need to be overcome for its successful implementation.

Fig. 4: Effects on PI from switch to non-carbon based economy.





5.2 Safety

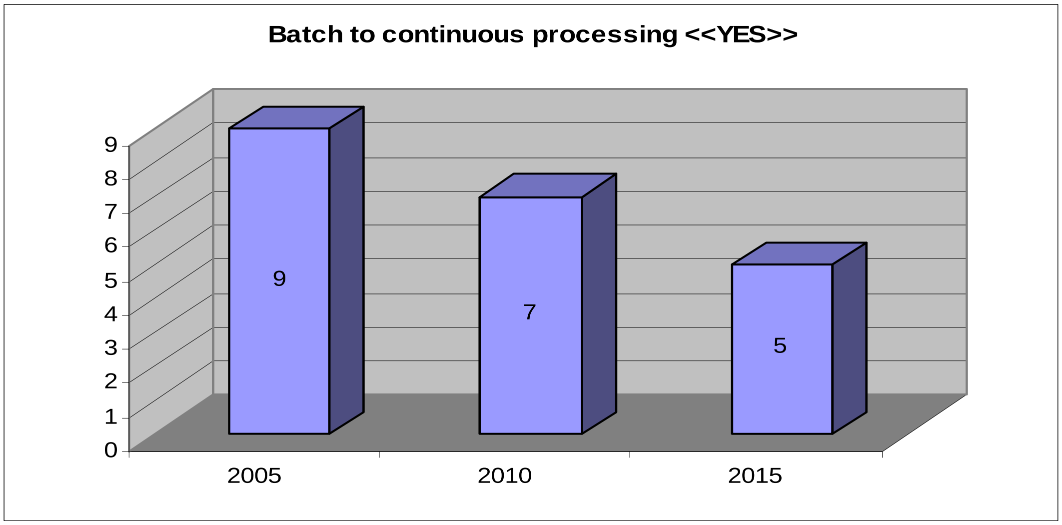
On the aftermath of past disasters, safety has been a growing objective of industry. PI's concept of promoting inherently safer design over a range of industrial applications is coherent with the above objective. The analysis of the respondents' feedback revealed (from Fig. 5) that it is indeed a short-term priority by 2005 as justified by 67% of cases. The remaining 33% is split to applying safer conditions in the medium or longer-term future, e.g. 21% by 2010 and 12% by 2020.

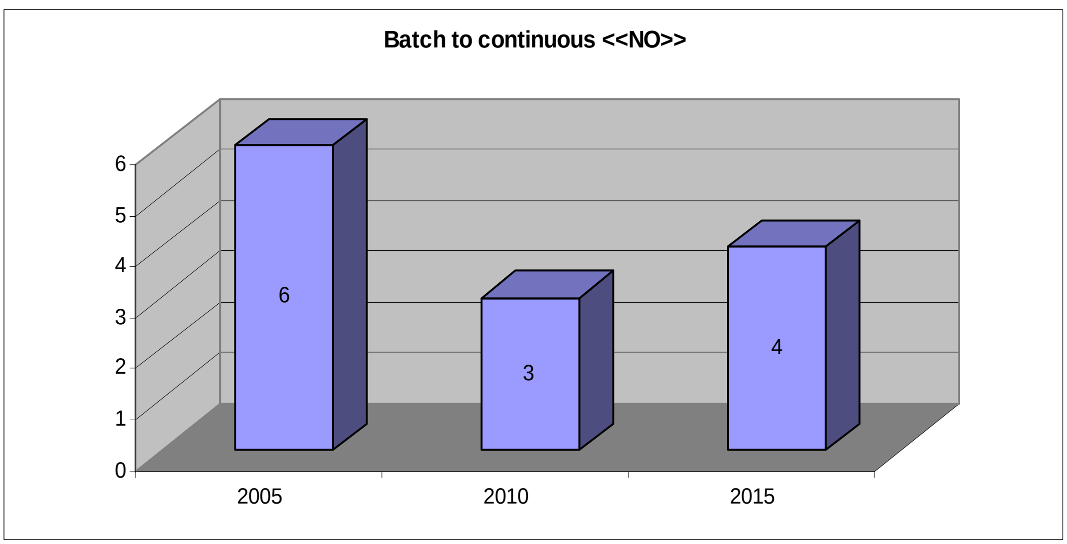
Fig. 5: Relevance of safety in the future.

If PI can be implemented to the degree anticipated, it is clear that there will be dramatic reductions in the hazardous inventory of a number of processes. The analysis has shown that the above statement is consistent with the industry's view of reducing the volume of hazardous inventories by 2010 (which is in line with the desirability of plant size reduction, see section 5.3). PI has an optimistic future in achieving the goal of safer plants, considering the results presented in Fig. 3 (safety being second in importance to energy).

Switching from batch to continuous processes can be an add-on to the public image of the chemical industry. 75% of run-away reactions occurred in batch vessels to date. A move away from batch would improve safety, since controlling the reaction is of paramount importance. PI technology based on continuous processes provides an improvement in heat and mass transfer, lower residence time, lower inventories, better control and better quality products. This view is further supported by the fact that 62% of the respondents expressed positive opinions for transforming chemical processes from batch to continuous (see Fig. 6), either in the short term (43%), in the medium term (33%) or in the long term (24%).

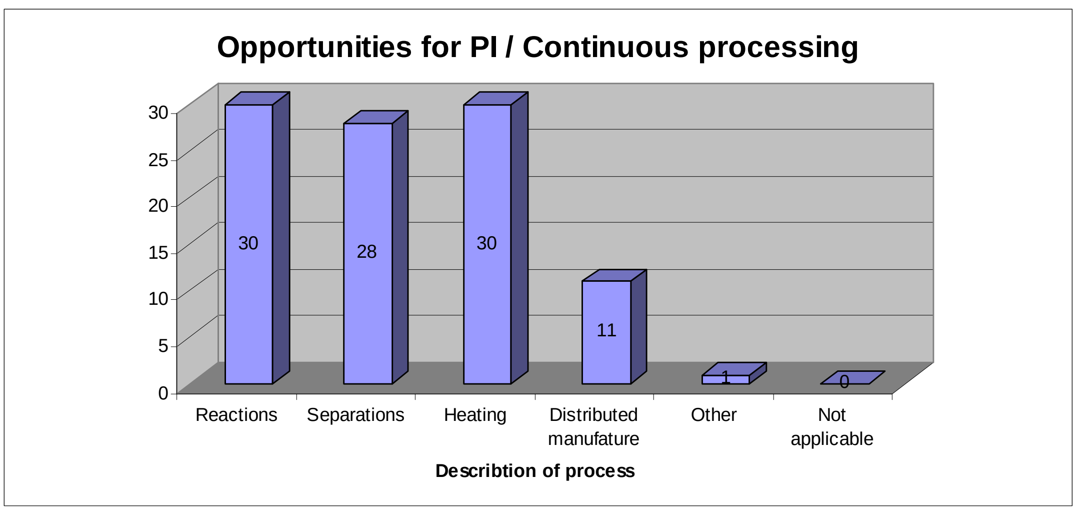
Fig. 6: A support from batch to continuous process.





According to the results, three main areas have been identified as having the most potential for continuous processing, these being reactions (30%), separations (28%) and heating (30%). Evident from the graph below (Fig. 7) shows no outright winner amongst the three. However, the survey identified the role of continuous processing in assisting a wider uptake of distributed manufacturing in the future (11%). Distributed manufacturing has not received as great interest as the others did, but there is a strong belief that it will develop further in the future, with multilateral benefits both to national security, ergonomics and global competition (specially suitable for rural development). In one case (1%), mixing has been highlighted as a further area of PI opportunity. Overall, the outcome has been very positive as no negative responses were received.

Fig. 7: Areas of opportunity for continuous processing.



5.3 Plant Size Reduction

Another area we have investigated in our analysis is the interest in plant size reduction. The demand on our natural resources is now so great we need to find a way to reduce bulk volume and waste. Intensified plants, with their lower capital costs, should allow smaller scale plants to compete economically with their conventional counterparts. Thus, in following a growing market, the capital investment can be made in smaller increments and thus be much less risky.

The main advantages associated with plant size reduction may also include the following:

- Lower capital cost of equipment.
- Increased safety.
- Lower maintenance requirements.
- Lower operation costs.
- Less waste disposal.
- Reduced time to market.
- Support decentralised production.

