# The Assessment of Future Environmental and Economic Impacts of Process-Integrated Biocatalysts


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The European Science and Technology Observatory (ESTO) has been commissioned by The Institute for Prospective Technological Studies (IPTS), Seville, Spain, to carry out the study 'The Assessment of Future Environmental & Economic Impacts of Process-Integrated Biocatalysts'.

The following ESTO partners took part in project*: Agence pour la Diffusion de l'Information Technologique* (ADIT) in France, *VTT Biotechnology* in Finland, *VDI-Technologiezentrum-Zukünftige Technologien* (VDI-TZ) in Germany, *Centre for the Exploitation of Science and Technology* (CEST) in the U.K., and the *Technical University of Denmark* (DTU) represented by *Kvistgaard Consult*. Background research and initial report writing was carried out by project partners from these institutions in the period from December 2000 to April 2001 with CEST as the operating agent.

DTU/Kvistgaard Consult did in August 2001 take over the role of operating agent and has in the period until December 2001 continued the study by undertaking interviews, analyses and the final reporting of the study.


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# Executive Summary

Biotechnology holds many promising prospects for an overall greening of the European Industry. The environmental benefits associated with substituting large quantities of harmful chemicals with environmentally friendly biocatalysts - often achieving improved quality of the end product as an added bonus -, is especially worth focussing on.

The key questions answered in this study are to what extent biocatalytic processes will be used in European industries in the future, and what impact on the environment can be expected. More specifically, the study examines which sectors hold good potential for the use of biocatalysts in production processes, and how sizeable this potential is. Further, the feasibility of fulfilling these potentials is assessed.

**Methodology**

This study is an assessment on a macro level. For some industry sectors it is possible to present one or more generic industrial processes - or archetypical processes. Although the specific processes differ between companies, production of similar products typically follows the same general production line. One or more such archetypical processes for each selected sector are used as basis for extrapolations in distinct sectors. Based on this comparative analysis of a traditional process and an enzyme-based process, it has been possible to give a quantitative assessment of the environmental impacts in terms of reductions in use - and subsequently in effluents of -, specific chemicals. Further, the difference in production cost between traditional chemical production and biocatalytic production is estimated to give a good basis for policy recommendations. The recommendations are also based on a row of factors identified in this study as sector specific drivers and barriers to a wider application of biocatalysts. All information needed to apply this methodology was gathered through desk research and interviews with both enzyme producers and users in selected industries.

**Sector Analyses and Future Potentials**

The selected sectors are the bulk industries pulp & paper, textiles, leather, and to a lesser extent fine chemicals & pharmaceuticals, and food Industry. For the last two, the assessment is of a more qualitative nature, due to the lack of generic processes in these very diversified industries dominated by a high degree of specificity.

***Pulp & Paper***

This study presents three archetypes in the pulp & paper industry - one for each major production technique prior to actual papermaking. The first represents enzymatic bleaching in chemical pulping, the second concerns energy conservation through use of cellulases in mechanical pulping, and the third enzymatic deinking in production of fibre from recycled paper.

The results can be summarised as follows: In bleaching of chemical pulp the production costs are lower for the enzymatic xylanases process compared to use of bleach chemicals ($ClO_2$), even before inclusion of environmental effects. In other words, this is an example of an application of enzymes, where factors other than average production costs stand in the way of fulfilling the potential. With respect to mechanical pulping, the saved expense to energy is not sufficient to tip the scale in favour of cellulases, when looking at the issues from the private companies point of view. Enzyme-aided deinking has been assessed to hold neither economic advantages nor disadvantages in comparison to the chemical alternative.

The potential environmental effects of applying these enzymatic processes industry wide are remarkable. Given the fact that the European production of chemical pulp was 22 million tonnes in 2000 and half was produced using ECF (Elementary Chlorine Free), total discharge amounts to 11 000 tonnes AOX (chlorinated organics) yearly. Applying xylanases to its full potential, means a 25 per cent reduction of the current level of AOX discharges, equal to nearly 2 700 tonnes.

Similar calculations can be made for mechanical pulping, which accounts for an output of 11.7 million tonnes of pulp. Looking at the reject refining step, the potential for energy saving is about 600 GWh per year. The reject step itself consumes about 900 kWh per tonne, but since only 30 per cent of the total flow reaches this step, the energy consumption relative to output is approx. 270 kWh/t. Assuming full market penetration and a potential of saving 20 per cent of the 270 kWh, total European energy need can be reduced by 632 GWh yearly. This potential saving is the equivalent of between 155 000 and 270 000 tonnes less $CO_2$ emissions depending on the emission factor applied, which is worth €1.4 million or €2.5 million at an emission trading price of 8$/t.

Figures for bio-pulping also reveal sizeable energy saving potential. Here, the reduction amounts to more than 8 000 GWh. However, the mere scale of this figure indicates that its realism is uncertain. Regarding this process, many questions still remain.

Many factors will impair full-scale, total adaptation of biotechnological methods, but the assessment of the feasibility reveals that the prospective for economic and environmental benefits in the sectors of pulp and paper is good. The main barriers in the pulp and paper industry are identified as the 'conservative thinking' in the mills and insufficient knowledge of biocatalysts among the managerial staff; chemicals are more familiar; suppliers are not present in the mills (unlike in the case of chemical suppliers); and there is no 'advertising' of biocatalysts in the mills. Other barriers are: Benefits (cost, process runnability, product quality) are small compared to those obtainable with traditionally used chemicals; little demand for products produced using biocatalysts; and finally that fierce international competition leaves a narrow margin for investments in new technology.

***Textile***

The selected enzymatic archetype process applies mainly to cotton as a raw material (approx. 25 per cent of the total industry output), and has three possibilities for substitution: Bio-desizing where amylases substitute caustics; enzymatic scouring with pectate lyases substituting caustic and peroxide; and finally enzymatic bleach clean-up where catalases substitute sulphite and reduce water usage significantly. The estimation of the effects of these archetypes is somewhat marked by incomplete baseline data for both economic and environmental costs.

All in all, this archetype shows good potential for substitution of the above-mentioned chemicals and thereby reducing the effluent levels of contaminants. The change in production technology does hold a significant scope for reductions in water and energy input. Most of the traditional chemical processes need a water temperature of 80-90°C, whereas enzymatic processes only require 40-50°C.

In two out of the three selected potential biocatalytic processes in this sector, the enzymes are cheaper than the chemical alternative: In scouring the saved expense to chemicals exceed the costs of pectate lyases by nearly €5 500 in processing of 1 000 tonnes of raw material. And in the bleach clean-up process, applying catalases means a net saving for the company of €21 000 per 1 000

tonnes of cotton. Further, there are considerably reduced water usage in these two biocatalysed processes compared to the traditional chemical techniques.

With regard to the third selected process, desizing, it is not reasonable to make an assessment on the basis of the figures for chemical savings and enzyme costs alone, since the change in energy, water and production capacity are sizeable, but hard to quantify due to lack of baseline numbers.

The potential environmental benefits are manifold: In the case of woven fabric, sizing agents represent 30 – 70 per cent of total COD of wastewater, and enzymatic desizing thus holds the potential to reduce COD significantly. The estimation of the future potential for desizing starts at 80 per cent, since this technique is already widely used. The potential for reducing the use of chemicals is therefore not enormous, but there is still a noteworthy difference of nearly 4 million tonnes of caustic. The estimations of the future potential for bio-scouring by contrast hold significant potential chemical reductions, since the current market penetration of pectinases is no more than 5 per cent. It is assessed that it can be applied industrially in 90 per cent of cotton processes in Europe and replace 24 million tonnes of peroxide and 14 million tonnes caustic annually. For bleach clean-up of cotton, the archetype showed a future potential saving on the use of sulphite with more than 10 million tonnes a year.

When looking at the feasibility of these potential environmental benefits, it is necessary to distinguish between mills and laundries. For the textile mills, the main drivers are quality improvements /added functionality of product; and that enzymes can help in complying with new environmental legislation. The list of barriers are longer and contains the following factors: Harsh economic restrictions in the sector limit investment resources; enzymes-aided processing does in some cases not reduce production costs; adoption of biocatalysts require new machinery; it is difficult to assess long term benefits and average production costs; inertia and risk aversion is present in management; and trials are very costly because large amounts of fabric at risk.

For the textile laundries, there is conversely a longer list of drivers than barriers. The drivers are: Strong focus on added functionality of product; no need for new machinery; trials are cheap / low risk of damaging small batches of raw material; and finally high and fast adaptability to new technology in management. Barriers are constituted by the facts that no reduction in production costs will accrue from switching to the enzymatic technology, plus a stigma that “eco-friendly products do not sell”.

***Leather***

The archetype established in this study contains two processes, where substitution of chemicals with enzymes can take place, namely bio-soaking of raw hides in a mixture of proteases and lipases as opposed to tensides, and bio-liming where proteases assist the chemical process of liming. These two processes are already in use and have a rather good market penetration of about 15 per cent in Europe. Technically, however, the penetration could be 100 per cent, or at least 70 per cent from a realistic market perspective.

The most effectual substitution at the liming step is selected, namely the “hair saving” technique. Baiting has a market share of 90 per cent, which is impressive, but it does not have any significant environmental effects and is therefore not examined in this report.

The biggest potential for reducing the environmental damage from the tanning industry comes from the substitution of lime (calciumhydroxide) and sodiumsulphide in the liming process step. It can potentially reduce the COD in the wastewater with up to 50 per cent if "hair saving" is applied. Sulphide can be reduced with as much as 40 per cent. This amounts to considerable quantities, as 1 tonne of processed rawhides on average results in 230 – 250 kg of COD and approx. 10 kg of effluent sulphide. For 1 000 tonnes of raw material input, this means a potential reduction of approx. 120 000 kg COD and up to 4 000 kg sulphide.

The results also show that the enzyme costs are higher than the chemical savings in both the soaking and liming production step, by €4 000 and €3 000 respectively per 1 000 tonnes of raw hides. There are quality improvements of the end products, which have not been included, but it is hard to imagine that they are significant enough to bridge the gap in costs.

When the environmental effects are included and valuated, the balance sheet looks very different for the two processes. With regard to bio-soaking, no quantifiable environmental effects have been identified, apart from the uncertainty surrounding BOD levels. Conversely for liming of hides, where even the most conservative valuation of the environmental effects tip the balance and make it socio-economically desirable to encourage the substitution towards enzymes.

For the total European sector, the study shows that with 100 per cent substitution, the use of tensides can be reduced with more than 34 million tonnes a year. Even with 'just' 70 per cent penetration, it would mean a reduction of 20 million tonnes tensides. Bearing in mind that there already is good market penetration today of around 15 per cent, and that enzyme suppliers deem a market share of 70 per cent technologically plausible, this is a rather uplifting prospect.

With regards to the liming process, there is a possibility of substituting a portion of the sodiumsulphide and calciumhydroxide (lime) with enzymes in a "hair saving" technique. It is estimated that around 40 to 50 per cent of these traditionally used substances can be replaced in this way. Looking at the effect for the entire sector, an increase from the present level of market penetration of 15 per cent to 100 per cent equals a reduction of 14 million tonnes of the liming chemicals. However, neither of these estimations of future potential are very likely without the appropriate incentive schemes for industry.

Looking at the environmental effects for the entire European industry, the maximum potential reduction of 3.4 million kg of sulphide can be realised whether "hair pulping" or "hair saving" is applied, since both techniques entail the same reduction in the sodiumsulphide input. The COD reduction of well over 100 million kg in the 100 per cent penetration set-up is estimated on the basis of the "hair saving" process only. In the more realistic estimation of future potential of 70 per cent market share for enzymatic processing, the effect is still a remarkable 65 million kg a year.

Regarding the feasibility increasing biocatalyst market shares, there are many similarities between the tanning industry and the textile mills. The drivers are: Quality improvements /added functionality of product; no need for investment in new machinery; and that enzymes help in complying with new environmental legislation. The barriers on the other hand are found to be the following: Enzymes aided processing does not reduce production costs; trials are very costly as they entail risk of damaging very valuable raw material; and again the presence of inertia and risk aversion in management.

***Other Sectors***
This section covers a range of industries that all have heterogeneous production processes, and for each process enzyme design must match exactly. This means that a general archetype cannot be developed for these industries.

Further, many "not bulk industry" companies are already very well acquainted with biotechnological R&D, contrary to industries in the pulp & paper, textiles and leather sectors. The companies are therefore able to produce biocatalysts themselves. This makes the market very difficult to analyse, since the demand and the supply side coincide. Revealing the true price and quantity of enzymes produced and consumed in-house are practically impossible.

This, in combination with the difficulty of constructing an archetype process, means that quantitative assessments of future environmental and economic impacts cannot be made. Nevertheless, there are indications that they have a biotechnological potential that may well surpass all other sectors. The food sector along with the fine chemical & pharmaceuticals industry are looked at as examples.

In food production, enzymes have a number of advantages. Among other things, they are more specific in their action than synthetic chemicals. Processes, which use enzymes, therefore have fewer side reactions and waste by-products, give higher quality products and reduce the likelihood of pollution. Furthermore, they allow some processes to be carried out which would otherwise be impossible.

The most important bottlenecks for increasing enzymes applications in food markets are public acceptance and legislation related to the use of enzymes, which are produced by genetically engineered micro-organisms.

Biocatalytic methods are used in both the fine chemical and pharmaceutical sectors in the synthesis of a wide variety of compounds. The synthesis of each particular class of molecule requires a unique series of steps, and there is no single bio-transformation process, which can serve as an archetype. Additionally, it has proven impossible to gather comparative data on costs of synthetic pathways using a bio-transformation step compared with a more traditional route. However, examples are described in this study of reactions in which biocatalysts have been successfully used to either substitute processes conventionally done by other chemical means, or of reactions that are only really economically viable through the use of a biocatalyst.

Drivers in this sector are mainly related to the properties of the enzymes: Specificity/selectivity; mild conditions; simpler processes; regulatory/safety preferences. The barriers on the other hand are identified as: Cost and instability of catalyst; need for precise control of conditions; slow rates/ high residence time; unfamiliarity and high R&D costs.

**Conclusions and Recommendations**
In conclusion, it is found that the relative production cost associated with enzyme-aided processes is a very important factor. In four of the archetypical processes assessed in this study, a change from chemicals to enzymes is not cost effective for the companies, so often the bare economic figures do not speak in favour of the enzymes. The assessment of environmental costs, shows significant environmental external benefits resulting from all but one of the selected biotechnologies. These effects include a potential decrease in clean-up costs, and saved water and energy costs. In three

archetypical cases, the production costs are however found to be lower for the enzyme process. For one archetype, there is no price difference, as the price of the enzymes equals the savings on chemicals. The fact that not all companies use the cheaper bio-techniques indicates the presence of other significant barriers, which in turn can be addressed by a variety of policy instruments.

The results from the established archetypes are used in the estimates of future potentials for environmental effects on a European level. They display significant potential reductions in both chemical input and wastewater effluents. Not only is it possible to substitute away large amounts of chemicals, but real savings can also be made with respect to valuable resources like energy and water. The introduction of biocatalysts has in sum proven to be a powerful tool as part of an overall strategy for greening the European industry.

A concluding discussion examines the drivers and barriers identified through interviews. Apart from the economic facts, a row of other influencing factors is identified. The aspect of risk involved in production line trials of new enzymatic processes stands out as a major deterrent, whereas pollution limit values act as a strong push force.

A number of policy recommendations are outlined on the basis of the results of the study. Both command and control instruments like legislation on pollution levels and economic policy tools like taxes, time-limited subsidies, transformation benefits, technology transfers, and public funding of full-scale production trials, are suggested. In addition institutional mechanisms are proposed, which include suggestions for information campaigns, practical demonstrations, R&D networks for managements of similar size (smaller) companies in different sectors, environmental performance indicators, and environmental management schemes.

Considering the potential for reducing the strain on natural resources by European industry, there are strong incentives for applying such policies, whereby assisting a wider application of process-integrated biocatalysts and thus supporting the greening of the European industry.

# 1. Introduction

The rich possibilities of utilizing biocatalysts in industrial processes continue to expand as a result of both private and public research and development. Biotechnology is now a mature industry with a broad range of possible commercial applications within the production of commodities. The potential of this technology has been highlighted in a number of reports[1] and case studies have shown that biocatalytic production processes tend to be more environmentally friendly and less cost-intensive than traditional chemically aided methods[2]. However, assessments and prognoses in this field have until now not been backed up with quantitative estimations and figures.

This study will provide an assessment of the impact that biocatalytic processes potentially can have for the European industry in the future. Within this context, it is of particular interest to identify in which sectors a strong development can be expected, and what the specific economic and environmental impact in each sector will be. The results of this process will serve as an information base for policy makers at a European level.

*The key question to be answered in this study is to what extent biocatalytic processes will be used in European industries in the future, and what resulting impact on the environment can be expected.* To help evaluate this, trends will be estimated for a series of time horizons, in order to approximate the development of the future application of biocatalytic processes.

The sub-questions in this study are:

- In which sectors is there good potential for the use of biocatalysts in production processes, and how great is this potential?
- What are the key economic factors for the relevant sectors – in other words what are the difference in techno-economic costs between traditional chemical and new biocatalytic production?
- What are the related environmental effects - can they be quantified and priced?
- Which policy recommendations can be made in order to achieve the full potential for substitution?

## *1.1. Methodology*

This part of the report explains the methodology applied in the estimation of the potential benefits from substituting harmful chemicals with biocatalysts in the European industrial production.

The core question of the study is an assessment on a macro level of the potentials of biocatalyst applications in industrial sectors and the economic and environmental impacts hereof.