It has been deduced that 43% of the respondents have stated that smaller plant is one of their primary goals in the short term (2005), while 38% of those have prioritised plant size reduction in the medium term (2010) – see Fig. 8. Being the biggest is not as desirable as it used to be in the past due to perhaps a gradual cultural change in engineering attitudes and a more active role of society on environmental concerns. Financial aspects related with decommissioning costs may also be considered as motives. With reference to Fig. 3, it appears that the third highest priority for PI's business opportunities is plant size reduction. A 50% plant size reduction target by 2010 is the most realistic approach according to the results received (60% of the respondents, see Fig. 9). A reduction of two orders of magnitude by 2010 is equally desirable. Further reductions, while being desirable, may not be achievable.

Fig. 8: Relevance of smaller plant in the future.

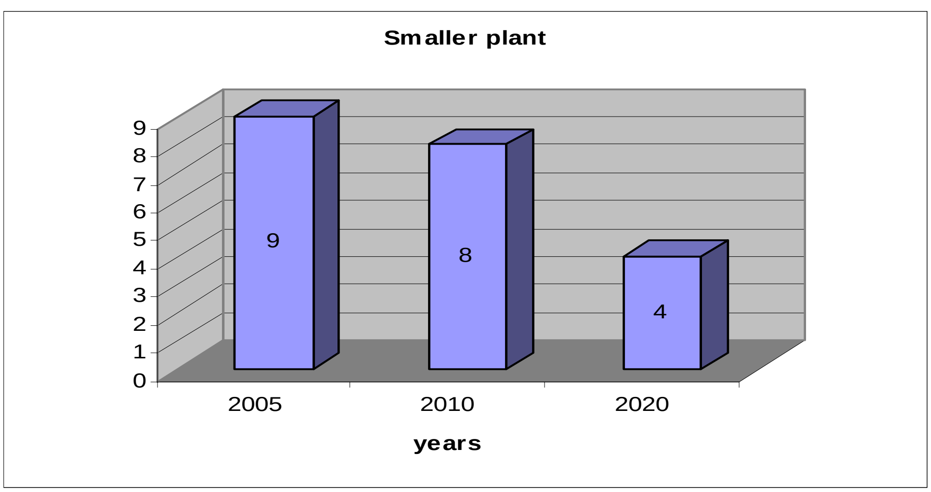
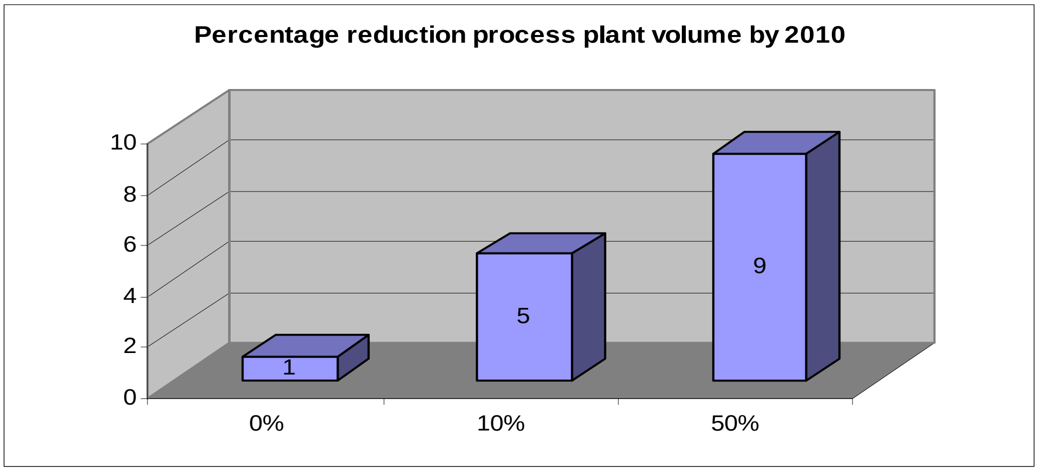
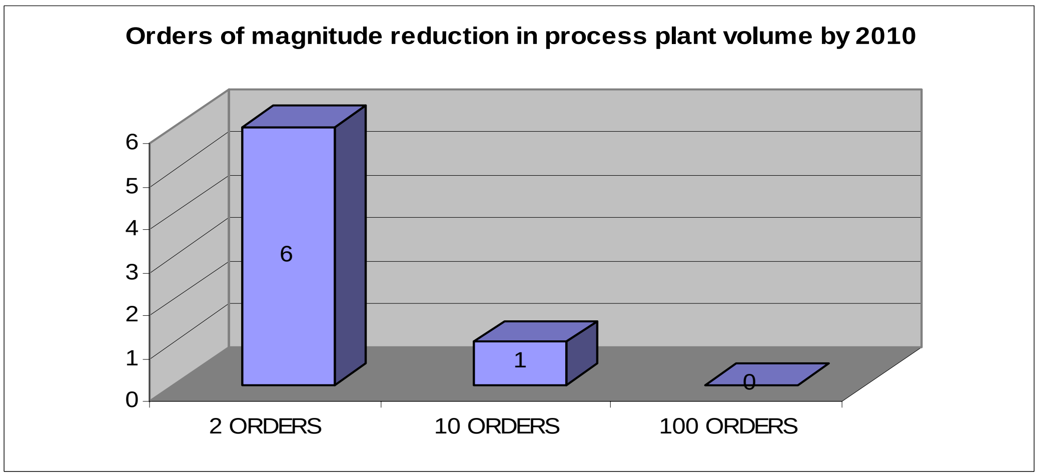


Fig. 9: Degree of plant size reduction desirability.



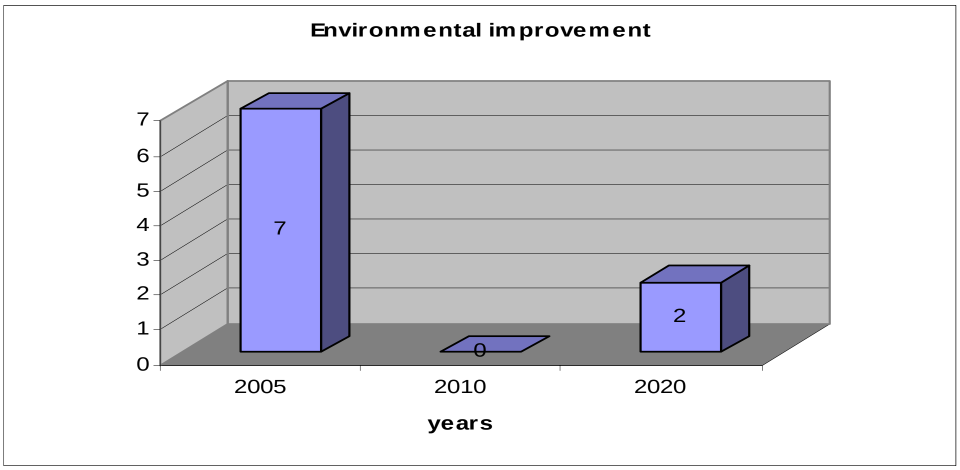


5.4 Environmental Improvement

Environmental improvement is the core for sustainable development. PI's concept has many benefits for the environment providing cleaner technologies, which can replace conventional and more environmentally damaging ones. This environmental awareness associated with PI can be interlinked with the already mentioned properties, i.e. safety, lower energy use and plant size reduction. The stricter codes of practices that are now incorporated into environmental policy regulation allow PI to be used as an effective tool in achieving these standards. Changes in moral attitudes should also encourage the implementation of PI.

The response in our study shows that 78% of the respondents consider environmental improvements as a priority in the short term (2005, see Fig. 10), but it is not a top priority as Fig. 3 highlights. The reason for this response may be that the companies surveyed are reactive to legislation rather than being proactive.

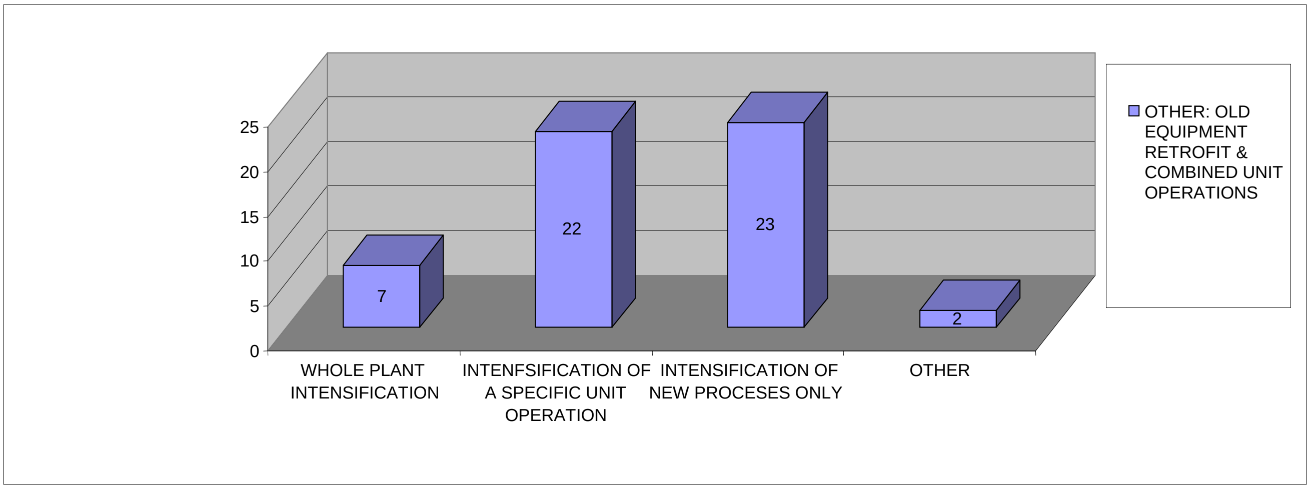
Fig. 10: Relevance of environmental improvement in the future.



5.5 Specific PI Technologies

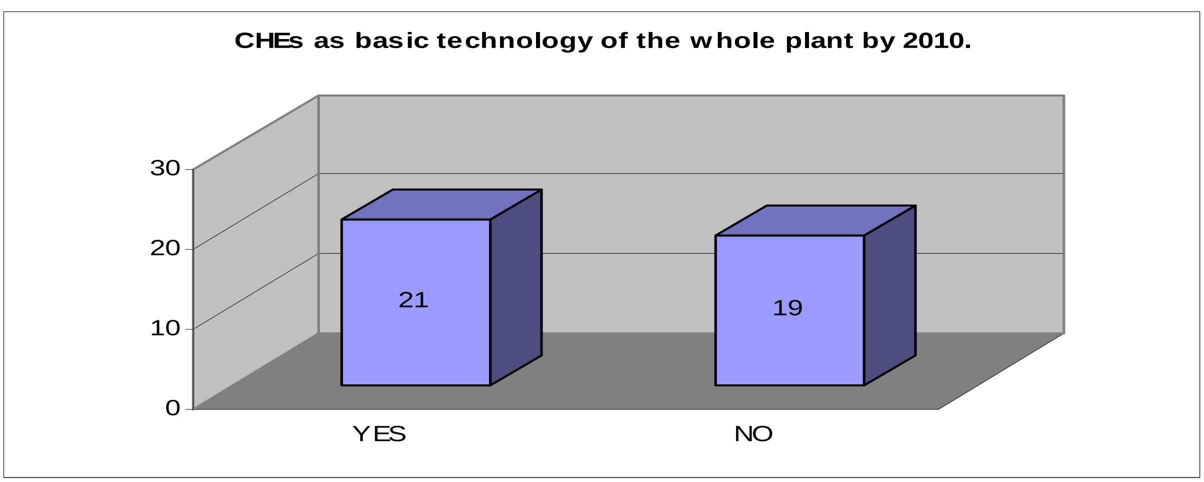
Before attempting to intensify a process using new technologies, full understanding of the process being modified/ intensified together with knowledge of how far the operating parameters can be modified are essential steps for a PI implementation. The respondents surveyed have shown a strong interest both with respect to the intensification of new processes, which amounted for 43% of the answers (See Fig. 11), and 41% with respect to the intensification of specific unit operations (debottlenecking). This result seems to supplement the existing potential benefits that PI technologies can offer to industries in the near future. Whole plant intensification has been found attractive only in 13% of the cases, which may be because of the general barriers that are still blocking PI's implementation. However, two new suggestions have been made for the adoption of PI, that is, in retrofit projects involving old equipment and combined unit operations.

Fig. 11: Impact of PI technology on plants in ten years time.



The compact heat exchangers (CHE) are a good example of an evolutionary process technology, which now forms the basis of very small reactors, as well as being routinely used for their primary purpose, heat transfer, in many demanding applications. Their versatility and high performance can provide significant energy savings in combination with other unit operations such as reactors, mixers or chiller plants. However, the response to whether a whole plant based on this technology is envisaged in production by 2010 has been diverse, with 52.5% supporting the future scenarios of a whole plant based on CHEs and 47.5% not viewing it as a potential outcome (See Fig. 12). This means that several technical and attitudinal barriers are still to be overcome, before the concept of PI and the strategy of applying it to the whole plant could be realisable.

Fig. 12: Future scenario for whole plant based on CHEs.



A major heat and mass transfer intensification opportunity centres upon the use of enhanced acceleration in a rotating system, with a view to creating a fluid-dynamic environment that will allow the intrinsic kinetics free rein. Therefore, in any rationally designed intensified reactor, the mixing and heat/mass transfer rates will be to match the fundamental process kinetics. In order to realise the full potential of this intensification strategy, it is imperative that all plant operations should be involved, rather than just the reactor, heat exchanger or separator. The principle of multi-functionality can be extended with considerable benefit to those operations performed within a cyclone/ vortex or rotor. It is evident that about $^{2}/_{3}$ of the unit operations in process engineering involve multiple phases and are therefore susceptible to this intensification approach. Vortex fluidic devices and Higee rotating packed bed developments and the recent spinning disc reactor (SDR) are typical examples of this technology.

With reference to the results received, 87% of the respondents expressed the opinion that a rotating plant is feasible by 2015, while only 13% did not find this idea attractive (See Fig. 13a,b). Expanding the answers favouring the rotating plant in a time frame from present to 2015, the distribution of results have shown that although 15% of the respondents believe that such a plant concept is feasible now or in the short term (2005), the majority (72.5%) place this technology in the longer term (2015).

Fig. 13a: Future scenario for rotating plant.

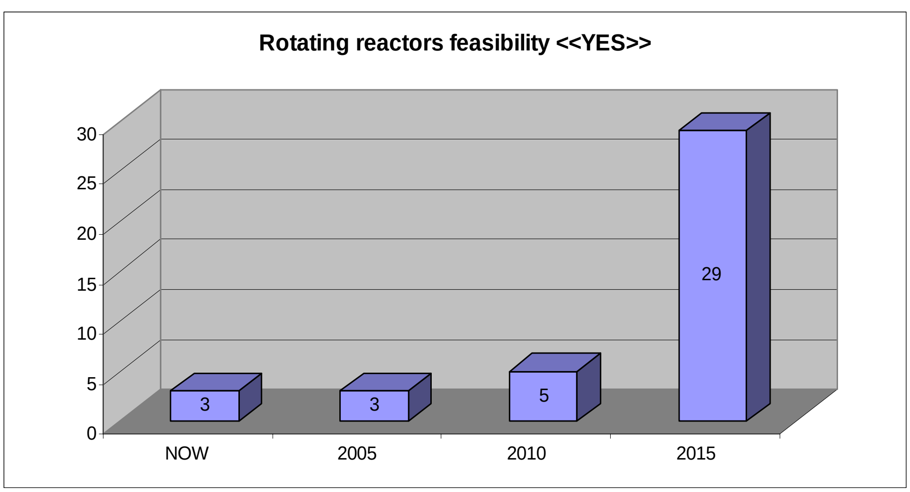
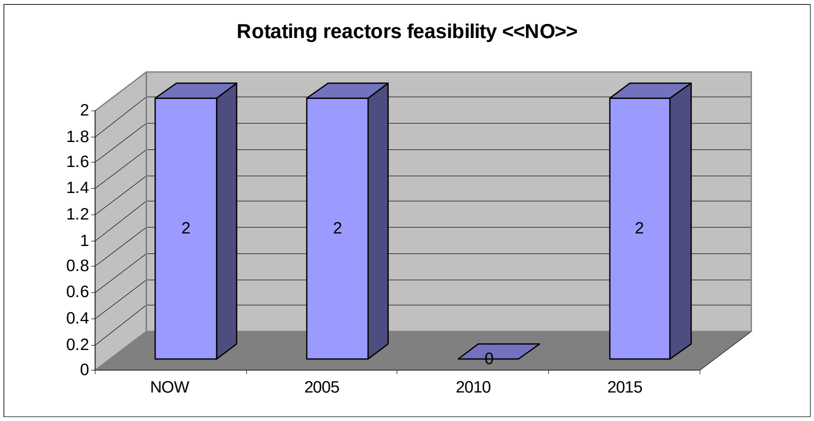


Fig. 13b: Future scenario for rotating plant.