It is important to emphasize the focus on the macro level, as it is not the intention to repeat existing studies and work focusing on cases and examples. In stead, generic or archetype processes are used as basis for extrapolations and estimations of the effects of applications of biocatalysts within selected sectors, leading to estimates of the future potentials.

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[1] UBA (1996): *Stand und Perspektiven der Katalysatoren- und Enzymtechnik, Sachstandsbericht des Büros für Technikfolgenabschätzung beim Deutschen Bundestag*, OECD (1998): *Biotechnology for Clean Industrial Products and Processes,* OECD (1994): *Biotechnology for a Clean Environment: Prevention, Detection, Remediation,* European Biotech /Ernst & Young (1997): *A new Economy*, and others.

[2] E.g. JRC/IPTS (January, 2000) and Etschmann/Gebhardt/Sell (2000).

## 1.2. The Archetype Approach

For some industry sectors it is possible to present one or more generic industrial processes - or achetypical processes. The archetype process is used in this study with inspiration from microeconomics and refers to a sector specific average production function representing the production output as a function of (a combination) of production factor input (typically labour and capital). In an open economy as the EU with full competition and free exchange of information, differences between firms will (theoretically) be eliminated and an average sector specific production function will be established. Although the specific processes might differ between companies, production of similar products typically follows the same generic and average production line.

When a process is drawn up, estimates are made of the throughput beginning with input of raw material and ending with the output of end products. The substitution relation between inputs of enzymes[3] and chemicals are incorporated, which requires detailed quantitative data on the volume of enzymes needed to process, say, 1 000 tonnes of raw material, compared to the amounts of chemicals traditionally used.

Based on this comparative analysis of a traditional process and an enzyme-based process, it is possible to give a quantitative assessment of the environmental impacts in terms of reductions in use. Subsequently, the environmental effects in the shape of change in effluents related to the archetypical process, is assessed. To this end a number of environmental baseline numbers are also needed, as well as specific information on the relation between chemical input and contents of the waste water.

The information needed to establish one or more archetypes for each industry with estimates of the economic and environmental effects is gathered through desk research and interviews with both enzyme producers and - to a lesser extent -, enzyme users in the different industries. More on this in section 2.1.3 regarding data and background information.

## 1.3. Selected Industries

**Brief Overview of the Enzyme Market**

Enzyme solutions today cover more than 20 different industries in the food, feed and technical sectors and there is thus a multitude of potentially relevant sectors in relation to this study.

The total market for industrial enzymes is relatively small but growing in commercial terms, with the number of companies selling enzymes doubling during the 1980's. However, the number of enzyme producers is still very small and three major suppliers dominate the market as a whole. Novozymes account for about 50 per cent of world enzyme sales and other major producers are DSM/Gist-brocades, Genencor International and Röhm.

The producers are the leading actors in the development of new enzymes, and Europe's economic capacity in this field is based very strongly on the position of these companies.

The largest group of buyer of enzymes today on both the global and European market is the detergent industry, followed closely by the textile, starch, dairy, other food and animal feed

[3] The terms *enzyme* and *biocatalyst* are used interchangeably in this report.

industries. A substantial portion of buyers fall outside these categories though, encompassing pharmaceutical and fine chemistry manufacturers, plus companies in bulk industries like pulp and paper production.

Among bulk commodity producers the main determinant of biocatalyst demand is the relative cost. In bulk commodities, markets tend to be mature in that competition and experience has accumulated over time and has ironed out most technological differences between manufacturers. The competition is thus mainly on price and the sub suppliers - including the enzyme producers -, have to deliver cost efficient products.

The cost competition may also restrict the extent to which it is economically feasible to develop new enzymatic processes. Even when efforts to develop new enzymes targeting bulk substrates have been technologically successful, the results have not always been commercialised. However, when biocatalysts are required by bulk product industries, the demanded quantities are almost automatically large, allowing biocatalyst producers to invest in the development of new/improved biocatalysts. At the same time does economies of scale secure a competitive price of the enzyme. This is all in theory, though! As enzymes are relatively expensive compared to chemicals, they are in reality rarely applied in the production of bulk products, unless environmental concerns or functionality are of critical significance.

The reason why pharmaceutical and fine chemistry companies are other substantial buyers is the high degree of value added in the production of their products.

The present relatively high cost connected with developing and producing enzymes for industrial use, do in sum mean that they are best suited for use in production processes that generate high added value to the raw material or bulk industries.

**Selected Sectors**

This report has chosen to focus on assessing the potential for substitution of chemicals with enzymes in the *pulp and paper*, *textile*, and *leather* industry. In addition to these three sectors, there is also a less quantitative treatment of the Food Industry, and Fine Chemicals & Pharmaceutical Industries.

The main rationale behind this choice is:

- The pulp and paper, textile, and leather industries generate serious environmental effects stemming from large quantities of chemical in- and output and therefore great need and potential for improvement.
- In the detergent sector, enzymes are used almost absolutely as additives and there is therefore no *process-integrated* substitution of chemicals.
- Sectors like food, animal feed, pharmaceuticals and organic synthesis in general are extremely heterogeneous. Quantification of future effects can therefore only be done rather superficially.
- Some industries manage adoption of biocatalysts quite well. One example is the detergent industry. Conversely, sectors where the private economic situation hinders embracing of new technology are relatively more interesting in this analysis.

- The methodology on this study builds on establishing generic archetype production processes, and this approach is simply not very applicable to other sectors, which are characterised by a high degree of specificity.

## 1.4. Data and Background Information

JRC/IPTS has carried out a series of relevant studies on industrial use of the biocatalysis and these will be taken into account throughout this study report[4]. A number of JRC reference documents on Best Available Techniques[5] are also very relevant as background information, since they give extensive technical information on production processes in a wide range of industries - including the bulk industries selected for analysis in this report. They do not however, look at biocatalysts at all. This is surprising and necessitated generation of new information to carry out the analysis in this study.

Generation of new knowledge and data has been achieved through a series of interviews and questionnaires directed at enzyme producers and users. This information have been the backbone in the set-up of archetype processes for the specific sectors covered in this study. This means that the archetype processes are designed with the help of experienced industrialists and that values as well as volumes of input and output constituting the average production function is experienced based, or at least reflecting qualified estimations based on practical experiences. On the producer side does Danish based Novozymes (formerly Novo Nordisk) have a total world market share of 45 per cent - and with regards to technical enzymes their market share is 50 per cent. This representative of the producer side and the German based Röhm Enzyme GmbH6 have both been very forthcoming and helpful.

General statistical background information has been gathered from industrial databases relevant to the different sectors plus from European economic and statistical institutions like OECD and Eurostat.

## 1.5. Economic Assessment

What is the production economics related to specific applications of biocatalysts? In many cases the price of the enzymes represent a significant cost element, but the implementation of this new technology can also result in decreases in production cost. E.g. continuous as opposed to batch-wise operations may mean the costs of both raw material, water and labour can be dramatically decreased (OECD, 2001, pp.39). It is therefore necessary to outline all relevant economic factors from the producer's point of view to get a better understanding of the internal decision making in the firms.

The economic factors include production costs like raw material, energy, water, labour and output factors like improved quality and resulting higher price of end products.

Via the archetype(s) established for each sector, it is possible to set up a balance sheet showing the economics of substituting chemicals with enzymes. This will form the basis for extrapolating prospective estimations to demonstrate the effects of full realisation of the potentials. This is by no

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[4] JRC/IPTS (1998): *Biocatalysis – State of the art in Europe*, EUR 18680 EN, Seville, 1998.
JRC/IPTS (2000): *The introduction of process-integrated biocatalysts in companies*, EUR 19582 EN, Seville, 2000.

[5] See References

[6] Special thanks to Dr. Gerald Jungschaffer for assistance on the substitution of emulsifiers by enzymes.

means an easy task, and - as with all efforts to make such predictions - it involves equal parts guesswork and crude assumptions. The main challenge is aggregating assumptions from a micro level to cover the total European market for several industries. The archetype approach does however make it possible to formulate such illustrative calculation, with a measure of uncertainty obviously still present.

## *1.6. Environmental Assessment*

In addition to the economic change stemming from improved productiveness and different costs related to inputs, an estimation of the environmental benefits should be made, if the calculations are to reflect the real socio-economic effect and serve as a basis for policy recommendations.

In general, enzyme related environmental savings can be reached by the following way: Enzymes work best at mild temperatures and in mild conditions. They can be used to replace harsh conditions and harsh chemicals, thus saving energy and preventing pollution. They are also highly specific, which means fewer unwanted side effects and by-products in the production process. Finally, enzymes themselves are biodegradable, so they are readily absorbed back into nature.

To deal with questions of environmental effects laid out in this study, it is first necessary to establish some baseline information. This is done for selected industrial sectors, but limited to issues relevant to the *process-integrated* replaceable chemicals, and thus not looking at end-of-pipe remediation problems.

With baseline information established for the different archetypes, it is possible to map out the potential benefits from the introduction of enzymes into the production. Not all effects are known and some are not quantified and the related environmental costs can therefore not be estimated. That does of course not make these effects less important, and they should not be ignored. In sum, as many of the environmental effects as possible related to the selected industries will be assessed in a qualitative way. Environmental economics will be considered whenever possible.

This in turn entails valuation of the potential reduction in environmental damage effectuated by a change in process technology towards enzymes - which is not an uncomplicated matter to handle. Actual plug-in values for foregone abatement/clean-up/ecological damage costs of e.g. one tonne of SS (suspended solids) in a particular concentration are not readily available today, though many initiatives have been taken to make it so. One example is the European Commissions' Sixth Environment Action Programme, which has published a number of reports on integrated economic and environmental assessment[7], stressing that such valuation should be endeavoured in assessments like this.

For the purpose of valuating the environmental effects in this study a number of illustrative values will be applied. These are based on earlier fieldwork studies of abatement costs in Europe conducted by Kvistgaard Consult and adapted to this study. The valuation parameters for effluents to water range between €3.0 per kg and €0.6 per kg[8] and reflect a quite conservative form of

[7] See: *Sixth Environment Action Programme,*
http://www.europa.eu.int/comm/environment/enveco/priority_study/index.htm

[8] These values are based on estimates of clean-up costs of COD and BOD in a wide variety of waste water treatment plants. The valuation of other types of effluents are therefore less robust than for these two measures.

environmental valuation, since it is based on alternative abatement costs and thus do not represent e.g. potential damage to ecosystems. This approach has been chosen for two reasons: First, there are less uncertainty and less variation related to estimated abatement costs, as they are based on actual market costs of waste water treatment. Secondly, nearly all of the industry in this study are either connected to - or have their own -, waste water treatment facility.

In table 1 below is a schematic overview of an account sheet for the calculation of the real socio-economic costs in relation to an archetype substitution of chemicals with an enzyme.

**Table 1 - Example of Socio-economic Estimation**

| | |
|---|---|
| ***Economic effects:*** | |
| - | Added Enzyme costs |
| + | Chemical savings |
| + | Energy savings |
| + | Water savings |
| = | **Total economic costs** |
| ***Environmental effects:*** | |
| + | Foregone cleanup cost of XX t/a COD |
| + | Foregone cleanup cost of XX t/a BOD |
| **=** | **Total environmental costs** |
| **=** | **Total socio-economic value added** |

## *1.7. Future Potentials and Policy Recommendations*

As the purpose of this report is to assess future potentials, it is necessary to outline estimations for the coming years. This will be done on the basis of current market shares and up to date information on technological possibilities and the likelihood of their industrial application.

The economic and environmental costs per tonne raw material input is scaled up for the industry as a whole to give indicative overall figures of the impact of full conversion to enzymatic processes. To give a more nuanced look at possible future situations, different levels of enzyme market shares of e.g. 30, 60 and 100 per cent are applied. The chosen illustrative market penetration levels vary according to present and realistic future expectations expressed by the interviewees.

Where possible, future potential environmental effects are also calculated relative to the different prospective market penetration of enzymatic processing. Note that all figures in the sections on future potential depict the annual European consumption/effluent level for an archetype.

However, setting up estimations of future potentials is not the same as achieving them. The study therefore also focuses strongly drivers and barriers in the selected sectors and archetypical processes. The economic factors in play include the unit costs related issues already calculated, but other factors like the industrial organisation and the restraints on investment funds may also play significant roles. Similarly is there a host of environmental and institutional factors, which are of great importance. The interviews with enzyme producers and users are used to identify all relevant factors - be they of the economic, environmental or institutional kind -, for the selected sectors respectively.

On the basis of this new information the report discusses and lists a row of policy recommendations, which can be instrumental in achieving the potential market penetration leading to environmental impacts in the magnitude calculated using the archetype approach. These policy tools contribute to changes in behaviour due to changes in the relative costs of the production factors and therefore contribute to the achievement of the impacts estimated.

If the estimated impacts are desirable from a Community point of view, then these or other political instruments can be employed to change behaviour and thereby create the foundation for the increased penetration of enzyme systems.

# 2. Sector Analyses and Future Potentials

## *2.1. Pulp & Paper*

The companies in the European pulp and paper sector are among the biggest in the world. Production and productivity is high, and the market is growing. A range of biotechnological techniques is available to the sector, but so far the use of these techniques is limited, primarily because they are still inadequate in terms of cost and performance. However, continuous technological improvements are rapidly overcoming these barriers, and within the next decade the sector may well find itself among the leading users of process-integrated biocatalysts.

### 2.1.1. Sector Description

In 1996, the number of European mills in the pulping business was 222, and 1 064 were in the paper business. The largest plants are located in Finland and Sweden, these two countries accounting for the bulk of pulp production (approx. 29.9 and 30.2 per cent of wood pulp for papermaking). Most of the pulp is used within the company as a direct input for paper production. The rest is sold on the market - hence its name; market pulp.

According to the JRC/IPTS document *Best Available Techniques in the Pulp and Paper Industry*, the distribution of the mill is as follows: Sweden and Finland have most of the larger mills with a capacity of over 250 000 tonnes per year and only a few small mills in the size range of less than 10 000 tonnes per year. The average size of pulp mills in Western Europe is thus 180 000 tonnes per year. Of the 222 pulp mills in Western Europe 74 are producing market pulp (JRC/IPTS, July 2000).

Paper mills are also mainly found in Sweden (12.4 per cent of EU paper production) and Finland (14.2 per cent), though the single largest producer country is Germany (20.2 per cent). France, Italy and the UK also have a significant production. Contrary to pulping, the paper industry is not directly linked to the presence of wood, since recycled paper constitutes a large part of the input. This explains why paper production is more spread out across Europe. Again, the largest mills are located in Sweden and Finland.

**Output/Production**

The EU-15 mechanical pulp production was in 2000 11.7 million tonnes, whereas chemical pulp production amounted to 22 million (FAO). Out of the total production[9] only 9 million tonnes was sold as market pulp. The bulk of the production is thus used as input in own production of paper. The total production of paper amounted to 84 million tonnes in the same year (FFIF/CEPI).

**Turnover**

The turnover of the whole sector is reported to be €114.6 billion in 1996, corresponding to a gross value added at market prices of €39.8 billion (JRC/IPTS, January 2000). The EU-15 consumption of paper amounts to 66 million tonnes per year in 1995 and it thus follows, that the sector is a gross exporter. The total turnover constitutes a 3 per cent share of the total European manufacturing industry (JRC/IPTS, July 2000).

[9] Which by FFIF/CEPI was reported to be 35 million tonnes of pulp in 2000, – leaving a discrepancy with the FAO statistics of 1 million tonnes.

**Employment**
Generally, pulp and paper production is capital intensive - not labour intensive. The sector employs around half a million people in Europe[10].

**Trends and Perspectives**
The sector does not find itself in a stable position. It is currently going through a general restructuring, which implies concentration and internationalisation. There have been considerable job-losses in the last decade, but things seem to be looking up and it is predicted that paper manufacturing will experience steady growth in the coming years. For world demand, a growth rate of about 2.4 per cent is estimated. The world demand for paper is expected to reach 410 million tonnes by 2010, where half is produced from recycled fibre.

**Process**
The sector encompasses a number of different production techniques and processes. However, the common processes are chipping, pulping, bleaching and then of course papermaking.

In chipping, wood logs are cut into thin wood chips, which are used in pulping where fibres in the wood chips are separated. This can be done chemically in high alkalinity and temperature (chemical pulping). In fibre separation can also be done mechanically using energy (mechanical pulping) or using a combination of energy and chemicals (chemi-mechanical pulping). Recycled paper is disintegrated in water with chemicals in order to liberate fibres for further use.

Pulp is either used directly in papermaking or bleached, if white fibres are needed in papermaking. Natural wood fibres are white in colour, but the lignin in the fibres yellows when exposed to light and heat. In chemical pulping, the chemical reactions turn lignin dark brown in colour. In bleaching, the colour forming structures - mainly lignin - are either removed from the fibres or converted to non-colouring structures.
Paper (or board) is formed from pulp and additives in paper (or board) machines. An essential part of both pulping and papermaking is the process water circuits and wastewater treatment. Water management is important for maintaining good process runnability, product quality and minimum pollution loads.

Chemical pulping, which accounts for the largest part (70-80 per cent) of world production, can be divided into two subtypes: Kraft pulping and sulphite pulping. The most widespread technique is kraft pulping.

Mechanical pulping accounts for substantial outputs, especially in Europe, where a total of 101 mills produce mechanical pulp. These are located in Finland, Germany, Sweden, France, Italy and Norway.

**Input**
The input in the papermaking process is fibres from both pulp mills and fibres from recycled paper (secondary fibres). Other substances like papermaking chemicals are also used in unfixed amounts

[10] Sources diverge somewhat on this issue: JRC/IPTS (July 2000) reports 260 000 employees in 1996, while JRC/IPTS (1998) reports 620 000 employees.

depending on the paper type produced. Energy consumption of paper manufacturing is in the range between 100 – 3 000 kWh/t.

Western European consumption of pulpwood used for pulping was 119.5 million $m^3$. Production of 1 tonne of chemical pulp requires 4 - 6.6 $m^3$ of wood according to the JRC/IPTS (July 2000), whereas UBA (1998) reports 7.6 $m^3$.

Apart from wood, the main pulp production inputs are water, energy, and chemicals. The amount of chemicals necessary to produce 1 tonne of kraft/mechanical pulp is reported to be:

**Table 2 - Chemical Input in Kraft Pulp Production**

| *Chemical* | *kg/tonnes* |
|---|---|
| NaOH | 25-50 |
| $O_2$ | 5-25 |
| $NaClO_3$ | 20-50 |
| EDTA | 0-4 |
| $SO_2$ | 2-10 |
| $H_2O_2$ | 2-30 |
| $O_3$ | 0-5 |
| $MgSO_4$ | 0-3 |
| CaO | 5-10 |
| *Source: JRC/IPTS, July 2000* | |

The above figures are indications of averages, as the mill-specific figures vary greatly. In relation to bleaching, much depends on whether so-called ECF (Elemental Chlorine Free) or TCF (Totally Chlorine Free) is used. Using ECF involves the use of chlorine dioxide ($ClO_2$ produced from $NaClO_3$), alkaline, peroxide ($H_2O_2$), and oxygen in defined sequence. TCF bleaching involves use of oxygen, ozone or peracetic acid and peroxide alone or with alkali.

Pulp processing also requires substantial energy input. Figures in the magnitude of 10-14 GJ/ADt heat and 600-800 kWh/ADt electricity are reported for the kraft pulping process.

The mechanical pulping process has different input characteristics than chemical pulping. Only about half the amount of wood is required to produce the same quantity of pulp, and chemical consumption is negligible. However, energy requirements are massive. On average, approximately 2 500 kWh electrical energy is required per tonne of pulp. This is a rough estimate, since there are large variations depending on the type of wood used as input.

Fibres from recycled paper is reported to account for 49 per cent of all paper production inputs in 1997 (JRC/IPTS, January 2000). The share can be expected to rise, as recycling infrastructure is being improved in many European countries. For the deinking process, chemical input is hydrogen peroxide and sodium peroxide. Further, an amount of approximately 2 kg/t of EDTA is used.

**Environmental Baseline Load**

The pulp and paper industry produces discharges to water and air, in addition to solid waste. Some processes (i.e. mechanical pulping) also carry a heavy resource burden due to high energy and water consumption.

The main emissions to air are well-known pollutants like $NO_x$, $SO_2$, CO, $CO_2$ and particulate matters. Some chlorine compound emissions are still reported, despite great efforts to avoid this. Wastewater from the industry is typically characterised by high biological and chemical oxygen demand (COD and BOD), and contains chlorinated organics (AOX), nitrogen and phosphor.

The amount of emitted substances depends very much on the choice of delignification and bleaching techniques. The use of chlorine has decreased significantly in the past years due to public concern, and thus the associated emissions have decreased similarly. Most production today is based on ECF (Elementary Chlorine Free) and TCF (Totally Chlorine Free) processes, while the utilisation of elemental chlorine ($Cl_2$) has been practically abandoned.

Mechanical pulp mills do not discharge chemicals at any significant level, but an average kraft pulp mill is reported to discharge the following:

**Table 3 - Average Effluents, Kraft Pulp Mill**

| | Flow m3/t | BOD kg/t | COD kg/t | AOX kg/t | TSS kg/t | Tot-N kg/t | Tot-P g/t |
|---|---|---|---|---|---|---|---|
| Unbleached pulp | 20 – 80* | 1 - 20 | 7 - 50 | - | 0.2 - 15 | 0.1 - 1 | 3 - 40 |
| Bleached pulp | 30 – 110* | 0.2 - 40 | 4 – 90** | 0 - 2 | 0.2 - 10 | 0.1 - 0.8 | 5 - 90 |
| *Explanatory notes:* **) Figures above 50 $m^3$/t usually include cooling water* ***) A green-field mill starting operating in 1996 reports 4 kg COD/t as annual average (1998)* | | | | | | | |
| *Source: JRC/IPTS, July 2000* | | | | | | | |

The typical process used when dealing with recycled paper does in contrast emit certain heavy metals, which are not biodegradable. The metals are removed from the process with EDTA in order to be able to bleach the pulp with hydrogen peroxide. Unfortunately, this study has not been able to uncover, what quantity of heavy metals is associated with the EDTA dose. Such data would be interesting, since enzymes (possibly in combination with other substances) has been claimed to be able to completely remove the need for EDTA. But since it is a new concept based on only one example of industrial application[11], it would not have been a very robust result at any rate.

However, enzymes have been clearly proven to reduce the need for hydrogen peroxide and sodium hydroxide in the process. These substances are strong bases and are not environmentally harmless.

Over the recent years, the pulp and paper business has improved its environmental standards significantly, and chemical discharges are not anywhere near as harmful as in the past. JRC/IPTS (January 2000) reports that the European pulp and paper industry have invested approximately 6-8 billion EURO in environmental improvements over the last 10 years, and that as much as 20 per cent of mill investment costs are environmental costs.

However, the industry remains very energy intensive. As previously mentioned, a typical mechanical pulping mill consumes 2 500 kWh/t electrical energy, and a chemical mill consumes 600-800 kWh/t. This excludes the energy needed for producing the input chemicals. TCF mills,

[11] Dalum Papir Maglemoelle, Denmark

though low on discharge, use substances like ozone, which is expensive to produce in terms of energy[12].

With regard to emissions to air, the situation is more complex, and the emissions are not as easily summarized[13].

### 2.1.2. Biocatalysts

**Technological Possibilities**
Table 4 below shows the potential of biocatalysts in different stages of manufacturing.

**Table 4 - Potential Biocatalyst Applications, Pulp & Paper**

| *Process stage* | *Biocatalysts* | *Benefits* |
|---|---|---|
| Raw material pre-treatment: | | |
| Debarking | Pectinases | Energy and raw material savings |
| Wood preservation | Micro-organisms (fungi) | Environmentally benign methods |
| Mechanical pulping: | | |
| Pre-treatment | Micro-organisms (fungi) | Pitch removal, energy savings |
| Refining | Cellulases, Lipases | Energy savings, improved product quality |
| Chemical pulping: | | |
| Bleaching | Hemicellulases (xylanase), Laccases | Improved brightness, chemical savings, increased capacity, reduced AOX-formation |
| Paper manufacturing: | | |
| Drainage | Cellulases, | Chemical savings, improved product quality |
| Deinking | Hemicellulases | Chemical savings |
| Wet end chemistry management | Various enzymes | Improved runnability, slime control, improved product quality, reduced chemical need |
| *Source: JRC/IPTS, 1998, pp. 33* | | |

The table illustrates options and possibilities for application of biocatalysts in the pulp and paper sector, but the list is by no means exhaustive.

This report will focus on a few of these techniques, namely those that are most promising and best documented.

- Biopulping: Woodchip pre-treatment with enzymes

JRC/IPTS (1998) states that this technique can cut energy consumption in mechanical pulping by as much as 50 per cent, but other literature gives more conservative estimates. A reasonable average saving estimate seems to be 30 per cent (OECD, 1998). The real effect of application is still quite uncertain, mainly because the technique has just emerged from its infancy stage and has only been tested on pilot project scale.

The preteatment consists of biotechnological modification of the raw material with white rot fungi. The fungi (like *Ceriopsis subvermispora* or *Phanaerochaete chrysosporium*) help overcome some

[12] Ozone is often produced at the mills.

[13] The JRC/IPTS (July 2000) BREF-document on Pulp and Paper includes a survey from Swedish pulp mills, which give an indication of the emissions of active chlorine to air.

of the drawbacks of mechanical pulping, namely generally poorer strength properties, high electrical energy requirements and the few suitable species of wood. (JRC/IPTS, 1998)

The process has also been shown to reduce the amount of pitch (substances such as resin) in the pulp. Pitch becomes a problem, when pulp is used for papermaking. Introduction of biopulping can reduce the need for further resource-consuming depitching activities.

Though the potential for energy saving appears to be immense, sceptics argue that large scale industrial application lies many years into the future. Biopulping requires considerable changes to the production facility and its processes, and it does not scale easily. Given the risk aversion in the industry, these investments may be prohibitive. For this reason, our focus on bio-pulping will not be strong.

- Enzymatic reject refining

This is a fairly new enzyme based technology aimed at improving the efficiency of mechanical pulp production. Considerable energy savings are obtained at the reject step in the mechanical pulping process. Not all woodchip enters the reject step; only the wood that did not reach a sufficient quality level during the first two steps of the pulping process. In quantitative terms, this is about 30 per cent of the input.

The reject is treated with cellulases, which modifies the fibres to be more susceptible to reject refining. Energy savings of 10-20 per cent, unchanged yield level and even improve fibre properties have been reported (Pere et al., 2000). Though the amount of energy potential saved is smaller than in the biopulping approach, this technique has the great advantage that it is very easy to apply. Some equipment like pumps and possibly a tank for retention are needed for reject refinery and these are only available in some pulp mills.

- Enzyme-aided bleaching #1: Xylanase-aided bleaching

This is a very promising technology and consists of using a fungal treatment in the bleaching step. It has already entered a stage of commercial use, though the number of companies using it remains low - maybe around 20 worldwide (UBA,1998). In fact, enzymes have been used as bleach boosters since 1991. Enzyme-aided bleaching is used in chemical pulping. The kraft process itself removes about 90 per cent of the lignin in the wood, leaving 10 per cent, which gives the substance a brown colour. Traditionally, chemical bleaching of the substance dissolves the remaining lignin, resulting in white pulp. Once, active chlorine was used, but this practice has been abandoned, due to serious environmental concerns. Today the most widespread techniques are ECF and TCF, which are described above. Even though no active chlorine is used, the chemical consumption is still heavy, and there is still some concern about the discharges (specifically AOX) to nature. Reduction and partial substitution of the bleaching chemicals with biological methods would therefore be advantageous.

Treating wood pulp with xylanase prior to bleaching reduces the need for chemicals. For ECF, the process is reported to reduce chlorine consumption by 10-25 per cent (JRC/IPTS, 1998, and others). However, the potential may be as high as 35 per cent according to experiences from a Japanese mill. Combined with low investment costs and low prices of xylanase, this technology has many aspects making it attractive to the pulping business. Some sources even report higher yields due to enzyme-aided bleaching (OECD), though this point is not entirely clear (i.e. JRC/IPTS, July 2000 reports reduction in yields).

- Enzyme-aided bleaching #2: Laccase-mediator bleaching

An interesting enzyme application for pulp and paper processes is the direct delignification of pulp by mediated enzymatic oxidation, i.e. by laccase-mediator system. Unlike xylanase-aided bleaching, the laccase-mediator concept in chemical pulp bleaching results in a direct enzymatic delignification. Thus, it is a true possibility for substitution of bleaching chemicals such as oxygen and chlorine dioxide. Delignification up to 40 per cent has been achieved by laccase-mediator treatment followed by alkaline stage. In the laccase-mediator concept, the mediator oxidized by laccase acts directly on lignin and results in efficient delignification. The most effective mediators in delignification usually contain N-OH functional groups. The high cost due to the mediator dosage needed, and the potential of generating toxic by-products in batch system are, however, concerns when the system is incorporated to mill scale bleaching. (Viikari et al., 2002)

- Enzymatic pitch removal

This is an interesting possibility, which previously has received attention in the literature. Quoting OECD (1998) *Biotechnology for Clean Industrial Products and Processes* (§108); 'pitch is the mixture of hydrophobic resinous materials found in many wood species, which causes a number of problems in pulp and paper manufacture. Traditional methods of controlling pitch problems include natural seasoning of wood before pulping and/or adsorption and dispersion of the pitch particles with chemicals in the pulping and papermaking processes, accompanied by adding fine talc, dispersants and other kinds of chemicals. During the past ten years or so, biotechnological methods have been developed and are now being used industrially. In the late 1980s, scientists in Japan discovered that the treatment of mechanical (groundwood) pulps with lipases, which catalyse the hydrolysis of triglycerides, reduces pitch problems significantly. In the early 1990s, Sandoz Chemicals Corporation in the United States (now Clariant Corporation) introduced a new product that is a fungal inoculum of the ascomycete *Ophiostoma piliferum*. Pitch, including toxic resin acids, is also metabolised quite effectively by lignin-degrading fungi in biopulping, which thus offers an additional benefit.'

The Japanese discovery of the pitch-removing effects of lipases was made in co-operation with Novo Nordisk, which have made a commercial enzyme product of it and this product has recently been introduced on large scale in a Chinese paper mill.
Though the future for enzymatic pitch removal seems promising, this particular technique will not be examined further in this report. The reason is that the available data on its economical and environmental implications were insufficient.

- Enzymatic deinking

The amount of recycled paper used for papermaking is steadily increasing. Consequently, it is of high importance to make the processes of old-paper treatment as environmentally clean as possible. Newly developed enzymatic techniques can help this, while at the same time making it possible to process recycled paper, which was previously hard to deink sufficiently to make white paper. Conventionally, deinking processes involve the use of caustic, silicates and peroxides along with a number of mechanical methods. Of particular interest is the use of EDTA, which has significant environmental consequences in the shape of heavy metal discharges. In an industrial operation, the use of enzymes could lower chemical costs and decrease these negative environmental impacts.

JRC/IPTS (1998) describes two principal methods of enzymatic deinking. One method uses lipases to hydrolyse soy-based ink carriers, and the other uses specific carbohydrate hydrolysing enzymes, such as cellulases, xylanases or pectinases to release ink from fibre surfaces. Novozymes and

Dalum Paper have kindly provided data on a cellulase based process, which is able to completely remove the need for EDTA, and reduce the need for hydrogen peroxide and sodium hydroxide.
It should be noted that the reduction in EDTA has not been documented elsewhere and does probably depend very much on the paper coming in – e.g. if it contains ink without heavy metals. The total replacement of EDTA from deinking might therefore only be applicable to a limited number of mills.

Currently, enzymatic deinking is not available for all grades of recycled paper. Process application is limited to mixed office waste (MOW), which constitutes approximately 40 per cent of all paper waste.

**Current and Future Application**
The current application of biocatalysts is very limited. According to OECD (1998) the current market size is only 1-2 per cent of total enzyme sales. Still, the sector is regarded as the fastest-growing market for industrial enzymes. This is however mainly due to new Cluster rules and regulations in USA and the growth potential in the long run might be limited. In general terms, the penetration is currently not more than 3 per cent of the total world market potential within the different processing steps.

The most mature technology is the xylanase-aided bleaching process. It has come far in terms of low running costs, low investment needs, and high productivity. It has entered commercial use, and some knowledge of practical use has been acquired.

**Archetypes**
We use the above data, along with available data on the price of enzymes and the price of the chemical/energy being substituted[14], to construct archetypical pulp and paper processes. Evidently, the archetypes are very rough in its nature (see chapter 1 on methodology for a discussion of this), but it enables us to give a pan-European assessment.

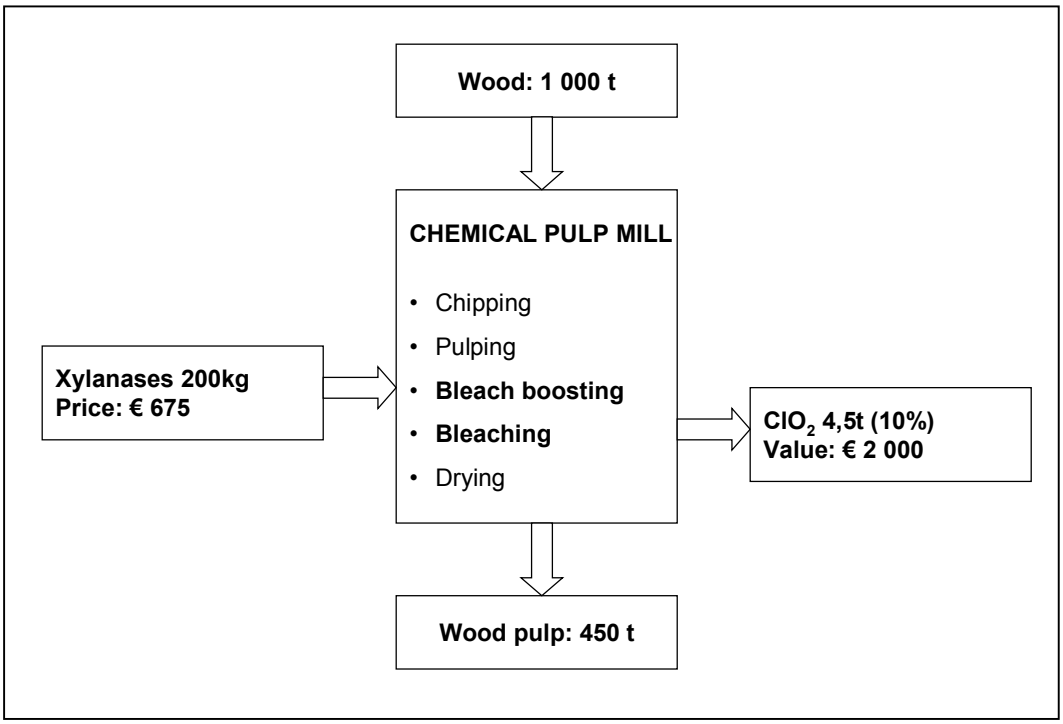
We present three archetypes, one for each major production technique prior to actual papermaking. The first concerns chemical pulping, the second concerns mechanical pulping, and the third production of fibre from recycled paper. Only a subset of the available biotechnological processes is described. Some processes are excluded due to lack of relevance.