It is claimed that heat pipes can overcome process heat and mass transfer limitations (e.g. reactions, cooling of microchips, refrigeration plant). Heat pipes are sealed vessels that transfer heat through the evaporation and condensation of a working fluid. The main advantage of heat pipes is that they can have a thermal conductivity tenfold or hundredfold that of copper, with no moving parts and therefore low maintenance requirements, making them reliable and desirable for many applications. The analysis of the results with respect to heat pipes applications in process plants has revealed that 57.5% of the respondents believe in the feasibility of this technology, mainly by 2010 (See Fig. 14a,b). Reasons that prevent wider use of this equipment in the process industries could be lack of awareness, both from manufacturers' point of view and end users, or conservatism (preference for traditional reactor cooling equipment). Further R&D and technology transfer may be required so as to enable wider range of heat pipes applications and to increase business opportunities.

Fig. 14a: Future scenario for heat pipes.

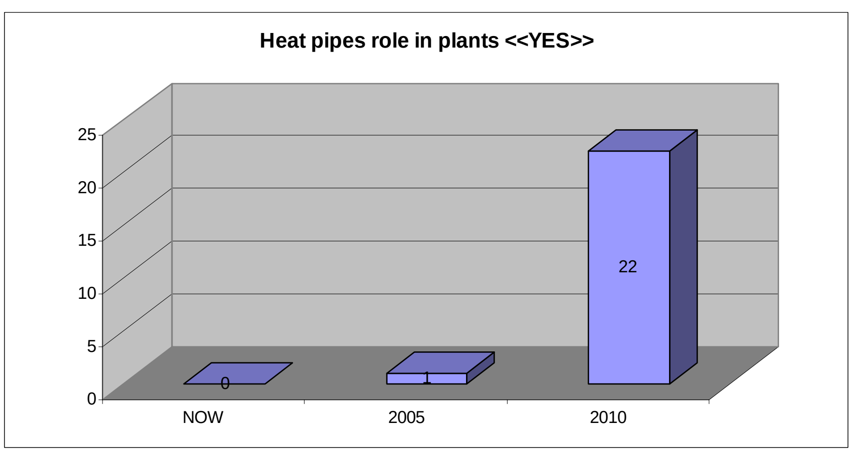
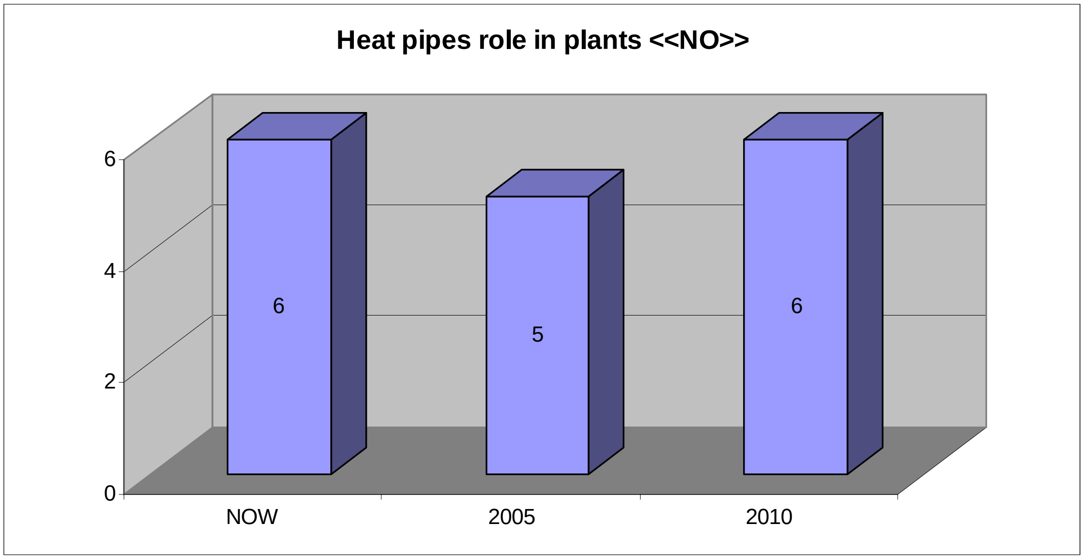
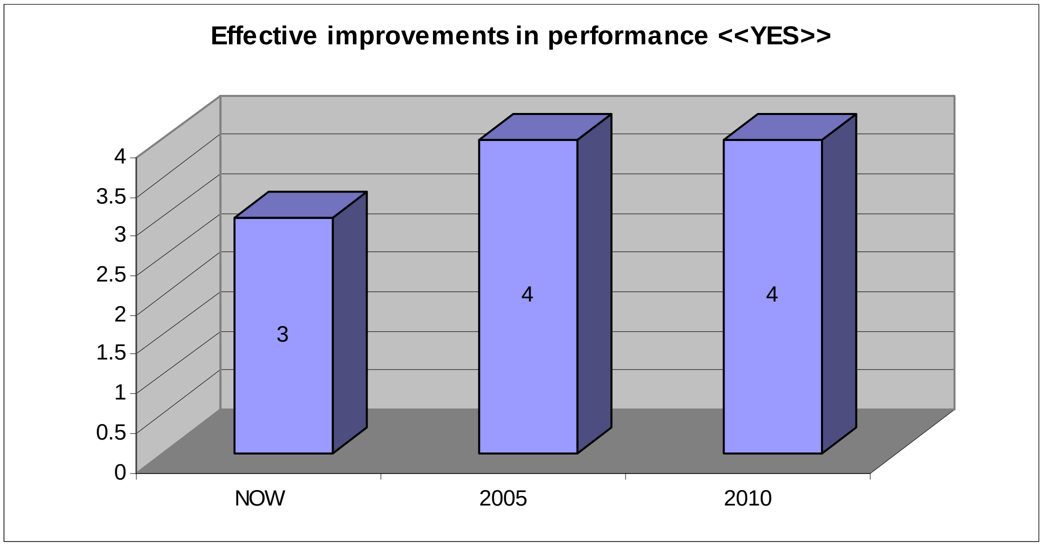


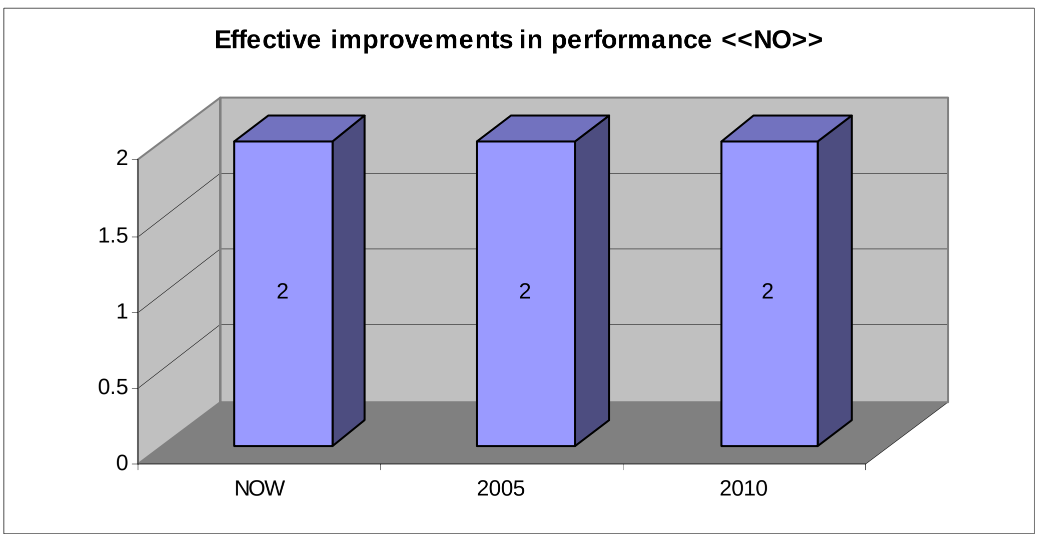
Fig. 14b: Future scenario for heat pipes.