For chemical ECF pulp bleaching, the following archetype process presented in Figure 1 has been developed.

The archetype gives a clear indication of the great potential of biotechnological processing. Adding a small amount of enzymes can substitute large amounts of chemicals.
In this case, the value of the savings is estimated to €2 000 each year, while the cost of the enzymes is only €675 yearly. Less pollution is an additional benefit.

[14] Novozymes has kindly contributed with much of the data. Further, has Dr. Anna Suurnäkki from VTT in Finland been very helpful with technical advice.

**Figure 1 - Archetype: Chemical Pulp**[15]




The potential for biotechnology in mechanical pulping is very promising too. Figure 2 shows an archetype with two enzyme steps: The pulping step using bio-pulping, and the reject pulping step using enzymatic reject refining.

Again we observe an immense potential for savings. Mechanical pulp mill energy consumption is very high, so the possibility of decreasing consumption with almost a third has a high economic value. As described in the previous chapter, the fungal *C. subvermispora* process involves high investments, but annual savings of €9 000 results in a simple payback period of three to four years. However, it is unclear how much the annual costs related to such system are. Some sources indicate that there are large practical difficulties of introducing the system, and naturally these have associated running costs.

The cellulases process does not have any major extra costs, if the basis equipment (pumps, tanks) is available at the mill, but the calculations indicate a negative net benefit. Energy price has much to say in this matter, so the result may easily change at some future point.

The final archetype for the pulp and paper industry is a paper mill archetype for recycled paper fibres and is represented in Figure 3. Though biotechnological options for improving the paper manufacturing process itself exist, they are not sufficiently documented to allow development of an

[15] *Source: Kvistgaard Consult based on interviews with users and producers of biocatalysts*

archetype. However, making an archetype model involving the equally significant deinking of recycled paper is possible.

**Figure 2 - Archetype: Mechanical Pulp[16]**

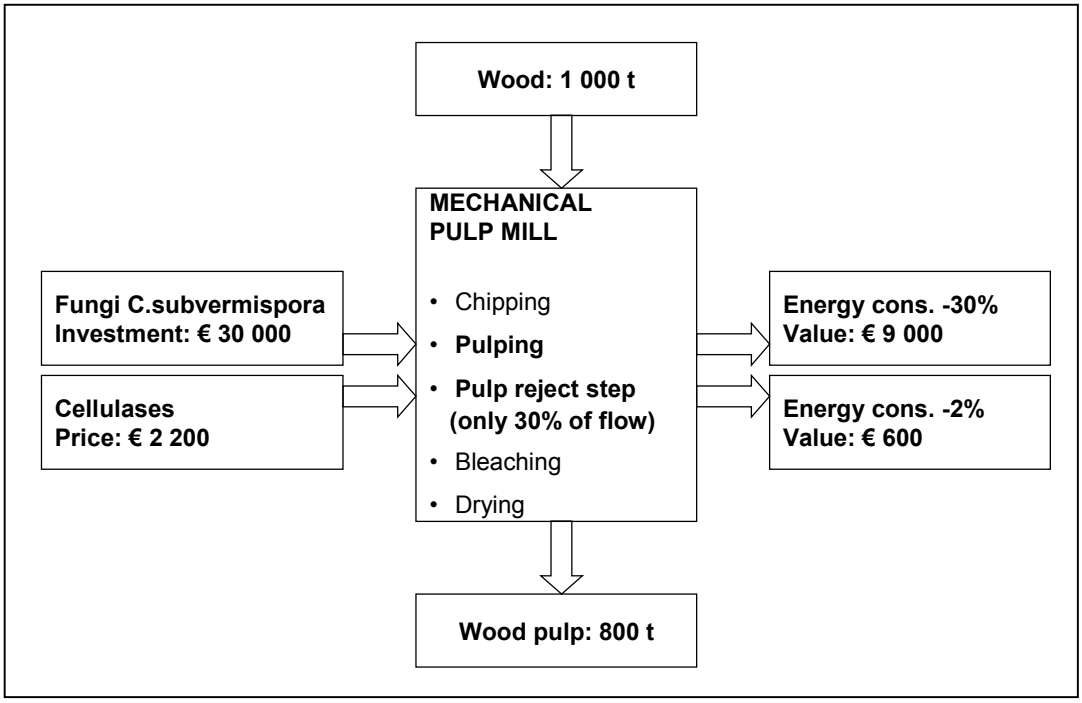
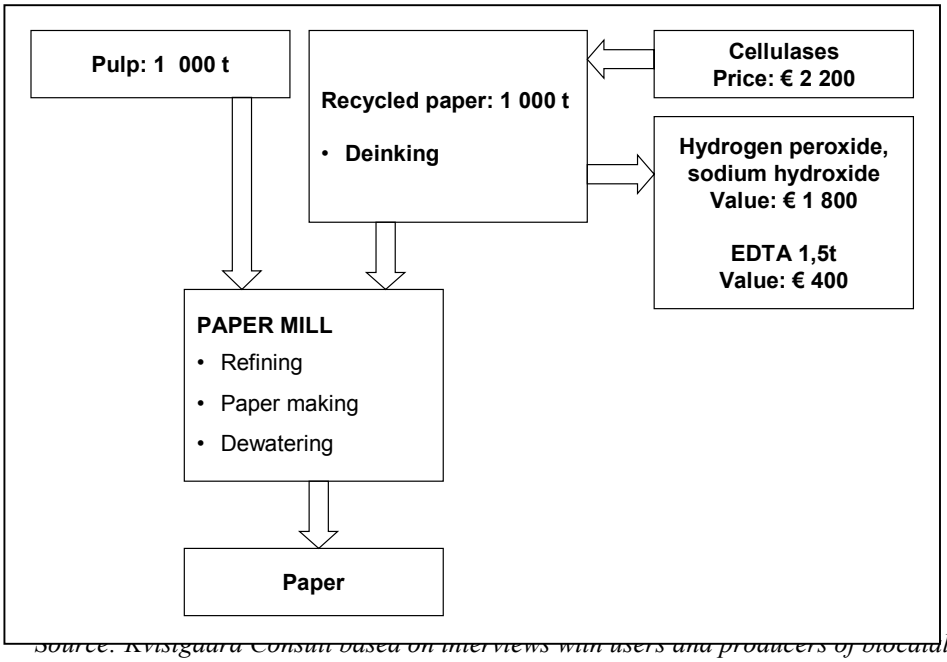



**Figure 3 - Archetype: Recycled Paper Fibres[17]**




*Source: Kvistgaard Consult based on interviews with users and producers of biocatalysts*

[17] *Source: Kvistgaard Consult based on interviews with users and producers of biocatalysts*

As mentioned earlier, there is good evidence from case studies that the reduction in hydrogen peroxide and sodium hydroxide are real, whereas the reduction in EDTA is based solely on the results from one Danish paper mill.

As an important final note, it should be stressed that the introduction of biocatalysts have none or only minor effects on yield in all the above archetypes. Some biocatalysts do even have positive effects on yield and quality, which are ignored in this study.

**Environmental Effects**

This chapter deals with the assessment of the environmental benefits obtained from introducing certain promising biocatalysts. Basically, we have identified 3 major benefits, one from each of the archetype processes:

- Reduced chloride requirements, leading to less AOX discharge.
- Reduced energy requirements, indirectly leading to less carbon dioxide emissions (both TCF process and mechanical pulping).
- Reduced need for hydrogen peroxide and sodium hydroxide input and possibly reduction in EDTA requirement.

**Economic Effects**

Based on the archetype, the economic effects can be summarised as shown in table 5 below. In bleaching of chemical pulping (Tech. 1), it is interesting to see that the economic cost-effectiveness of completely substituting chemicals with xylanases is actually positive, even before the inclusion of environmental effects. This is in other words an example of an application of enzymes, where factors other than average production costs stand in the way of fulfilment of the potential.

**Table 5 - Environmental and Economic Factors, Pulp & Paper**

| Effect of Change from Chemical to Enzyme-aided Processing | | | |
|---|---|---|---|
| **Costs related to treatment of 1 000 tonnes of raw material input** | Tech 1: Chemical pulping | Tech 2: Mechanical pulping - Reject refining | Tech 3: Recycled paper - Deinking |
| | Substitution of bleaching chem. with xylanases | Energy conservation through use of cellulases | Substitution of hydrogen peroxide and sodium hydroxide with cellulases |
| ***Economic factors*** | | | |
| Chemical savings* | € 2 000 | | € 2 200 |
| Biocatalysts costs | € 675 | € 2 200 | € 2 200 |
| Energy savings | | € 600 | |
| ***Total economic costs*** | ***€ 1 325*** | ***-€ 1 600*** | ***€ 0*** |
| ***Environmental factors*** | | | |
| AOX high / medium / low valuation | € 135 / 73 / 28 | | |
| CO2-reduction | | ++ | |
| (Heavy metals) | | | (++) |
| ***Total environmental costs*** | ***€ 135 / 73 / 28*** | ***€ 0*** | ***€ 0*** |
| ***Total socio-economic value added*** | ***€ 1 460 / 1 398 / 1 353*** | ***-€ 1 600*** | ***€ 0*** |
| **) Value of chemicals in Tech. 3 estimated* | | | |

With respect to mechanical pulping (Tech. 2) the saved energy expense is not sufficient to tip the scale in favour of cellulases. The price gap is rather big and a price subsidy on cellulases in this use must have the magnitude of 70 per cent, in order to make it as cheap as the chemical alternative. Whether this is reasonable in relation to the social gain in the shape of, say, foregone external $CO_2$ emissions of energy production, is not possible to assess in this study.

Enzyme-aided deinking (Tech. 3) is assessed to hold neither economic advantages nor disadvantages in comparison to the chemical alternative. This does not make it uninteresting by any means, since the fact that there are no economic disadvantages related to switching to the enzymatic process is a significant 'selling point' for a company.

### 2.1.3. Future Potentials

We have now set up an economic and environmental estimation of the costs and benefits of fully implementing biocatalysts in selected processes within the pulp and paper industry. These estimations can be aggregated to the whole European industry and form the basis for a more informed discussion of the policy options in this area.

Note that all figures in this chapter - and the chapters on future potentials for the other selected sectors -, depict the annual European consumption/effluent level for an archetype.

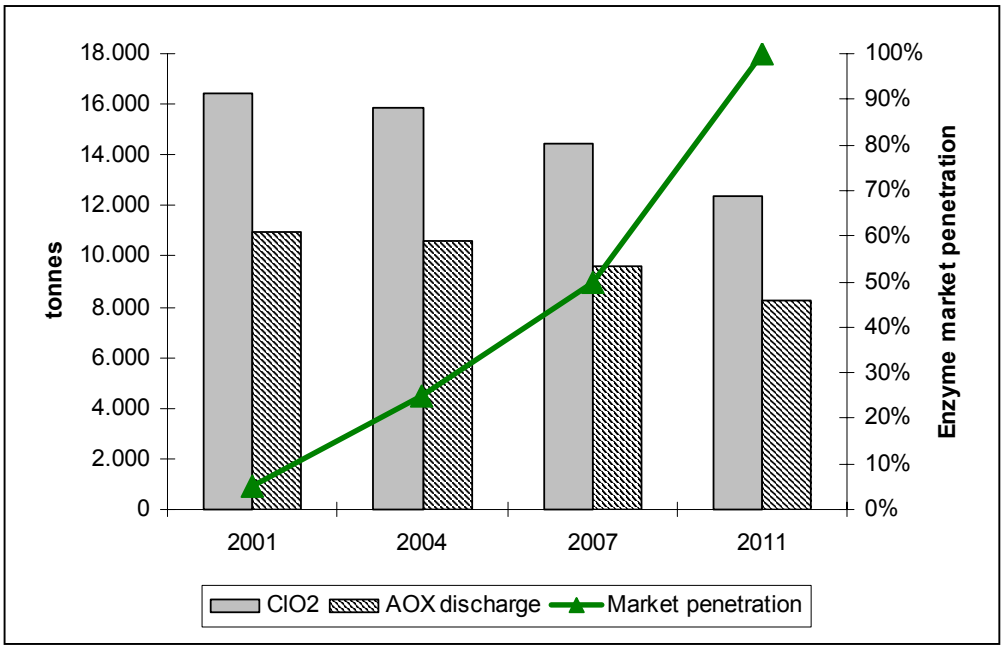
Again it should be stressed that the estimations are merely illustrative tools and will not stand alone. Attention is also given to the feasibility of the selected process substitutions. Very important factors in this respect are potential structural changes in the industry, institutional and political factors like environmental legislation, along with future technological possibilities.

#### *2.1.3.1. Estimation of Future Potentials*

The following section gives an indication of the potential for environmental benefits Europe-wide. For pulp and paper, three estimations of future potentials are developed, one for each of the archetypes. Each archetype has an associated environmental benefit, and this can be scaled according to the degree of market penetration. Each biocatalytic process is assumed to start out at a low level of market penetration, and is then assumed to rise over the next 10 years, reaching the theoretical maximum in 2011.

Given this set-up, the future for chemical pulping may look like in Figure 4. Reaching maximum enzymatic market penetration, the environmental benefits will equal a reduction of $ClO_2$ discharge of almost 35 per cent. The reduction of AOX is relatively proportional. Given the fact that the European production of chemical pulp was 22 million tonnes in 2000, half was produced by ECF, and discharges of AOX average 1 kg/t, total discharges amount to 11 000 tonnes. Full-scale industrial application of xylanase (a 25 per cent reduction of the current level, at full efficiency) means reduction of AOX discharges with nearly 2 700 tonnes a year.

**Figure 4 - Future Potential for ECF Chemical Pulping ($ClO_2$ Consumption)**




As it can be seen from figure 4, market penetration needs to be quite high before any significant reductions occur. Another important factor to consider is that the estimation of future potential assumes an unchanged share of ECF and TCF mills. Production from TCF mills was 15 % of total production volume in 1998. Changes in the relation between TCF and ECF mills will of course affect ClO2 use. A higher share of TCF to ECF based production will diminish the ClO2 further, while a lower share will restrict the reduction. As previously described, enzymes are also applicable for TCF mills, where they have energy saving properties. Unfortunately, construction an estimate of future potential for this particular process has not been possible. However, production from TCF mills was only 15 per cent in 1998, but estimated to become 40 per cent in 2001, so clearly these mills are gaining market share. Therefore, ClO2 use may diminish further. As previously described, enzymes are also applicable for TCF mills, where they have energy saving properties. Unfortunately, constructing an estimate of future potential for this particular process has not been possible.

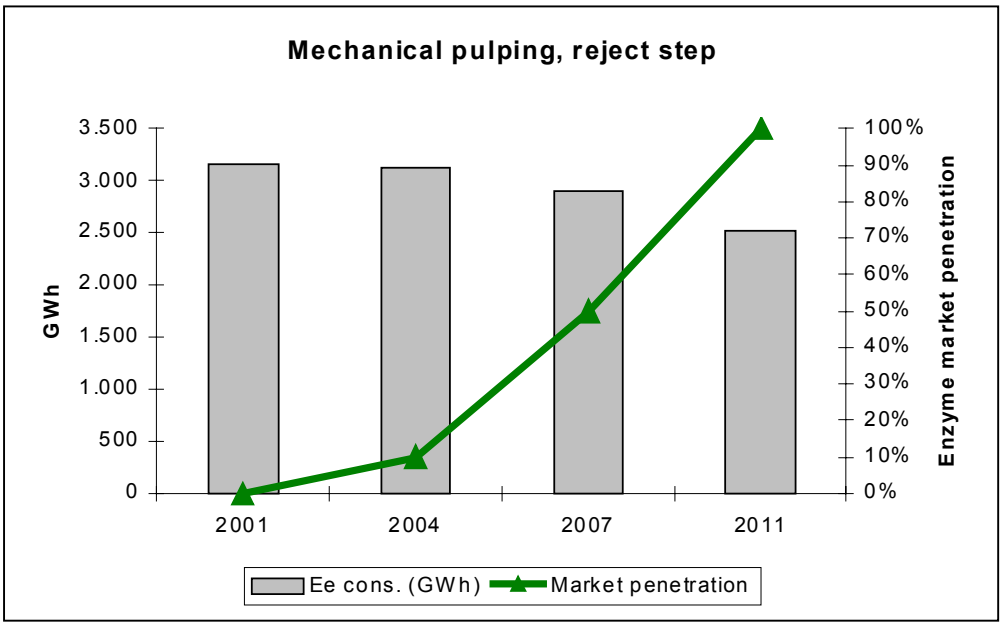
Directing our attention to mechanical pulping, an estimation of future potential for the next 10 years can be made. Figure 5 shows the potential for energy conservation when applying enzymes at the reject step. Again, the interviews conducted in this study have indicated a very low prospective market penetration in the next few years, which means that the total energy savings will remain minimal. Only when enzymes become very widespread in the industry does energy conservation approach 20 per cent. Note that this figure is for the reject step only. For the entire mechanical pulping process, savings are only about 2 per cent.

Mechanical pulping accounts for an output of 11.7 million tonnes. Looking at the reject refining step, the potential for saving energy is about 600 GWh per year. The reject step itself consumes about 900 kWh per tonne, but since the only 30 per cent of flow reaches this step, the energy consumption relative to output is approximately 270 kWh/t. On an European scale, this equals 3159 GWh. Assuming full market penetration and a potential of saving 20 per cent of the 270 kWh,

energy needs can be reduced by 632 GWh. This potential saving is the equivalent of between 155 000 and 270 000 tonnes less $CO_2$ emissions depending on the emission factor applied, which is worth €1.4 million or €2.5 million at an emission trading price of 8$/t[18].

However, due to the weak market penetration of enzymes (cellulases) today, this significant potential benefit is not included in the calculation in table 5, but only illustrated as a potential environmental benefit with the ++ indication.

**Figure 5 - Future Potential for Mechanical Pulping (Energy Conservation)**




Still, since energy prices are rising, and the mechanical pulp industry itself is large, expectations for the market are high. Novozymes state a potential market for these enzymes in the order of 10 to 100 million EURO.

The same type of calculation, using the figures for bio-pulping, reveals immense saving potential. Here the reduction amounts to more than 8 000 GWh. However, the mere scale of this figure indicates that its realism is uncertain. Regarding this process, many questions still remain.

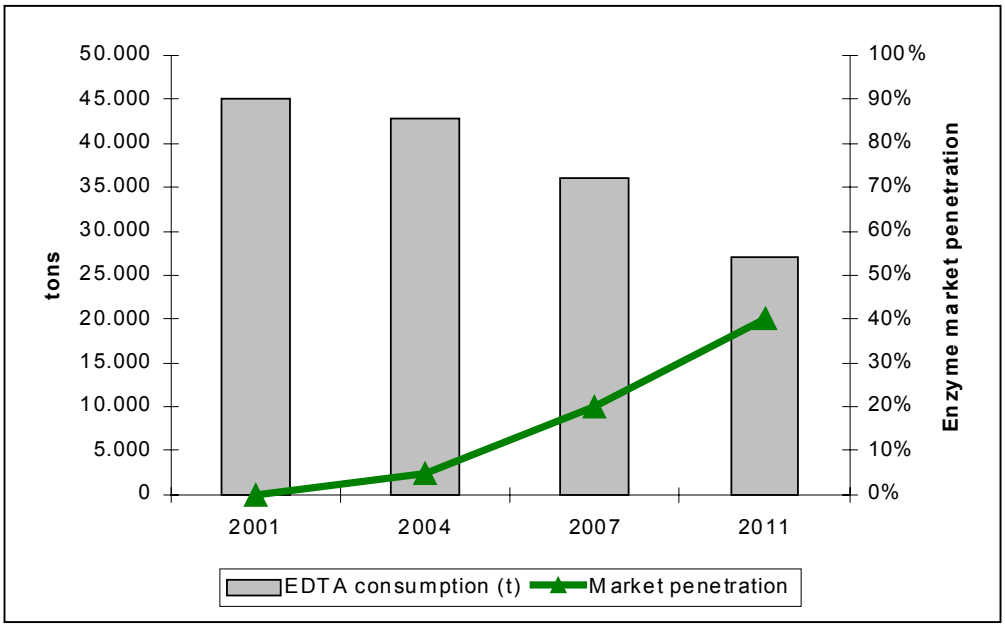
Figure 6 above relates to the last archetype, which is processing of recycled paper. An interesting aspect of the process is that enzymes might completely substitute EDTA. This makes it possible for lower levels of market penetration to have relatively large impacts on chemical consumption[19], even though market penetration cannot reach more than 40 per cent due to current technical limitations of

[18] These estimates are made as follows: The main pulp and paper producing countries are Germany, Finland and Sweden, where electricity is produced using 57 per cent fossil fuels on average (estimated on the basis of OECD IEA statistics for the three countries). The $CO_2$ emission factor for electricity generated using fossil fuels vary among countries and generators, and both a low factor of 0.43 and a high of 0.74 are therefore applied (based on work by National Energy Foundation, UK and the Emission Trading Scheme, UK).

[19] Once again it should be pointed out however that this information is based on only one paper mill, and might not by widely applicable. But considering the remarkable potential this technology might hold, it is still interesting to set up an estimation of future potential.

the technology. The process is only applicable at mills processing certain types of paper (Mixed Office Waste).

**Figure 6 - Future Potential for Recycled Paper (EDTA Consumption)**




Calculations regarding the EDTA consumption (based on estimation of European recycled fibre production of 30 million tonnes, where 40 per cent is based on mixed office waste) reveal that EDTA consumption can be brought from a level of 45 000 tonnes down to a level of 27 000 tonnes. These results are however not especially robust and should only be quoted with the appropriate reservations. The effect on heavy metal emissions cannot be assessed, due to lack of reliable data.

### *2.1.3.2. Feasibility of Future Potentials*

Will the future of biocatalysts really look like the illustrations above? Many factors will impair full-scale, total adaptation of biotechnological methods.

The prospective for economic and environmental benefits in the pulp and paper sector is good. For one, current market penetration is low. Even the most developed biocatalysts do not have a degree of penetration above 5 per cent. Combined with steady technological improvements and rising environmental standards, this makes for a large market potential.

In a 'pull' and 'push' perspective, the basic elements towards increased market penetration of enzymes are:

- Pull: Increased quality and productivity
- Push: Required by environmental standards

Increased quality and productivity is definitely a primary force. For instance, as market demand increases (or simply fluctuates), some chemical pulp mills meet capacity problems. Xylanases is an example of a biocatalyst that can ease this problem, without the need for large investments in fixed

assets. Similarly, enzymatic deinking increases the possibility of using fibres from recycled paper in paper making. Since these fibres cost approximately half as much as woodpulp fibres, the economic and production advantages are evident.

Environmental standards do presently not give a standard mill incentive to make use of biocatalysts. Chronologically speaking, the 'push' factor definitely lies after the 'pull' factor. However, if the price paid for energy rise, the pushing force gains momentum. Especially in mechanical pulping, where energy consumption is high, energy prices can become a major determinant of the success of enzymatic processes.

How close to the estimation of future potentials Europe can come depends on the *barriers* and the *drivers* facing the industry. Elaborating on the push-pull discussion, the following *drivers* have been identified:

**Table 6 - Drivers in the Pulp and Paper Industry**

| DRIVERS |
|---|
| • Economical advantage, i.e. cost savings<br>• Increased processibility and efficiency in production<br>• Improved product quality<br>• Environmental pressure (especially previously in the case of chlorine bleaching) / need for reduction of effluents<br>• New generations of technicians are more knowledgeable about biotechnology |

Of the three archetype processes, only one is really able to sell itself on grounds of economic benefits. This is the enzymatic reject recovery process, where the savings for the mill are bigger than the extra costs. Xylanases attractiveness is not based on cost savings, but on its ability to increase efficiency and improve quality. A better environmental characteristic is also an important factor for this product. Finally, enzymatic deinking is in a transition. The paper mill Dalum Papir originally undertook the process, because their parent company wished to test the feasibility of the process. At that time, the cost prospects where not particularly attractive. Since then, the costs have changed, and the process now looks economically advantageous.

In the end, legislative environmental pressure may become the driving factor, which presents the biggest opening of the market for biocatalysts. Experience has shown that a combination of increased green taxes, and increased awareness of environmental issues concerning standard commodities among consumers [20], all work in favour of biocatalysts penetrating the market. Regulation is also an important factor. For instance, the German BGVV is considering regulation on chlorinated compounds in certain household products, such as tea bags.

As it will become apparent, common for all the industries described in this report is that inertia is a major barrier. Mill personnel often have an educational background in chemistry. Only slowly are new generations taking over, which are more familiar with biotechnology. Up to now, mills facing capacity or environmental restrictions have preferred traditional technical solutions to

[20] For instance, due to information campaigns and green labelling of products

biotechnological. This can however be characterised as risk aversion or sound business sense, rather than inertia or conservatism. This is bulk product business, where failure of a new technology can result in large quantities of damaged goods.

**Table 7 - Barriers in the Pulp and Paper Industry**

| BARRIERS |
|---|
| • Inertia in the mills – incomplete knowledge of biocatalysts among the managerial staff, chemicals more familiar, suppliers not present in the mills (unlike in the case of chemical suppliers), no 'advertising' of biocatalysts at the mills.<br>• Benefits (cost, process runnability, product quality) small compared to those obtainable with traditionally used chemicals<br>• Little demand for products specifically produced using biocatalysts<br>• International competition leaves narrow profit margin for investments in experimental processes |

Finally, the international scene has a role to play. Supposing wages, green taxes and environmental standards rise, the industry may find itself unable to compete while situated in Europe. This could push the industry to relocate to countries where regulations are more lax, and this might impair the success of biocatalysts. However, two factors talk against this. For one, mills all over the world are slowly introducing biocatalysts, not just in Europe (for instance in Japan, China, Canada and USA) – mainly because biocatalysts have many attractive properties other than environmental. Secondly, location is directly connected to the availability of wood (or recycled paper), since transportation costs are considerable.

## *2.2. Textile*

The textile sector is highly fragmented and is made up of heterogonous groups of small and medium scale companies. The intra sectional relations are very complex and there are few large-scale operators.

### 2.2.1. Sector Description

There are at present 113 848 European companies in the textile industry, predominately in the south of Europe. Italy has by far the largest production, followed by Germany, the UK, France, and Spain. These five countries together account for over 80 per cent of the Europe's textile and clothing industry (JRC/IPTS, February 2001). Emerging producer nations are Poland and Turkey, which will become especially significant with respect to production from mills (information based on interviews).

**Output/Production**[21]

A wide variety of products are output from the textile industry: Yarn & thread, woven fabric, textiles, and carpets to mention a few. All in all Euratex estimates the EU-15 total output corresponds to over 5 million tonnes in 2000, with 3.5 million tonnes hereof being produced from synthetic raw materials. This should be seen in relation to the world total production of over 50 million tonnes the same year.

**Turnover**

The textile industry is one of the larger industries in Europe with a turnover of more than €198 billion in 2000 (Euratex).

**Employment**

2.2 million people in Europe were employed in the textile industry in 2000 and the number of employees per company is less than 20 on average (Euratex).

**Trends and Perspectives**

Many companies face difficult economic circumstances, with significantly decreasing sales. The last decade has seen a significant relocation of industry to Asia and other countries with low wages and fewer environmental restrictions. This has meant an overall decline in European production and benefited the environment. There is however still a very significant production in European countries, as the numbers above show. Whether the re-location trend continues or not is very hard to say, but there is a tendency towards a European specialisation in high-tech fabric with functional finishes, which might shift the focus from cheap labour towards stronger links to the R&D community.

**Process**

The textile and clothing production chain runs all the way from production of synthetic raw materials, over semi-processed products like yarns, woven and knitted fabrics, to final/consumer products, which include carpets, home textiles, clothing and industrial use textiles.

[21] Estimates in this section are based on data on raw material input.

This report will not look at the manufacturing of synthetic raw materials, but focus on textile and clothes, which are manufactured and treated in mills and laundries respectively.

The processes are highly diverse and very difficult to give a brief and yet not over simplistic description of. Keeping this in mind, here is an overview:

1) Textile mill operations
   - Raw fabric production
     i) Fibre modification
   - Preparation
     i) Desizing
     ii) Scouring
     iii) Bleaching (optional)
   - Dyeing
     i) Bleach clean-up
     ii) Dyeing
     iii) Rinsing
   - Finishing
     i) Softening
     ii) Defibrillation

2) Cutting / Sewing – *No relevance*

3) Laundry operations
   - Preparation
     i) Desizing
     ii) Wax removal
   - Garment wash
     i) Abrasion
     ii) Dying/finishing
     iii) Softening
   - Bleach & Finishing
     i) Bleach
     ii) Rinsing
     iii) Softening

*Desizing* is the removal of sizing fats[22] added at an earlier stage to improve the weaving behaviour of the warp. *Scouring* is the removal of foreign impurities - like naturally occurring grease and dirt or residual spinning oils - from textiles. *Finishing* addresses both the sequence of wet treatments that are carried out to give the fibre the required colour and final properties, and any specific operation to apply functional finishes like mothproofing or 'easy-care'.

**Input**

The raw material for the textile industry is a variety of fibres, which can be broadly categorised as either natural or man-made. Man-made fibres encompass both purely synthetic materials of

[22] Suitable materials include sulphated fats and oils and mixtures of fatty acid esters with non-ionic and anionic emulsifiers.

petrochemical origin, and regenerative cellulosic materials manufactured from wood fibres. The table below show the composition of the fibre input.

**Table 8 - Fibre Input in the Textile Industry EU-15, 2000**

| | ***1 000 tonnes*** |
|---|---|
| ***Man-made fibres:*** | |
| • Polyamide | 645 |
| • Polyester | 1 454 |
| • Acrylic | 330 |
| • Other synthetic | 758 |
| • Cellulosics | 498 |
| ***Natural fibres:*** | |
| • Cotton | 1 220* |
| • Wool and other | 299 |
| *Total consumption of fibres* | *5 204* |
| **) Estimated* | |
| *Source: CIRFS, Euratex* | |

Fibre raw material makes up a large portion of input costs, but the industry is also very energy and labour intensive. This is why low-wage countries have a competitive advantage, and technologies that can reduce labour input are very much in demand in Europe.

**Table 9 - Chemical Input, Textile Industry**

| **Chemical Consumption** | **Per cent** |
|---|---|
| ***TYPE:*** | |
| Dyes and organic pigments | 37 |
| Emulsion polymers | 20 |
| Surfactants | 19 |
| Other chemicals | 23 |
| ***Total*** | ***100*** |

Chemical consumption is very high in this sector, which can be illustrated by estimates by interviewees that chemical cost on average is more than €300 per tonne fibre. Table 9 above details the distribution of this expense on type of chemical.

**Environmental Baseline Load**

Primarily, the textile industry uses wet processes, e.g. when removing contaminants, bleaching, and applying dyes and finishes. Losses to the product are negligible and the bulk is consequently discharged as aqueous effluent. The main environmental issues are therefore related to waste water. There are also emissions to air from drying and steaming, but these are minimal in comparison. Energy consumption however, is an environmental factor to be investigated, as it is considerable and holds good potential for reductions.

A large number of organic dyestuffs/pigments and auxiliaries are applied in the textile industry. They can be categorised in three main categories: Dyestuffs and pigments; basic chemicals that

include all inorganic chemicals; organic reducing and oxidising agents; aliphatic organic acids; and finally auxiliaries, which comprise all textile auxiliaries containing mainly organic compounds[23].

Many of these chemicals have serious environmental effects if emitted to the local ecosystem and represent environmental costs to the companies if they are required by laws and regulations to contain these effluents. As a result of low fixation, dyestuffs that are poorly bio-eliminable pass through the wastewater treatment plant and are ultimately found in the effluent. The first undesiderable effect in the receiving water is colour. High doses of colour not only cause aesthetic impact, but can also interrupt photosynthesis, thus affecting aquatic life. Other effects are related to organic content of the colorant (expressed as COD and BOD), its aquatic toxicity and the presence in the molecule of metals or halogens that can give rise to AOX emissions (JRC/IPTS, February 2001).

To give an idea of the magnitude of the environmental effects table 10 below shows the estimated average discharge from a textile production site.

**Table 10 - Effluents, Textile Industry**

| **ESTIMATED AVERAGE* for textile industrial site** | |
|---|---|
| | Substance in waste water kg/yr |
| Salts | 2 212 |
| Natural fibres contaminants | 885 |
| Sizes (mainly starch derivatives, but also polyacrylates and polyvinylalcohol) | 0 |
| Preparation agents (mainly mineral oils, but also ester oils) | 265 |
| Surfactants (dispersing agents, emulsifiers, detergents) | 221 |
| Carboxylic acids (mainly acetic acid) | 18 |
| Thickeners (starch derivatives) | 133 |
| Urea | 9 |
| Complexing agents | 44 |
| Organic solvents | - |
| Special auxiliaries with more or less ecotoxicological properties | 44 |
| *) Based on high estimates | |
| *Source: JRC/IPTS, February 2001, Euratex* | |

[23] Except organic reducing and oxidising agents and organic aliphatic acids.

## 2.2.2. Biocatalysts

**Technological Possibilities**

Enzymes have been used in the textile industry for a long time, and are continuously being improved and adapted to various conditions of temperature or pH. Table 11 gives an overview of the multitude of uses of biocatalysts in the industry.

**Table 11 - Biocatalyst Applications, Textile Industry**

| Process stage | Biocatalysts | Benefits |
|---|---|---|
| Prewashing (desizing) | Enzymes | Simultaneous cotton prewashing and desizing |
| Silk treatment | Proteases | Natural fibrin is removed from the silk fibres |
| Desizing | Amylases | Desizing of starch sizes |
| Bleaching | Laccase-mediator system | Enzyme-aided bleaching |
| Post-bleaching | Catalases | Removal of bleaching agents residues |
| Dying | Biosynthetic dyes and pigments | Substitution of chemical dyes |
| Biostoning | Cellulases | Replaces pumice stones |
| Biopolishing | Cellulases | Processing of cotton fabrics and viscose |

The most widely adapted applications that show potential for substitution with chemicals are listed below. The archetype for the textiles industry is form on this basis.

- Enzymatic desizing

The size (starch) that has been applied as coating of the thread before weaving of the fabric, have to be removed again so the fabric is more absorbent in further processing. This can be done by lengthy soaking in hot water or with the use of harsh chemicals like acids, bases or oxidising agents. Amylases can replace these chemicals and have been used in this capacity ever since the beginning of the century.