Effective improvements in performance of existing conventional heat exchangers with substantial energy cost savings across the whole of the process industries can be realised through heat and/or mass transfer enhancement techniques. Enhancement is normally concerned with increasing the heat transfer coefficient on one or both sides of the heat exchanger by means of active or passive techniques, such as fins, tube inserts, electrostatic fields, and rotation or surface enhancement. The goal of enhancement techniques may be a reduction in size for a given duty, an increase in capacity of existing equipment, a reduction of the approach temperature difference or a combination of the above factors. The response to the likely scenario of applying these techniques to conventional equipment has highlighted that 65% of the respondents are favouring their use, either now (27%), in the short term (2005, 36%) or by 2010 (36%, see Fig. 15). On the other hand, 35% of the respondents expressed a negative opinion with regard to these techniques. This may be due to the fact that passive enhancement can result in an extra energy need because increased resistance to flow leads to a subsequent higher-pressure drop, and active enhancement requires an external energy source.

Fig. 15: Future scenario for heat transfer enhancement techniques.





5.6 Organisations' Response.

PI can bring substantial business benefits, assisting national economies and the process industries and other sectors that compete in the global markets. The traditional high technology sectors, such as aerospace and electronics have long realised the need to invest in new processes and products in order to maintain competitiveness. The need to learn some of the lessons of, in particular, the electronics industry has been appreciated by some sectors within the process industries during the past four decades.

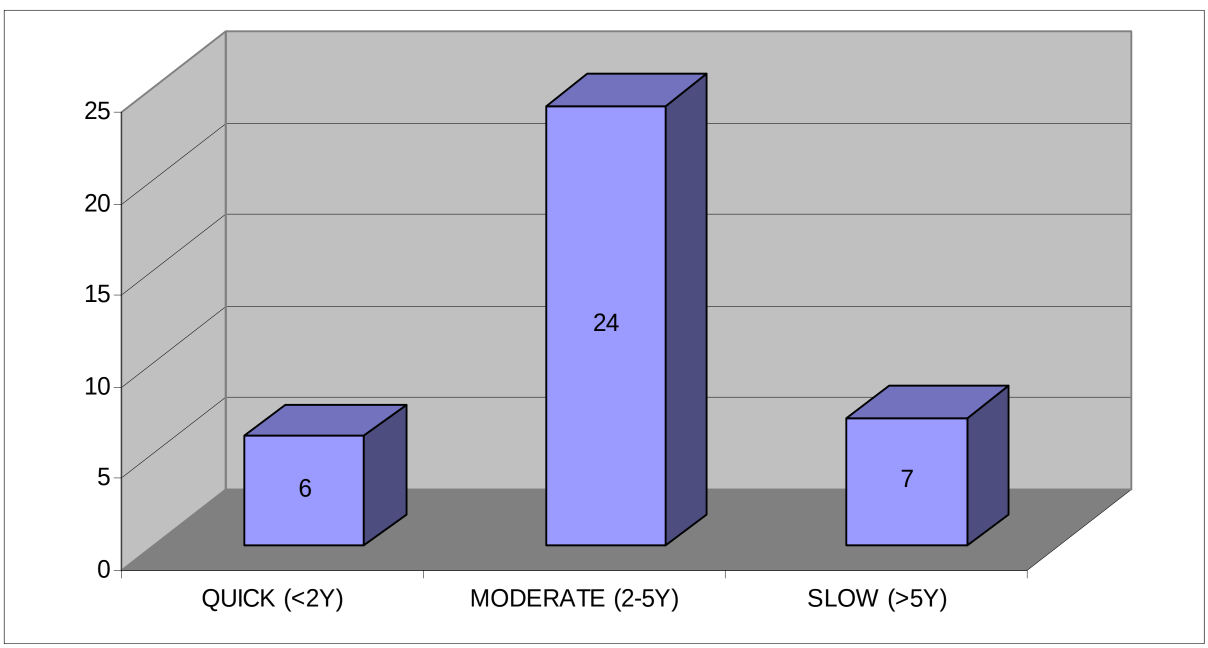
Investment in R&D can be directly linked to profitability, especially when bringing these R&D results to the market place is also driven by positive responses to three major influences:

- Response to rapid advances in science and technology.
- Response to customer requirements.
- Response to the global market.

Thus any technology (i.e. PI) which can help a company to respond positively to the above three influences is worthy of consideration. In our study, the responsiveness of firms to these three influences have been analysed, based on the results received from the respondents.

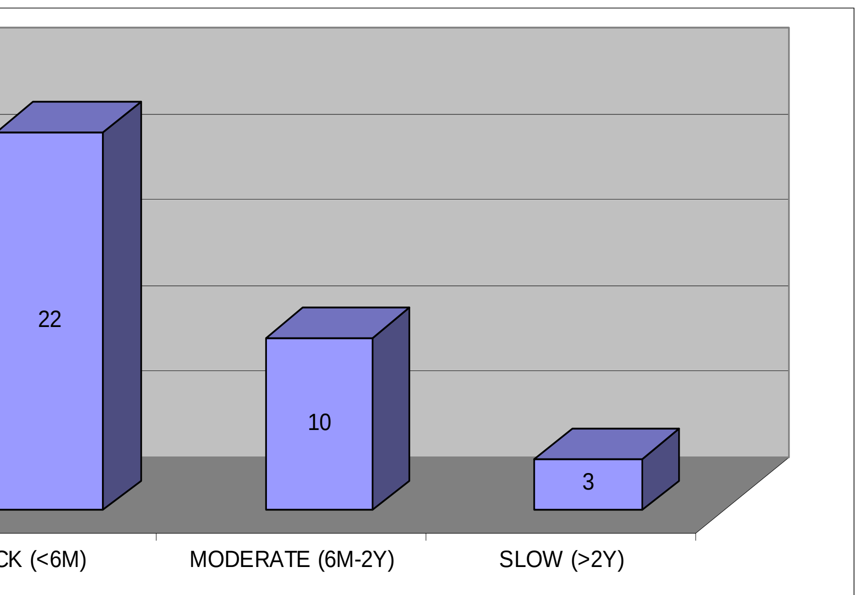
To start with, data presented show that 65% of the organisations consulted respond moderately to rapid advances in science and technology, while only 16% react in a quick way, and for the remaining 19% the response is slow (See Fig. 16). This distribution of response timing to the above influences may be due to diversity in industrial sector, the size or the infrastructure of the organisations in question.

Fig. 16: Organisations' response to rapid advances in science and technology.



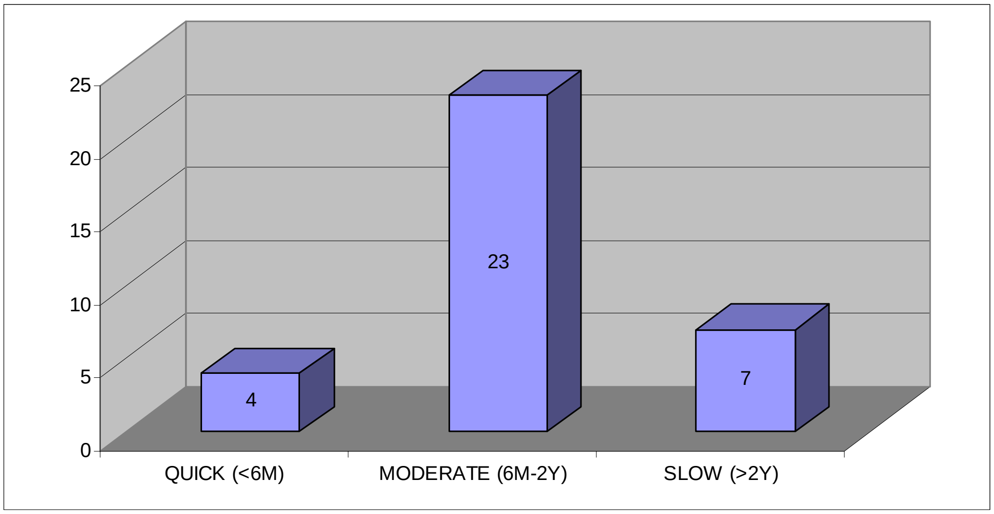
An interesting outcome has been deduced for the organisations' response to the influence of customer's requirements. In 63% of the cases the response has been highlighted as a priority (less than 6 months, See Fig. 17). Only 9% of the organisations have a slower response to their clients' requirements (more than 2 years). The moderate response is found in the 28% of the cases examined. Considering these results, it is evident that the power of customers is high, thus, playing a key role in creating a highly responsive policy to customers' requirements. (Incidentally, customer power is one of five sets of criteria used in a Porters Five Forces Analysis to determine the competition a firm has within a particular industry; if all criteria are high, it is likely to be a highly competitive industry).