- Enzymatic scouring (cotton)

Scouring takes place just before dying and is the removal of non-cellulosic material in native cotton as well as impurities from machinery and size lubricants. Traditionally chemicals like sodium hydroxide are used to improve the fabrics 'wettability' and thereby make it easier to dye and bleach afterwards. An alkaline pectinase can successfully replace chemical scouring.

- Post-bleaching treatment/ Bleach clean-up

Catalases added to rinse water to break down the bleaching agent hydrogen peroxide (chemical used for cotton whitening that must be eliminated prior to dyeing) have replaced reducing agents like sodium thiosulphate and hydrosulphite. When the enzymes have worked for about 10 –20 minutes the dye can be added directly and a change of water is eliminated. The advantages of this application are several and include severe reduction in the consumption of rinse water, energy and labour time.

**Current and Future Application**
Of the three technologies mentioned above, the use of enzymes in desizing is the oldest treatment dating back to the 1950's. Today it has an impressive market penetration of roughly 80 per cent for removal of natural starch. Bio-preparation and bleach clean-up are also fairly well established technologies, but with a low current market penetration of below 5 per cent. The potential market penetration level is estimated by interviewees in this study to be as high as 80-90 per cent.

The enzyme producers have particularly high hopes of breaking into the mills section of the industry in the coming years, and from a European viewpoint this is mostly related to Poland and Turkey.

New enzymes have been tested and proven to efficiently substitute other chemical procedures used in textile industry. Very promising (and already in use on a very small scale) is an enzyme, which combines the desizing and scouring processes into one single step. Also, several enzymes catalysing oxido-reductive reactions are being tested in various dying methods (solubilization, colouring, fixing, etc.). An enzyme-based treatment called 'super wash' to keep wool from matting (or felding) is currently in development. Further there is research into laccases to polymerise dye precursors and create dye in situ, as well as tests of lipases for the elimination of fatty compounds and the development of several proteases with a high degree of specificity.

Looking at the future potential from an environmental point of view, there will be exceptionally positive benefits from development and implementation of biocatalyst technologies for bleaching and dying. This is a simple deduction, as these steps traditionally involve a multitude of toxic chemicals in large quantities.

**Archetype**
As it has already been described, there are a large number of steps in the industrial production of yarn, textile and clothes. It is therefore important to emphasize that the archetype in this report does not reflect the precise production process, but only the fractions, which are of interest to the analysis.

Since production in the textile industry is so complex the archetype might seem very simplistic. The processes that we are interested in, apply mainly to cotton as a raw material, so we focus on this section of the industry even though it only accounts for a quarter of the total industry. The selected enzymatic processes are: Bio-desizing, Enzymatic scouring, and Bleach clean-up.

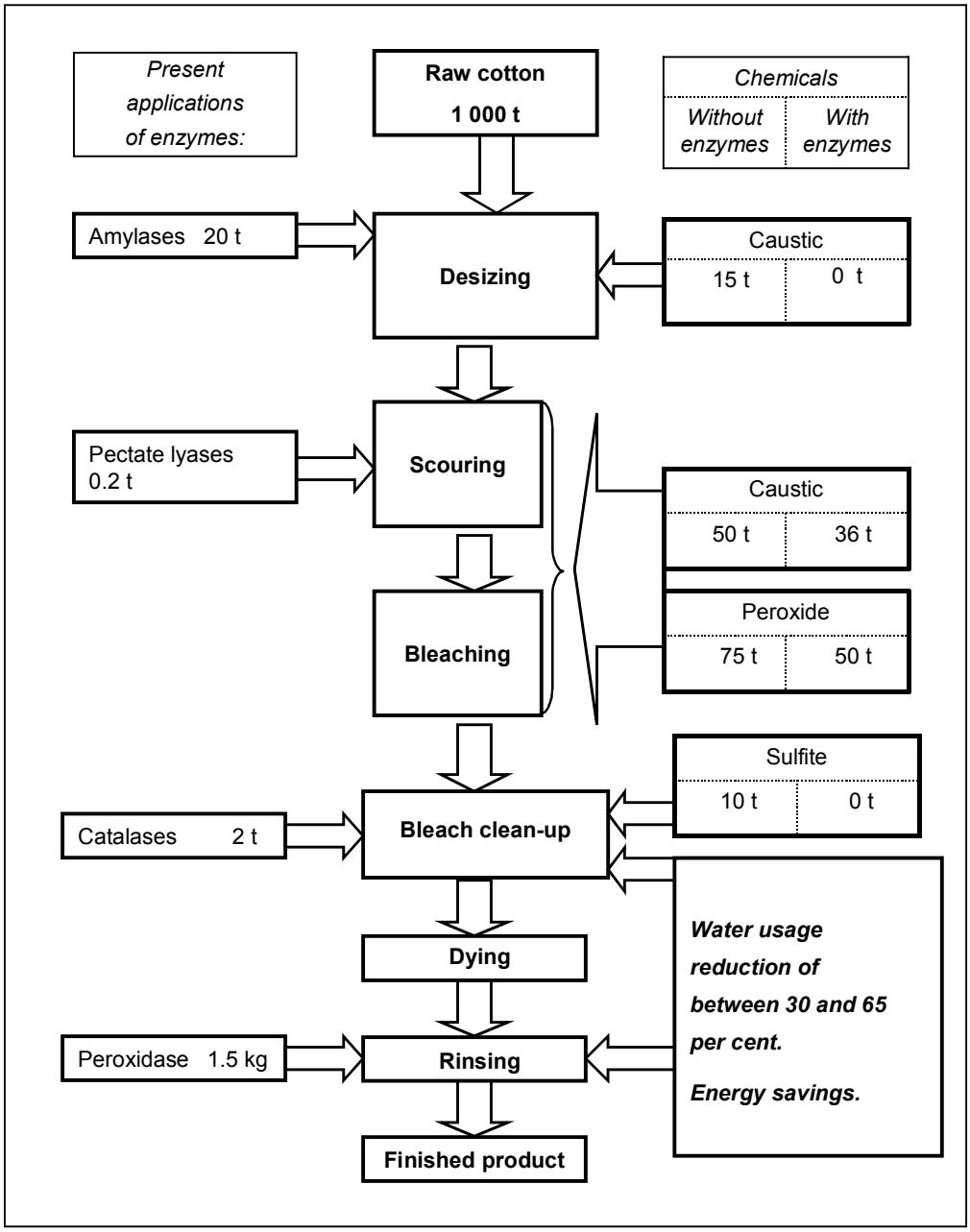
The connection between scouring and bleaching is strong in this type of enzyme-aided process. The explanation is that not only does the pectate lyases replace chemicals for scouring, but the fabric scoured in this way is more absorbent and will therefore require less chemicals when bleached.

This archetype shows good potential for substitution of chemicals and thereby reducing the effluent levels of contaminants. The relevant chemical substances are: Caustic, peroxide and sulphite, whereas the use of tensides - approx. 5 tonnes per 1 000 tonnes raw cotton fibres - cannot be reduced with this selected biotechnology.

This change in production technology has significant scope for reductions in water and energy input. Most of the traditional chemical processes need water temperatures of 80-90°C, whereas enzymatic processes only require 40-50°C. While there probably are no energy savings in the

desizing and scouring processes, energy savings might be possible with regard to the bleach clean-up step. There are definitely energy savings from introducing peroxidases in the final rinsing step, but it is not possible to quantify.

**Figure 7 - Archetype: Manufacturing of Dyed, Woven Cotton Fabric[24]**




As for reductions in water usage, such reductions are very significant in the bleach clean-up step and have economic benefits for the manufacturer. Traditionally this process is either done by

[24] *Source: Kvistgaard Consult based on interviews with users and producers of biocatalysts*

rinsing in clear water or in a sulphite solution. Table 12 below is based on interviews conducted in this study and shows the reduction in water usage depending on the process at the starting point.

**Table 12 - Water Usage**

| Water Usage in Bleach Clean-up, 1 000t cotton | | | |
|---|---|---|---|
| | Sulphite solution | | Clear water |
| | Water (l) | Sulphite (kg) | Water (l) |
| Traditional process | 30 000 | 10 | 50 000 |
| Enzymatic process | 20 000 | 0 | 20 000 |

As seen from table 8 earlier in this chapter, manufacturing of cotton makes up approximately 24 per cent of the total industry output. So the archetype is applicable for a quarter of the sector. For desizing and bleach clean-up this proportion is probably larger however, as these processes are not exclusive to cotton.

The environmental effects related to the desizing process are high wastewater loads. In the case of woven fabric, sizing agents represent 30 – 70 per cent of total COD in wastewater. The lower figure is for finishing of woven fabric mainly consisting of flat filament yarns. The higher is for staple fibres, especially for cotton and in the case of native sizing agents. The additives present in the formulations also influence the aquatic toxicity and BOD of the resulting emissions (JRC/IPTS, February 2001).

**Environmental Effects**

As pointed out above, there are severe wastewater COD loads stemming from the traditional desizing agents. *Enzymatic desizing* holds the potential to reduce this significantly.

In connection with enzymatic *bleach clean-up*, up to 50 per cent of the water consumption can be cut, as several hot or cold rinses can be eliminated. Further, a case study in Egypt involving two laundries also shows that energy consumption can be reduced by 25 per cent and that the concentration of TSS (Total Suspended Solids) can be reduced even more[25].

There is also good potential for environmental improvements regarding *enzymatic scouring of cotton*. The aggressive chemical sodium hydroxide traditionally used produce wastewater with high COD, BOD and salt content. The scouring catalysed by an alkaline pectinase runs under moderate conditions of pH and temperature and can use as much as 50 per cent less rinsing water, depending on the equipment. Trials performed in important cotton producing countries like China and India, showed that BOD and COD can be reduced by 30 per cent and 40 per cent respectively[26]. Manufacturers of yarn, knitted and woven fabrics have shown interest in trying the new process.

As it is the also case for the other industries in this report, there are some possibilities for direct substitution of chemicals with enzymes, but not all the potential environmental gains is that simple

[25] Based on interviews carried out in this study.

[26] Based on interviews carried out in this study.

to bring about. An interesting future application of biocatalysts is preparation of materials so that it will not require as much dyestuff in the following finishing stages. Dyes and pigments are expensive inputs and do have serious environmental impacts if released into nature, so this is a promising future possibility.

**Economic Effects**

The assessment is now ready to be summarised and table 13 below shows the estimated values for the three selected applications of enzymes in the textile industry. The table is somewhat lacking in units, but this is due to incomplete Baseline data for both economic and environmental costs.

**Table 13 - The Economic and Environmental Effects, Textile Industry**

| **Effect of Change from Chemical to Enzyme-aided Processing** | | | |
|---|---|---|---|
| **Costs related to treatment of 1 000 tonnes of raw material input** | Tech 1: Desizing<br>Substitution of caustic or tensides with amylase | Tech 2: Scouring<br>Substitution of caustic, tensides and peroxide with pectate lyases | Tech 3: Bleach clean-up<br>Substitution of sulphite with catalases |
| ***Economic factors*** | | | |
| Chemical savings | € 10 000 | € 26 500 | € 6 800 |
| Biocatalysts costs | € 40 500 | € 5 400 | € 1 350 |
| Change in energy costs | approx. 25 per cent | | |
| Change in water costs | approx. 50 per cent | ++ | ++ |
| Increased production capacity | approx. 30 per cent | | |
| ***Total economic*** | ***-€ 30 500*** | ***€ 21 100*** | ***€ 5 450*** |
| ***Environmental factors*** | | | |
| BOD | | approx. 30 per cent | |
| COD | | approx. 40 per cent | |
| TSS | ++ | | |
| ***Total environmental effects*** | | | |
| ***Total socio-economic value added*** | ***-€ 30 500*** | ***€ 21 100*** | ***€ 5 450*** |

In two out of three technologies in this sector, the enzymatic technology is actually cheaper for the private company to apply, than the chemical. Even more so than indicated by the total economic effects of over €21 000 and nearly €5 500 for *scouring* and *bleach clean-up* respectively, since the considerable savings related to reduced water usage have not been possible to quantify. Furthermore, there are considerable positive environmental effects to be gained using enzymatic *scouring*, which have not been valuated, as the baseline emissions are uncertain.

With regard to *desizing*, the economics are hard to determine on the basis of the figures for chemical savings and enzyme costs alone, since the change in energy, water and production capacity are sizeable, but hard to quantity due to lack of baseline numbers. It does therefore not seem reasonable to estimate the magnitude of a tax or subsidy that can balance the pure difference in price. However, it seems clear that increased internalisation of external environmental costs through 'green' pricing of the public amenities would assist in the move towards enzymatic aided manufacturing.

### 2.2.3. Future Potentials

Three processes were identified in the textile industry as holding potential for substitution of chemicals with enzyme. These are all related to the manufacturing of cotton fibres and have very different market penetration levels today.

**Figure 8 - Future Potential for Desizing of Cotton**

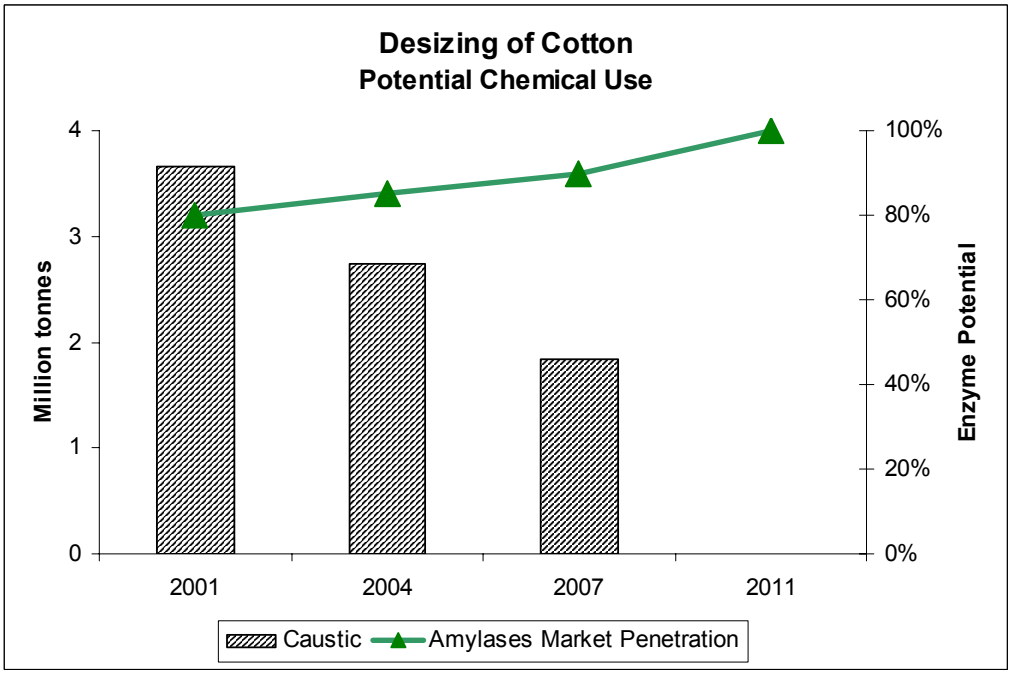
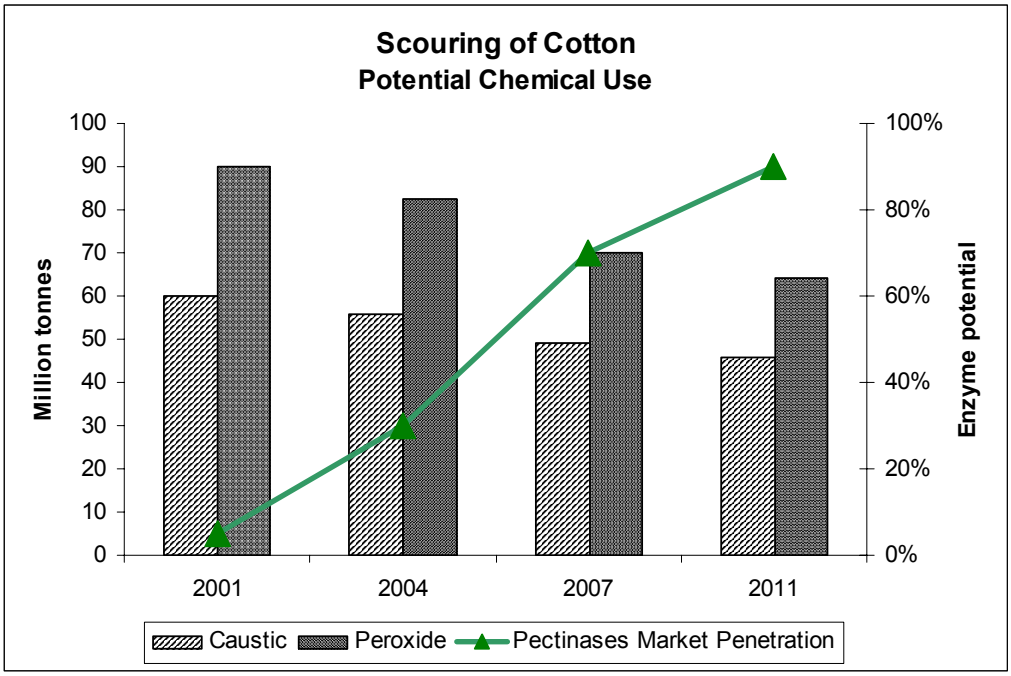



**Figure 9 - Future Potential for Scouring of Cotton**



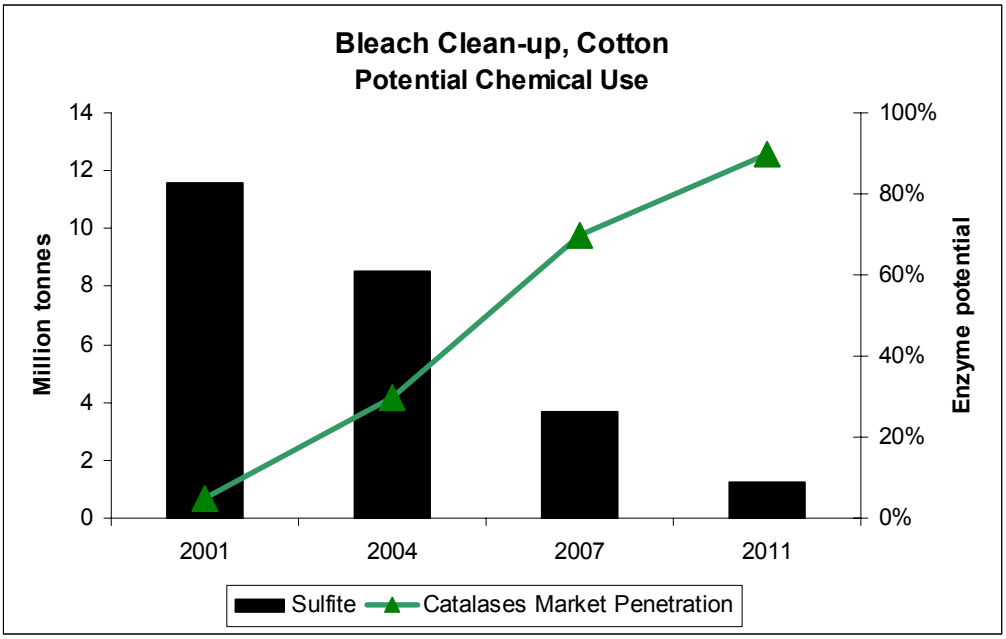
The estimation of future potential for desizing starts at 80 per cent, since this technique already is widely used. The potential for reducing chemical use is therefore not enormous, but there is still a noteworthy difference of nearly 4 million tonnes of caustic annually in the case of 100 per cent fulfilment of the potential.

The estimations of future potential for bio-scouring by contrast hold very significant potential chemical reductions. The current market penetration of pectinases is no more than 5 per cent, but it was assessed in this study that it can be applied industrially in 90 per cent of cotton processes in the Europe. This percentage is therefore the top mark in the estimation of future potential for the next ten years.

The archetype for the sector showed that both the input of caustic and to a lesser extent peroxide can be reduced via substitution towards biotechnological processes. Figure 9 reveals these reductions to have the magnitude of 24 million tonnes of peroxide and 14 million tonnes caustic a year, which is the difference between pectinases market penetration of 5 per cent and 90 per cent. The in-between stages in the estimation of future potential are 30 and 70 per cent respectively.

For bleach clean-up of cotton, the archetype showed the possibility of substituting sulphites with catalases and save large amounts of water for rinsing.

**Figure 10 - Future Potential for Bleach Clean-up, Cotton**




This estimation of future potential - depicted in Figure 10 -, also takes its starting point from the current level of market penetration, namely 5 per cent, and ends up at the attainable level of 90 per cent market penetration[27]. The result is a potential reduction on the use of sulphite with more than 10 million tonnes a year.

[27] Again, this builds on interviews.

#### *2.2.3.1. Feasibility of Future Potential*

In the case study for the textile industry in the JRC/IPTS report on the dynamics of introduction of biocatalysts in companies it was found that the difficult economic situation facing the industry was a significant deterrent for the introduction of biocatalysts – as indeed for the introduction of any new technology (JRC/IPTS, January 2000). This study has found that to apply for textile mills, but not for laundries.

For the laundries, reduced production costs is not a driver for the adoption of biocatalysts, but on the other hand is there little expense related to adoption of the new technology (no new machinery needed etc.). For the mills it's another matter. Here the producers of the enzymes find very limited willingness to spend time or investments on introducing new biotechnologies in the industry. The processes in mills are very fast, and the enzymes simply need more time to react (½ hour). This means that completely different production lines would have to be set up in order to convert to enzyme-aided production, which in turn implies large investments.

In Europe, smaller textile companies located in the North of France and in Germany say they do not have the financial resources to invest time or money in the replacement of a well established and well controlled chemical process in the production chain with a new technology. SMEs are reluctant to introduce biocatalysis into their plant, but insist that they are not fundamentally opposed to the principle. Rather, they state that they are seriously limited by economic restrictions. Integration of biocatalysis is considered as possible, only if the enzymatic method is significantly cheaper than the chemical procedure and if the change of technology does not involve any sunk cost. This means that the prospective biocatalytic step must not require significant physical changes in the factory, and that the proposed enzymes must be cheap and/or reusable, for the technique to break through.

With regard to environmental factors, most companies are already within the permitted threshold values and are not being restricted in production by environmental laws (unlike the pulp and paper industry). But if production factors like energy and water were more expensive for the companies, reduction of these indirect environmental costs would be a selling point, so to speak.

Environmental standards are powerful tools and can act as a strong push factor. Companies definitely feel threatened by upcoming environmental laws. For example, the legislation evolving towards the total interdiction of chlorine use for fibre whitening is a big concern for SMEs operating in the field. Conversely, there is not any need for the companies to implement more environmental friendly processes if they are already in compliance with environmental standards.

The enzymes producers see 'conservatism' in the administration of the mills as a significant barrier. From the mills point of view it looks more like risk aversion. There are no economic margin to conduct full-scale production trials with enzymes, as a whole kilometre of ruined fabric would be very costly.

Laundry companies by contrast have low risk when conducting experiments, as one batch of, say, jeans can be rewashed and dyed if the desired effect is not achieved with enzymes. The laundries are also very used to trying new processes, as they continuously have to adapt to changes in demand led by fashion trends.

There is an increasing focus on new clothes with new properties and qualities, somewhat dictated by fashion. Many of the enzymatic processes in the textile industry have quality-improving properties and do not substitute any chemicals as such. For the laundries it is doubtful whether it can be directly translated into higher prices, as there are very complex market pricing mechanisms with regards to finished products – think of the huge mark-up prices for designer label clothes. But with regards to the mills, there is more of a straightforward link between quality and price. The mills are very demand driven. If the demanders were offering a higher price for a certain product (e.g. 'eco friendly'), the mills would be willing to take on the extra production costs. At present, the respondents on the producer side were very clear that environmental friendliness does not 'sell' in itself.

Enzyme producers generally find good awareness and goodwill toward biotechnologies in the laundries, but they show a tendency to wish for other companies to go through the trials first. This is closely connected to difficulties in assessing the long-term benefits and thereby the future average production costs. On the other hand, the European textile industry focuses increasingly on high-tech products, which in turn implies a need for unique products.

In summary the main drivers and barriers are:

**Table 14 - Drivers and Barriers, Textile Mills**

| DRIVERS | BARRIERS |
|---|---|
| • Quality improvements /added functionality of product<br>• Enzymes help in complying to new environmental legislation | • Harsh economic restrictions in sector<br>• Enzymes aided processing does not reduce production costs<br>• Adoption of biocatalysts require new machinery<br>• Difficult to assess long term benefits and average production costs<br>• 'Conservatism' /risk aversion in management<br>• Trials are very costly (- large amounts of fabric are at risk) |

**Table 15 - Drivers and Barriers, Textile Laundries**

| DRIVERS | BARRIERS |
|---|---|
| • Strong focus on added functionality of product<br>• No need for new machinery<br>• Trials are cheap / low risk of damaging small batches of raw material<br>• High and fast adaptability to new technology in management | • No reduction in production costs<br>• Stigma that 'Eco-friendly products do not sell' |

## *2.3. Leather*

The tanning industry is highly pollution-intensive, even more so than e.g. the pulp & paper industry. Contrary to other bulk industries however, the product is fairly high value, which gives promise of an economic margin for the introduction of the relatively expensive biocatalyst-technology.

### 2.3.1. Sector Description

EU is by far the worlds' largest supplier of finished leather, Italy being the single largest supplier country accounting for 65 per cent of the European production and 15 per cent of the world market. Other major producers on the world market are USA, Argentina, and the former USSR republics. The sector is dominated by SME's and 90 per cent are so small that they have less than 20 employees. Many of these are traditional family businesses.

**Output/Production**

The production can be measured in either tonnes or $m^2$ and can be categorised by type of leather. Using the square measure, the production for EU-15 amounts to 239 million $m^2$ of bovine leather and 75 million $m^2$ ovine, making a total of 314 million measured in $m^2$. Weight wise, the total production in Europe in 1996 was about 1 million tonnes (JRC/IPTS, May 2001).

**Turnover**

The European leather industry had a turnover of nearly €9 billion in 1996 (JRC/IPTS, May 2001, pp.7) and is a small industry compared to both pulp & paper and the textile industries.

**Employment**

The tannery sector is labour intensive and employment is just over 50 000 in the EU-15 countries. 25 000 are employed in the Italian tanning industry alone, which is three times more than the second largest employer; Spain (JRC/IPTS, May 2001).

**Trends and Perspectives**

Europe's share of the world market is falling as new producers in Asia and the Americas emerge. The prospect for growths in production are not optimistic, as the period from the mid-eighties to the mid-nineties saw a drop in European production capacity of 25 per cent. Today, one third of the world production stems from China alone and this share is expected to rise along with production in other countries outside Europe.

**Process**

The production process in a tannery involves a multitude of steps in the transformation of raw hides into the end products - leather -, for further manufacturing. There are variations to the processing sequences across tanneries depending on the type of products produced, but there are usually four different sections in most tanneries, namely:

1) Storage and beamhouse operations
   - Soaking, unhairing, liming, fleshing and splitting.
2) Tanyard operations
   - Deliming, bating, pickling, and tanning.
3) Post-tanning operations
   - Samming, setting, splitting, shaving, re-tanning, dyeing, fatliquoring and drying.
4) Finishing operations
   - Finishing operations include several mechanical treatments as well as the application of a surface coat. The selection of finishing processes depends on the specifications of the final product.

Additionally, tanneries also employ abatement techniques for the treatment of wastewater, solid waste and air emissions generated during these processes. Operations carried out in the beamhouse, the tanyard, and the post-tanning area are often referred to as wet processes, as they are performed in processing vessels filled with water. After post-tanning the leather is dried and operations are therefore referred to as dry processes. Enzymes cannot be applied in these dry processes.

Pickled skins are tradable intermediate products, and fellmongers do generally not carry out any tanning at their site. The tanned hides and skins are also tradable intermediate products, as they have been converted to a non-putrescible material. It is in fact very common that the different steps of the production are carried out at different locations. For example, 75 per cent of the Italian industry begins their production with the so-called 'wet blue' intermediate product.

**Input**

The main input material is skin/rawhide, which make up around 60 per cent of the total operating costs.

**Table 16 - Composition of Chemical Consumption, Leather Industry**

| | Per cent |
|---|---|
| Standard inorganic (without salt from curing, acids, bases, sulphides, ammonium containing chemicals) | 40 |
| Standard organic, not mentioned below (acids, bases, salts) | 7 |
| Tanning chemicals (chrome, vegetable, and alternative tanning agents) | 23 |
| Dyeing agents and auxiliaries | 4 |
| Fatliquoring agents | 8 |
| Finish chemicals (pigments, special effect chemicals, binders and cross-linking agents) | 10 |
| Organic solvents | 5 |
| Surfactants | 1 |
| Biocides | 0,2 |
| Enzyme | 1 |
| Others (sequestering agents, wetting agents, complexing agents) | - |
| ***Total*** | ***100*** |
| *Source: JRC/IPTS, May 2001, pp.31* | |

Chemicals make up an estimated 10 - 15 per cent of the total production costs, which is not a lot compared to the value of the skins, but still a significant input factor. Table 16 breaks the total chemical consumption up into categories.

Further, it is estimated that 80-95 per cent of the world's tanneries use chromium (III) salt in their tanning process (JRC/IPTS, May 2001). The energy consumed in processing 1 tonne of rawhide varies greatly from 9.3 to 42 GJ (JRC/IPTS, May 2001, pp.26).

Equally relevant to the core issue of this report, is the fact that the environmental cost in the industry is as high as 5 per cent of the turnover (JRC/IPTS, May 2001, pp.8). This suggests significant scope for reducing the use of chemicals and simultaneously benefiting both the industry's competitiveness and the environment.

**Environmental Baseline Load**

As all the main steps in the production of leather are wet processes, the main concern is the environmental loads carried in the wastewater. The discharge from an archetypical chrome-tanning plant can be seen in table 17 below.

**Table 17 - Average Effluents, Leather Industry**

| | Air | Water | | | | |
|---|---|---|---|---|---|---|
| Per tonne material | Organic solvents kg/t | BOD kg/t | COD kg/t | SS kg/t | Chrome Kg/t | Sulphide kg/t |
| Rawhide | 40 | 100 | 230 - 250 | 150 | 5 - 6 | 10 |
| Finished leather* | 8 -10 | 20 - 25 | 46 – 62.5 | 30 – 37.5 | 1 – 1.5 | 2 – 2.5 |
| *) The relationship between input and output of rawhide and leather is approx. 1t. / 200-250 kg | | | | | | |
| Source: (JRC/IPTS, May 2001) | | | | | | |

This is only a selection of pollutants from the tanning industry, but include the environmental factors that are likely to be reduced in the event of increased use of biocatalysts.

## 2.3.2. Biocatalysts

It is estimated that biocatalysts today make up just 1 per cent of the chemical consumption used in the main and auxiliary process of tanning (see table 16). The enzymes currently used in the leather industry are mainly proteases and lipases, but there are other emerging applications.

**Technological Possibilities**

The following table shows the potential of biocatalysts in the different stages of leather manufacturing.

**Table 18 - Biocatalyst Possibilities, Leather Industry**

| Process stage | Biocatalysts | Benefits |
|---|---|---|
| Soaking | Proteases, Lipases | Can replace the use of environmentally damaging tensides |
| Liming | Proteases | Can reduce the use of chemicals like sodiumsulphide and calciumhydroxide and thereby, reduces COD with up to 10-20 per cent.<br>If chemicals are fully substituted and 'hair saving' is applied, a 50 per cent reduction can be achieved. |
| Baiting | Trypsin | Qualitative improvements |
| Tanning | Future potential | Reduce use of cross binders like chromium (III) |
| Re-tanning | Future potential | Expand skins 3-5 per cent |
| Finishing | Future potential | Reduce use of other cross binders |

This report will focus on the most promising with regard to environmental effects.

- Bio-soaking: Soaking of raw hides in proteases and lipases.

A proteases solution is used to remove proteins, carbohydrates, and lipases remove fatty material. Both of these processes are traditionally performed using large quantities of tensides.
The use of the enzymes can be optimised to obtain maximal efficiency and cost effectiveness by controlling factors like Ph, temperature, concentration, and recovery of side products.

- Bio-liming: Enzymes assist the chemical process of liming.

The liming step of leather production traditionally consists of soaking the hides in lime (calciumhydroxide) and sodiumsulphide in a so-called 'hair burning' process. This can be aided with enzymes (proteases), and the amount of chemical can be reduced, in what is called 'hair pulping' or simply 'low sulphide' processing. A further reduction can be made if 'hair saving' is applied, which entails using the enzymes to loosen and separate the hair from the skin instead of dissolving them. The latter method requires installation of a filter system, to filter the hairs from the wastewater. This considerably reduces the COD of the effluent water along with a reduction in the use of the two chemicals traditionally used in this phase. Furthermore, the process can be sped up and save time.

**Current and Future Application**

The two processes mentioned above are already in use and have a quite good market penetration of about 15 per cent in Europe. However, the penetration could theoretically be 100 per cent, or at least 70 per cent from a realistic market perspective, based on interviews conducted in this study.

Baiting has a market share of 90 per cent, which is impressive, and is not related to any significant environmental effects and will therefore not be dealt with in this report.