Fig. 17: Organisations' response to customers' requirements.



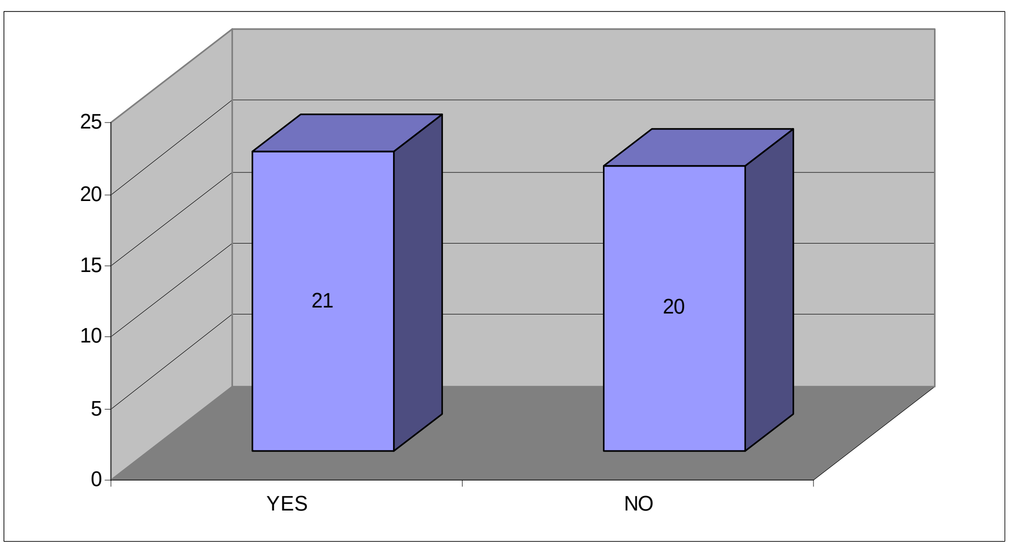
Globalisation and liberalisation of markets makes competition even more intense, encouraging more players in the market place that threaten the commercial relations/ status quo with the existing customer base of a certain organisation. However, the response to global market trends/ requirements was moderate (6 months to 2 years) in the 68% of the organisations consulted (See Fig. 18). 21% of the respondents have a slow reaction (over 2 years), while only 12% support a more immediate response (less than 6 months). In the rapidly growing world market, it will be essential for a firm to respond rapidly to global market changes and trends, so as to be able to maintain its core customer base and expand its market share by adding potential new customers.

Fig. 18: Organisations' response to the global market.



An awareness of the importance of the above-mentioned influences is necessary in making the case for investment in new plant or equipment. Although process intensification with its inherent advantages can assist a company to respond positively to these influences, our study revealed an inconclusive situation with respect to the companies surveyed. While 51% agreed that PI could support their organisation's response, the remainder revealed a negative feeling (See Fig. 19). Perhaps the recent global market recession and the preserved PI barriers (See section 5.7) are influencing at a great level their views and create the above paradox.

Fig. 19: PI role as a marketing tool for organisations.



5.7 Barriers to PI Implementation

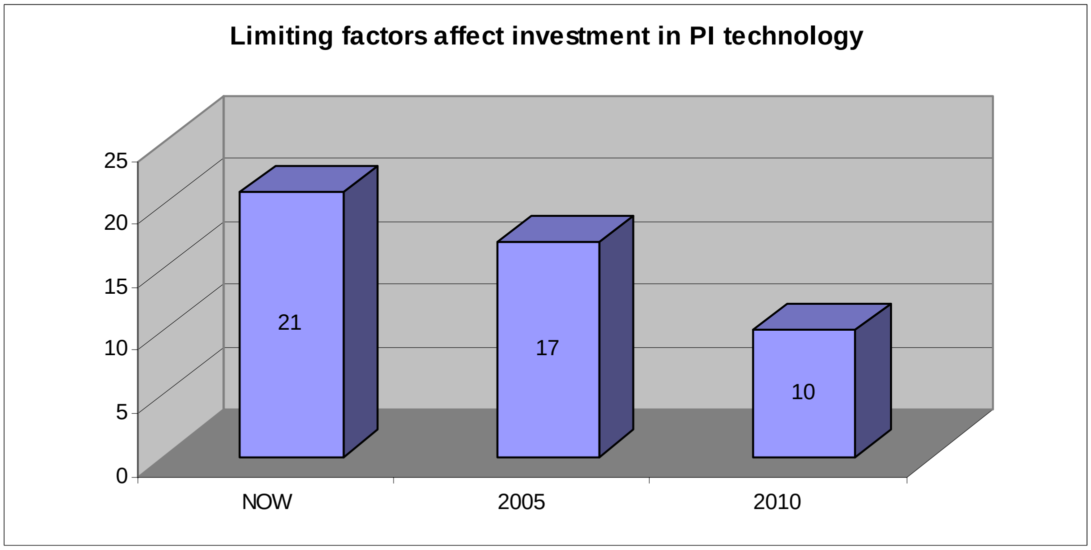
Barriers to entry present formidable problems to the uptake of PI technologies. Such technological and business related barriers might include:

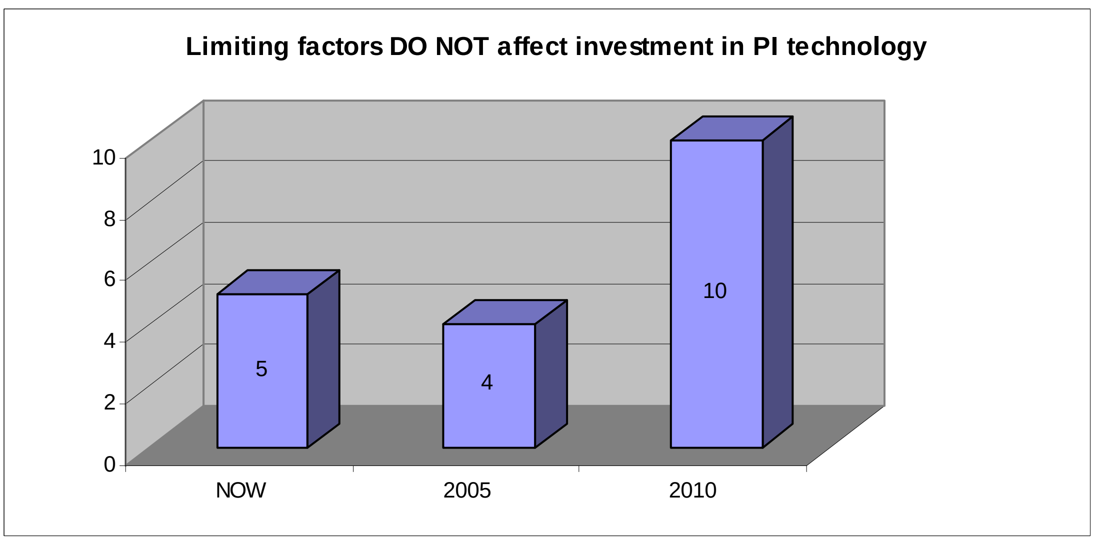
- Conservatism in the user industries.
- The rush to be 'second', avoiding positive risk.
- Lack of industrial and academic awareness.
- Loss of the buffering effect of large volumes.
- Lacks of codes of practise.
- Limited choice.
- Concern about fouling.
- Lack of supporting tools and backing from senior managers.
- Movement of production to countries where there is less innovation.

Conservatism has been identified as the major barrier for PI implementation, split into two categories within an organisation, namely company structure and management attitudes. Of intermediate importance, the lack of supporting tools from senior managers has been recognised. Consistent with the results of section 5.3, the desire to be the biggest rather than the smallest in terms of equipment/ plant magnitudes was not conceived as a significant limitation for PI adoption.

From the results analysis (see Fig. 20), 72% of those surveyed feel that the perceived PI limitations, as listed above, need to be overcome in order to assist a realisable investment in PI equipment. On a time frame up to 2010, 44% envisage that these barriers are impossible to be conquered at present, 35% expressed that they will limit PI's uptake by 2005 and 21% that this situation will hold even up to 2010. On the other hand, 28% reckon these barriers are not limiting the organisation's decision to invest in PI technology. The majority of these respondents (53%) set 2010 as the threshold year.

Fig. 20: Barriers to uptake of PI technologies.





6. Strategic Analysis

Encouragement for the establishment of PI has previously received little attention. Besides technical considerations, it is important that trends in the economic, social and political environments are not overlooked in the Delphi study, as this is often a weakness of many forecasts made by technologists in isolation. From this point of view, the PI originators acting as an emerging energy technology supply company should indeed encourage the production of PI based equipment for the marketplace. A strategic plan, which predates, but is heavily linked with foresight, would be a useful exercise to carry out so as to fully consider the current environmental conditions affecting the firm.

A strategic process model is a structured and comprehensive method of determining long term goals and objectives, the adoption of courses of action and the allocation of resources to carry out these goals. Strategy may be market based (such as the competitive forces or the strategic conflict based approach) or may be resource based, focusing on a firm's strategic architecture and core competences. Based on one of these, a strategy may be chosen and implemented to achieve the objectives of the company, which may be quantifiable or non-quantifiable and may focus on economic, financial, social or environmental aims. Such objectives may include increasing shareholder value or market share, balancing product portfolio or providing expertise services (response to rapid advances in science and technology).

A view of the macro environment is a requirement and will take into account economic, political and social factors before a organisation can identify its strategic possibilities. For a company involved in PI (either a producer or end user), important factors may be governmental support by means of subsidies or tax discounts, academic response, global market trends or public response to environmental policies. Such environmental scanning can be carried out using a PEST analysis. The approximate position on the business cycle will provide a useful indicator, although it must be remembered that forecasts of the future, aligned to the business cycle, may go wrong due to unpredictable events or exogenous shocks which cannot be foreseen. This may have positive or adverse effects to a certain technology. As an example, it may be considered that the recent events of the 11th of

September 2001 had stimulated the development of flexible, reliable and compact distributed power generation plants to secure national energy supply. PI, with its ability to radically reduce the size of plant equipment, may benefit from this situation.

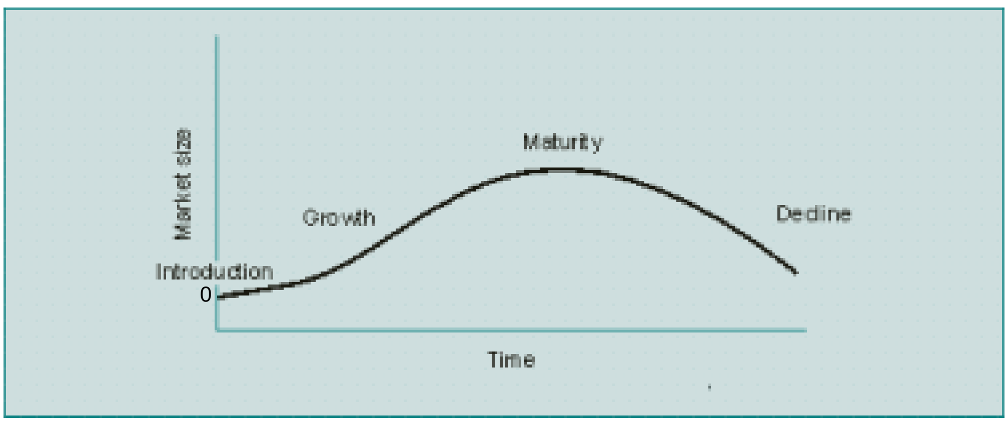
An analysis of the industry environment and the likely competition that exists is also a necessary step in attempting to identify the best generic strategy. Determination of the competition type (perfect, imperfect, monopoly, oligopoly) will allow the organisation to decide what pricing options can be taken as for instance, in a perfectly competitive industry, all firms are price takers. It is worth considering the two most important determinants of product success, i.e. perceived product price and perceived product differentiation by consumers and the position of the likely innovative product on this (See Fig 21). Therefore, when the situation comes to the present industry environment for PI, it is evident that the competition type is imperfect. That means that PI, in order to penetrate an already established market dominated by conventional technologies, needs to be competitive in price-wise terms. Governments should play a central role in the shift of the commercial balance in favour of PI technologies, which will allow them to justify their beneficial contribution and gain credits of markets confidence. For example, in the offshore industry, the importance of weight is dominant – saving of one tonne in process equipment weight saves five tonnes of structural weight, which has a value of US $25,000/tonne. PI has the potential to deliver such a weight reduction in a range of processes, which makes its application cost-effective for the company.

Fig. 21: Perceived Price vs. Perceived Differentiation.

It is also necessary to consider what is the market product life cycle i.e. whether it is a young, growing market or not (See fig.22). Stages include:

- *Introduction*: the product is invented and introduced to the market; it can take some time for information about the product to be disseminated.
- *Growth*: the product becomes increasingly well known, markets are penetrated and it possibly replaces other products.
- *Maturity*: all markets are exploited and there is no further increase in sales.
- *Decline*: the product is superseded by technological progress, or substitutes appear.

Fig. 22: Product Life Cycle.



With respect to the above description and the analysis of the results in the previous sections, it can ascertained that most PI technologies are currently undergoing an introductory stage, while others like the CHEs are situated in the growth phase as they have already penetrated the market and are currently substituting their conventional counterparts in many applications. CHEs, while accounting for between 5 and 10% of the US $15 billion plus world-wide market for heat exchangers, have a sales increase index by about 10% per annum, compared to 1% for all heat exchangers. It can be concluded that all the technologies studied, heat pipes, rotating equipment and enhancement devices, may approach the growth stage in the medium-term (2010–2015). A factor that will contribute to a higher extent for a more rapid growth is the multifunctionality that characterises these technologies. For instance, heat pipes can benefit from their wide use in the micro-electronics industry and expand their market share by exploiting their potential in the chemical industry.

The introductory stage of a product can be significantly reduced by the application of the concept of a "desk top" chemical plant, which intensifies the whole life cycle of the product. The laboratory scale would be the full scale plant and, provided that the current industrial batch culture can be supplanted by a continuous mind set, pharmaceuticals could be brought to market much more quickly. This would increase competitiveness and could help speeding the company's response to global market and the customers' requirements, as well as allowing more production of drugs/fine chemicals within patent cover.

Generic strategic alternatives, based on the previous information, can then be viewed and may include corporate strategies such as expansion, stability, retrenchment or a combination of all. A strategy of expansion via related diversification may be one such strategy to maximise shareholder wealth, pending on all other factors being favourable to its likely success.

Thus, it can be deduced that it is indeed a wise and cautious move to perform a comprehensive strategic analysis to determine how realistic opportunities exist in exploiting the forecasted technology of PI as this Delphi study has shown. However, it must be accepted that forecasts can and do indeed turn out to be often wrong, but with a comprehensive analysis of all factors as discussed, risk of this can be minimised. Managerial attitudes will determine whether the forecast result is the route to be chosen. This allows greater probability of achieving a sustainable competitive advantage for the firm.

7. Conclusion

This group assignment has been based on the results of the Delphi study conducted in order to identify the possible future scenarios of PI technologies. A number of questionnaires has been forwarded to industry and academia and the data collected were analysed to recognise their views with reference to the subject. Due to the limited time available, this study has utilised the results of only one round of questionnaires, and the views of experts have been summarised in a final report.

The PI areas covered in the study included energy use, safety, plant size reduction, environmental improvement, specific PI technologies, organisation's response and barriers to PI development. An attempt has been made to analyse the interaction of these areas and their relevance to PI's implementation, along with the basic strategic planning model needed by a company to successfully market this technology.

A great progress has been identified in the classification of lower energy use as the most immediate goal for the majority of the experts consulted. In the context of a liberalised electricity market, the prospects of using more than 90% renewable sources by 2020 has been recognised as the most appealing business scenario, closely followed by an increased interest in improving safety. The desirable shift from batch to continuous processing and the aspiration of plant size reduction and lower inventories stated by the experts reflects the great importance attributed to safety issues in the short to medium term. Environmental improvement has not received as much attention as expected. This may be due to the fact that the heart of decision making policies is driven by business interests within an elastic environmental legislation frame.

All analysed PI technologies have been favoured by the experts, although the idea of whole plant intensification or a plant totally based on CHEs appears to be more distant. The business opportunities for PI manufacturers have been identified to be in the provision of tailored products meeting the requirements of specific unit operations or new processes. Rotating PI equipment and heat pipes have been credited as feasible by the majority of the experts in the medium/long term (2010–2015). Heat transfer enhancement devices have experienced a more homogeneous distribution over time with regard to their potential application. The above findings acknowledge the trend towards the use of cleaner technologies, which comes in line with the fundamental design concept of PI equipment and will assist its wider industrial uptake.

However, conservatism still has to be overcome in order to fully implement PI technologies. This is concluded by the contradictory views that experts showed with respect to the overall influences that PI can have in the company's response to global market, customers requirements or advances in science and technology.

8. APPENDIX I

The essential part of the Delphi study conducted was the preparation of the questionnaire. Great care has been exercised during its development in order to frame the questions properly. Questions have been cast with a view to quantifying, specifying and including a probability, with respect to the likely occurrence of a future scenario, so as to trigger the views of the respondents and identify the trends of the PI technology in question within a specified time dimension.

The areas of interest that this study has been focused on were selected to be the emerging issues of energy use, safety, plant size reduction, environmental improvement, specific PI technologies, organisation's response and the barriers to PI development.

Since this study involved experts from different disciplines and a variety of industrial sectors, it has been recognised that the level of familiarity with the concept of PI and the relevant technologies that are reflecting it would vary respectively. And indeed this fact has been realised during the analysis of the results and the various comments of the respondents.

The questionnaire used can be found in the following pages.

TECHNOLOGY FUTURES MODULE

PROCESS INTENSIFICATION QUESTIONNAIRE

1. What industry is relevant to your employment?

☐ Chemicals
☐ Oil & Gas
☐ Textiles
☐ Paper & Board
☐ Rubber & Plastics
☐ Academia
☐ Environmental systems
☐ Other (please specify) ______________________________

2. Are you familiar with the concept of Process Intensification (PI)? (see www.ncl.ac.uk/pin)

☐ Yes
☐ No

3. Which of the following features of an improved process/plant would appeal to your business by the year:

	2005	2010	2020
☐ Lower Energy Use	☐	☐	☐
☐ Smaller plant	☐	☐	☐
☐ Safer plant	☐	☐	☐

4. On a scale of 1-10 which of the following scenarios would appeal to your business?

☐ More than 90% renewable energy supplies by 2020.

☐ A reduction in plant physical volume by an order of magnitude by 2015.

☐ Accounting reduction in hazardous inventories of 70% by 2010.

☐ Targeting a reduction in your greenhouse gas emissions of 20% (more than Kyoto target) by 2010.

☐ An increase in market share and/or output of 20% by 2010.

5. What areas do you consider relevant as regards to continuous processing?

☐ Reactions

☐ Separations

☐ Heating / Cooling

☐ Distributed manufacturing (small plants near to the customer)

☐ Other (please specify)______________________

☐ Not applicable

6. If you use chemical reactors, would you be attracted to move from batch to continuous processes by:

	Yes	No
☐ 2005	☐	☐
☐ 2010	☐	☐
☐ 2015	☐	☐

7. By what order of magnitude would you like to reduce your process plant VOLUME by 2010:

☐ 0% ☐ 2 orders of magnitude

☐ 10% ☐ 10 orders of magnitude

☐ 50% ☐ 100 orders of magnitude

8. There are concerns for PI such as fouling, lack of codes of practice or limited choice of equipment. Do you believe these limitations would affect your company's decision to make an investment?

	Yes	No
☐ Now	☐	☐
☐ 2005	☐	☐
☐ 2010	☐	☐

9. Imagine in ten years time PI is a mature technology. How do you forecast the impact of PI on your plant?

☐ Intensification of the whole plant

☐ Intensification of a specific unit operation (debottlenecking...)

☐ Intensification of a new process

☐ Other (please specify)________________________

10. There are indications that Compact Heat Exchangers (CHEs) can be the basis for many other intensified technologies or unit operations (e.g. reactors, chiller plant, mixers...). Can you envisage a whole plant based on this technology being in production in 2010?

☐ Yes

☐ No

11. Would you see an integrated rotating (e.g. combined separator and reactor units) as feasible by 2015?

☐ Yes

☐ No

12. Some people claim heat pipes can overcome process heat / mass transfer limitations (e.g. reactions, cooling of microchips, refrigeration plant...) – for more information on heat pipes, visit www.thermacore.com. Do you believe heat pipes could assist your process plant by 2010?

☐ Yes

☐ No

13. Do you think the utilisation of PI will be assisted by a switch from the current oil based economy to an alternative energy source (i.e. Hydrogen/Ethanol) by 2050?

☐ Yes

☐ No

14. What is your organisation's response to rapid advances in science and technology?

☐ Quick

☐ Moderate

☐ Slow

15. What is your organisation's response to customer's requirements?

☐ Quick

☐ Moderate

☐ Slow

16. What is your organisation's response to the global market?

☐ Quick

☐ Moderate

☐ Slow

17. Do you think that intensified technology could assist your organisation to respond positively to the above three influences (questions 14, 15, 16)?

☐ Yes

☐ No

YOUR NAME……………………………………………….

ORGANISATION………………………………………….

Thank you very much for your kind support and assistance.

9. APPENDIX II

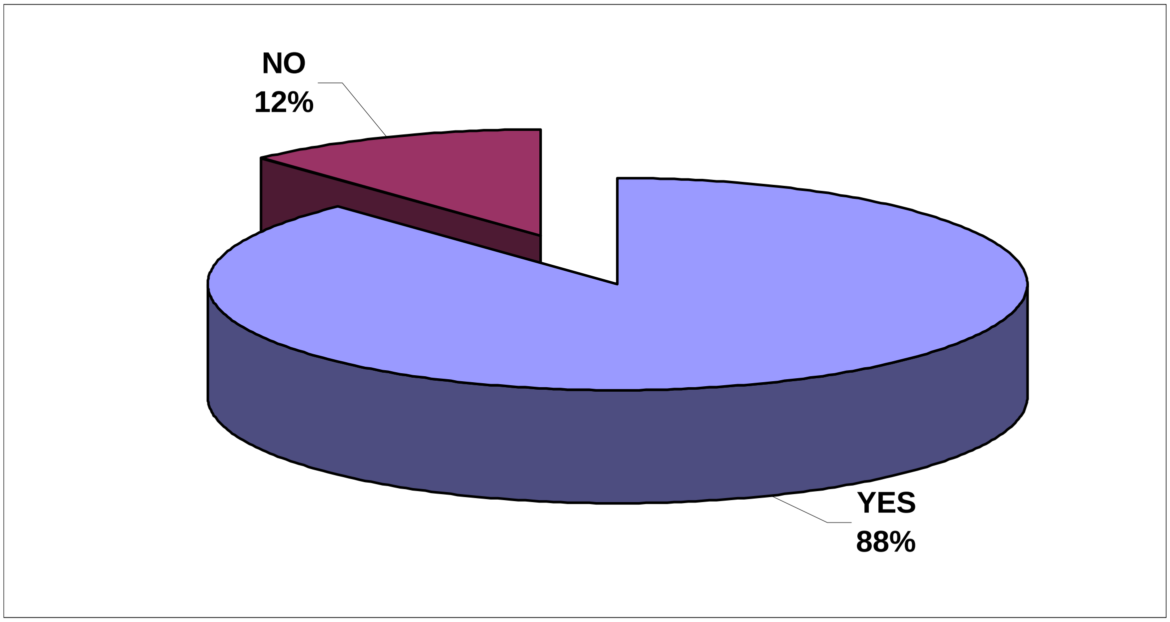
It should be taken into account that some of the experts belong to different sectors simultaneously, thus the total number of responses received can not be deduced from table 1.

Table 1: List of respondents by industrial sector and percentage of PI awareness.

TYPE OF INDUSTRY	Nº OF RESPONSES	% OF PI AWARENESS
Chemicals	16	100 %
Academia	13	100 %
Oil and Gas	12	83 %
Pharmaceuticals	7	43 %
Rubber and Plastics	6	100 %
Environmental systems	7	85 %
Paper and Board	4	100 %
Food and Drink	3	67 %
Process Safety	3	67 %
Textiles	2	100 %
Gov. Agency Energy and Env.	1	100 %
Engineering Consultancy	1	100 %
Power Generation	1	100 %
District Heating	1	100 %
Machinery	1	0 %
Aeronautical and Aerospace	1	0 %

Although the potential of the pharmaceutical sector to harvest the benefits of PI is enormous, it has turned out to have a minor knowledge of PI technologies (43%), which means that a worthy market opportunity for promoting its uptake has been identified.

Fig. 1: Experts familiarity with the PI concept.



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