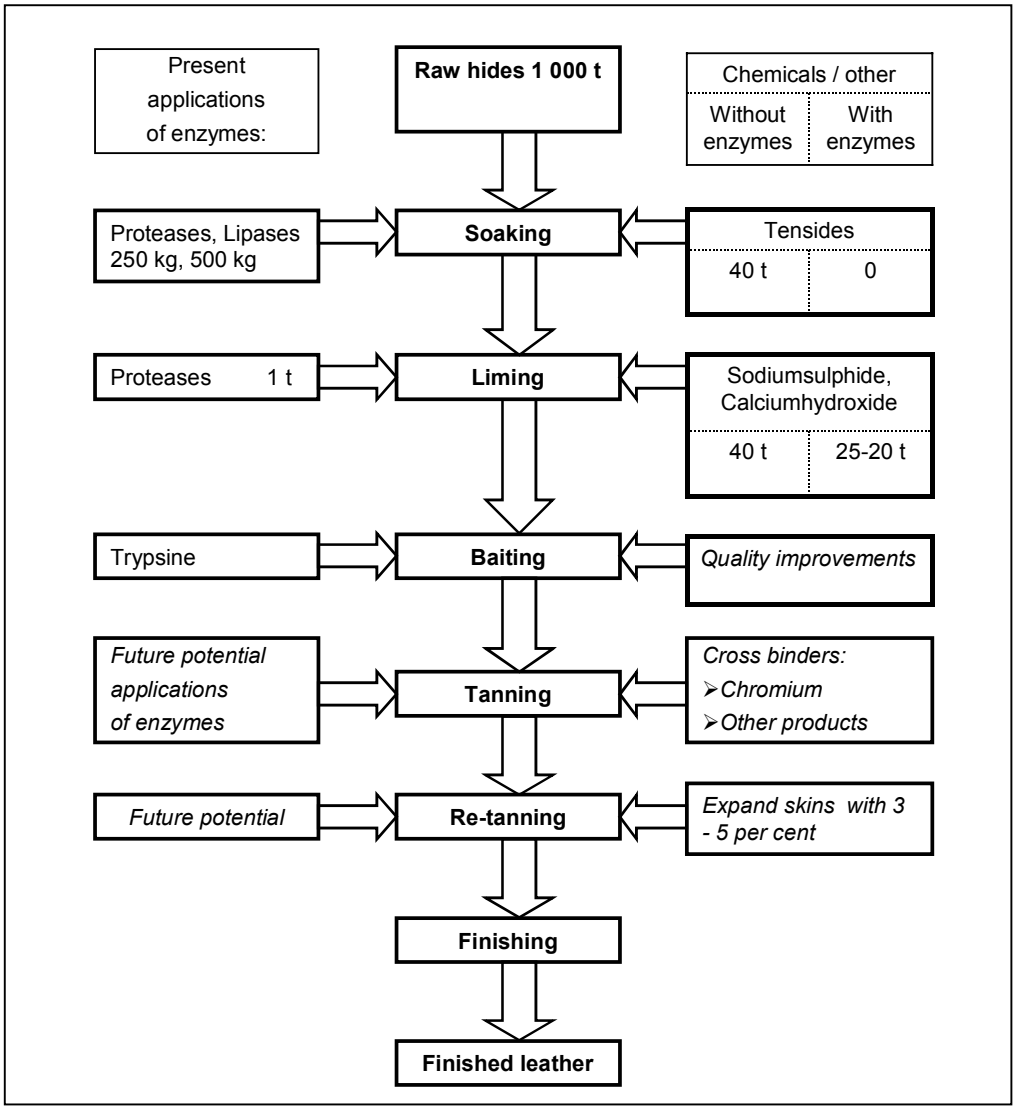
Future applications of biocatalysts in the leather industry are under development, as it can be seen in table 18 above, outlining the technological possibilities. Most are related to quality improvements however, and do not have many direct environmental effects.

**Archetype**

Determining an archetype process for the leather industry requires broad generalisations. Still, since 80-95 per cent of the world's tanneries use more or less the same tanning process, it is reasonable to stick with one archetype for this industry. As mentioned earlier, there is a growing tendency towards splitting up the different stages in manufacturing of leather, with a considerable trade of intermediate products. However, this does not make any difference in an overall look at the industry, like the one we are taking here. The fact that there seems to be an increasing division of labour between European manufactures and fellmongers in countries outside Europe is *not* insignificant, but we will return to that discussion in the later chapter concerning estimation of future potential.

The figure below shows an archetypical tannery process, where the most effectual substitution at the liming step is selected, namely the 'hair saving' technique.

**Figure 11 - Archetype: Leather Industry, '*Hair Saving*'[28]**




[28] *Source: Kvistgaard Consult based on interviews with users and producers of biocatalysts*

There are not expected to be any significant changes in the input/output relations when introducing biocatalysts. It is possible that the use of enzymes will prove gentler to the skins and reduce the proportion that is damaged during production processes. But since the skins are very valuable, this damage is already minimised and there is little room left for improvement on this front.

**Environmental Effects**

The biggest potential for reducing the environmental damage made by the tanning industry, comes from the substitution of lime (calciumhydroxide) and sulphide in the liming process step. It can potentially reduce the COD in the wastewater with up to 50 per cent and sulphide effluent with as much as 40 per cent, if 'hair saving' is applied. This amounts to very considerable quantities, as 1 tonne of processed rawhides on average results in 230 – 250 kg of COD and approx. 10 kg of sulphide. For 1 000 tonnes of raw material input this means a potential reduction of approx. 120 000 kg COD and 4 000 kg sulphide.

There is also potential for reducing BOD in wastewater produced in soaking of hides. This is not a straightforward relation however: Traditionally used tensides diluted in water or organic solvents like gasoline attack the fat in the hides and dissolve it. The lipases and proteases enzymes, which can substitute these chemicals, work differently and dissolve the fat in such a way that it is easier degradable in nature. However, this does mean that the organic pollution measured by BOD may rise, as the substitution towards enzymes progresses. One can debate whether this is an environmental improvement or not.

**Economic Effects**

We now turn to look at the economic and environmental effects of changes in production input and reduced environmental damage, due to the application of biocatalyst processes. As explained in chapter 1.1 (methodology), these effects are assessed based on the definition of the archetype process for the industry.

For the leather industry it was established that the potential for use of enzymes in the soaking and liming steps are quantifiable. Table 19 lists the potential effects for the leather industry, including only these two biocatalyst-technologies.

**Table 19 - Economic and Environmental Effects, Leather Industry**

| **Effect of Change from Chemical to Enzyme-aided Processing** | | |
|---|---|---|
| **Costs related to treatment of 1 000 tonnes of raw material input** | Tech 1: Soaking | Tech 2: Liming |
| | Substitution of tensides with lipases and proteases | Substitution of sodiumsulphide, calciumhydroxide with proteases *"Hair saving"* |
| ***Economic factors*** | | |
| Chemical savings | € 6 800 | € 12 000 |
| Biocatalysts costs | € 10 800 | € 15 000 |
| Quality improvement of end product | (++) | |
| ***Total economic costs*** | ***-€ 4 000*** | ***-€ 3 000*** |
| ***Environmental factors*** | | |
| BOD | + / - | |
| COD high / medium / low valuation | | € 359 000 / 195 00 / 74 000 |
| Sulphide high / medium / low valuation | | € 12 000 / 6 500 / 2 500 |
| | | |
| ***Total environmental costs*** | ***€ 0*** | ***€ 370 000 / 200 000 / 77 000*** |
| ***Total socio-economic value added*** | ***-€ 4 000*** | ***€ 367 000 / 197 000 / 74 000*** |

For the liming step it is relevant to note that an investment in a filter system costing in the range of €20 000 to €40 000 is needed, in order to switch to the hair saving process. This is however a 'one-off' expense, and does therefore not enter into the estimations of average costs in table 19. The significance of the presence of sunk costs will be discussed in detail in chapter 3.2.

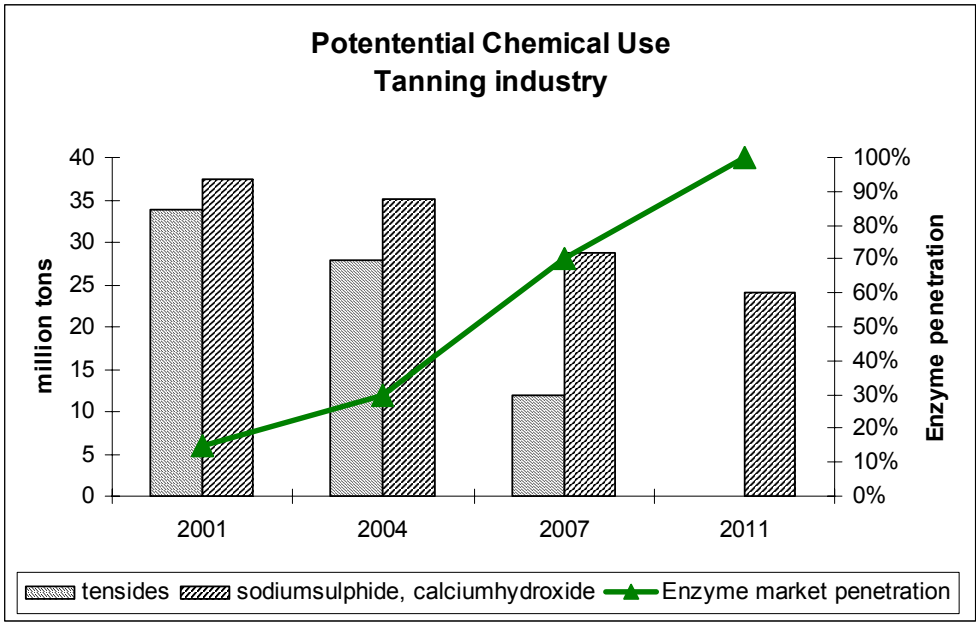
Table 19 also shows that the enzyme costs are higher than the chemical savings in both the soaking and liming production step, by €4 000 and €3 000 respectively. There are quality improvements of the end products, which have not been included, but it is hard to imagine that they are significant enough to bridge the gap in costs. Illustratively, it can be calculated that a value added corrective tax must be nearly 60 per cent on tensides, which corresponds to approximately €0.1 per kg. For the liming chemicals, a tax must be 25 per cent or roughly €5.25 per tonne, for the price on the amount of enzymes needed in this process to be equal to the price of the chemicals.

When the environmental effects are included and valuated, the balance sheet looks very different for the two processes. With regard to soaking, no quantifiable environmental effects have been identified, apart from the uncertainty surrounding BOD-levels. Conversely for liming of hides, where even the most conservative valuation of the environmental effects tip the balance and make it socio-economically desirable to politically encourage the substitution towards enzymes, - e.g. via a tax.

### 2.3.3. Future Potentials

For the tanning industry it was found that there is considerable potential for substitution of chemical substances used in both the bating and the liming process. The use of tensides in bating of hides can potentially be totally substituted by lipases and proteases.

**Figure 12 - Future Potential for the Leather Tanning Industry**



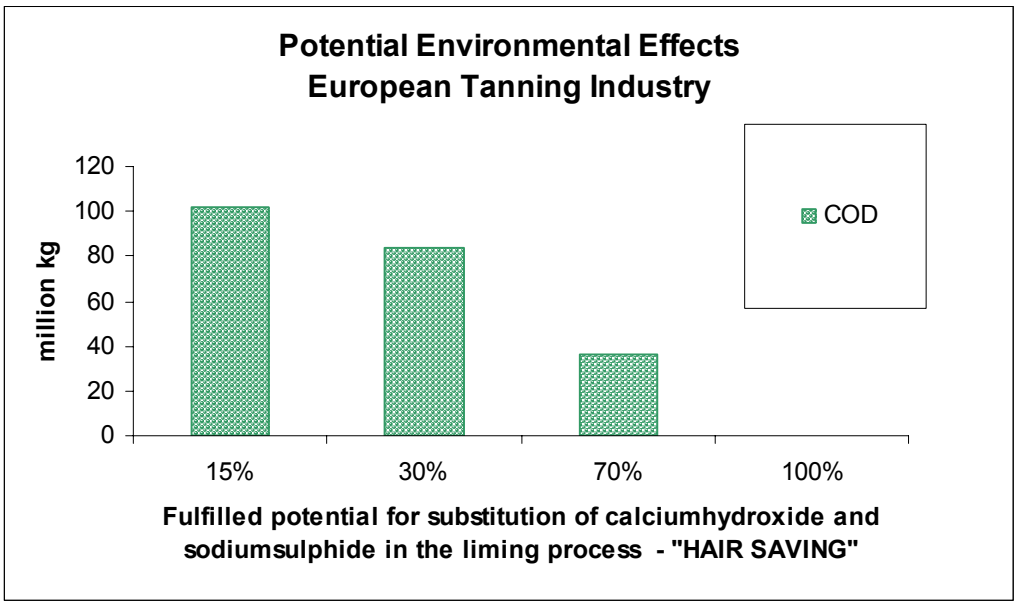

Looking at the total European sector, the estimations of future potentials in Figure 12 show that tenside consumption could be reduced by 34 million tonnes. This assumes 100 per cent substitution and unchanged production level in the sector. Even with 'just' 70 per cent penetration, the result is a

reduction of 20 million tonnes tensides. Bearing in mind that there is already today quite good market penetration of around 15 per cent, this is a rather uplifting prospect. Enzyme suppliers in the interviews deem a market share of 70 per cent technologically plausible,.

With regards to the liming process there is the possibility of substituting a portion of the sodiumsulphide and calciumhydroxide (lime) with enzymes in a 'hair saving' technique. It is estimated that somewhere between 40 and 50 per cent of these traditionally used substances can be replaced in this way. Figure 12 illustrates the effect for the entire sector, starting at the present level of market penetration, namely 15 per cent. The estimations of future potential show the possibility of a reduction of 14 million tonnes, when the potential is 100 per cent fulfilled, or 7 million tonnes with 70 per cent market penetration. Neither of these estimations of future potential are likely without political intervention, considering the estimated archetypical economic factors for this specific substitution.

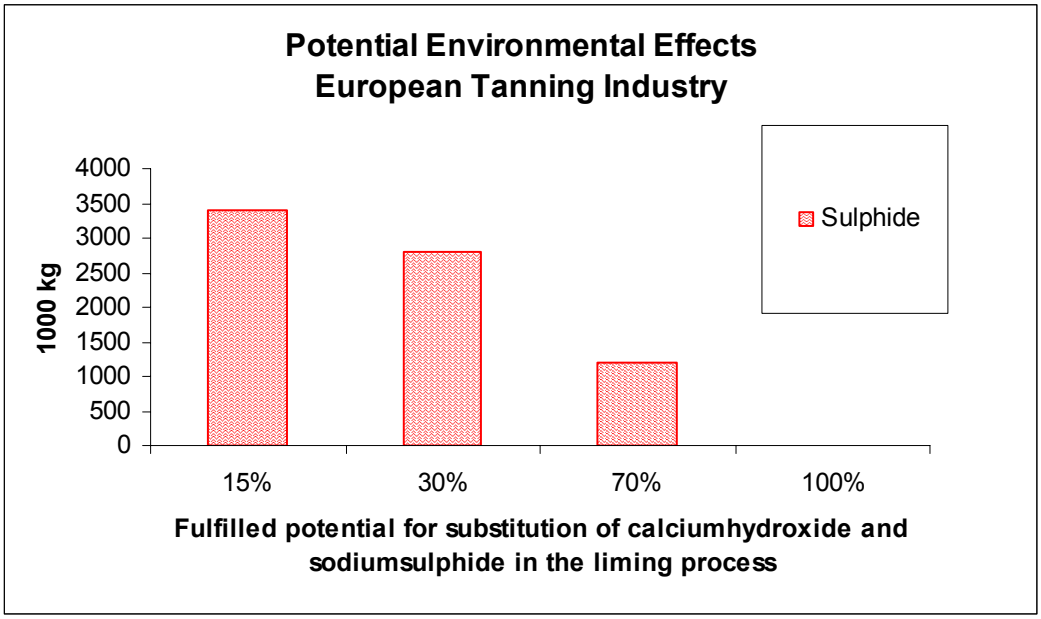
Looking at the environmental effects for the entire European industry, the tables 13 and 14 show the gradual reduction of sulphide and COD in the wastewater as the potential is fulfilled.

**Figure 13 - Future Potential Environmental Effect, Tanning Industry**




The maximum potential reduction of 3.4 million kg of sulphide can be realised whether 'hair pulping' or 'hair saving' is applied, since both techniques entail the same reduction in the sodiumsulphide input. The COD reduction of well over 100 million kg in the 100 per cent penetration case, is estimated on the basis of the 'hair saving' process only. In the perhaps more realistic estimation of future potential of 70 per cent market share for enzymatic processing, the effect is still a remarkable 65 million kg a year in Europe.

**Figure 14 - Future Potential Environmental Effect, Tanning Industry**




The effects depicted in both figure 13 and 14, stem from the liming process step, which was the less likely to occur without political intervention.

### *2.3.3.1. Feasibility of Future Potentials*

Tanneries have many similarities with textile mills. The economic situation in the sector is difficult due to increasing competition from countries outside Europe, time-honoured methods dominating processes etc. However, one very significant difference is that hides/skins are treated in batches and the reaction time of enzymes therefore constitutes less of a problem.

Inertia in the business is a significant hindrance, when trying to introduce new technologies. As mentioned earlier, it is often traditional, tried and tested processes, which guide the small tanneries. A lot of the processes have not been fully analysed and the relations between the different chemical reactions remain somewhat enigmatic, so that the same exact procedure must be followed each time to reach the same end result. In such environment it can be hard to convince tanners to deviate from tradition and take on new technology.

The most significant barrier to the implementation of new production processes like the use of enzymes, is the simple fact that the skins are both the most valuable input factor and constitute a substantial part of the final product value, and the tanneries are therefore very careful about not damaging them. This means less inclination towards experimentation with new methods. The hope is that this barrier should be easy to overcome, once the biocatalysts have been proven safe and easily applicable.
In conclusion the main drivers and barriers for adopting biocatalysts in the leather industry are at present:

**Table 20 - Drivers and Barriers, Leather Industry**

| DRIVERS | BARRIERS |
|---|---|
| • Quality improvements /added functionality of product<br>• No need for investment in new machinery<br>• Help in complying to new environmental legislation | • Enzymes aided processing does in some cases not reduce production costs<br>• Trials are very costly – risk of damaging very valuable raw material<br>• Inertia in management – tradition rather than science guide processes |

## 2.4. Other Sectors

This chapter covers industries, which have heterogeneity in common. We have chosen to focus on the food and the fine chemicals & pharmaceutical.

The food industry, fine chemicals and pharmaceuticals industry produce many different products and for each process, enzyme design must match exactly. This means that a general archetype cannot be developed for these industries. A quantitative assessment of future environmental and economical impacts can therefore not be made using the archetype method.

Further, fine chemical and pharmaceutical industries are companies that are already very well acquainted with biotechnological R&D, contrary to industries in pulp, paper, textiles and leather. The companies are therefore able to produce biocatalysts themselves. This makes the market very difficult to analyse, since demand and supply side coincide. Revealing the true price and quantity of enzymes produced and consumed in-house is practically impossible.

### 2.4.1. Food Industry

#### *2.4.1.1. Sector Description*

The largest food enzyme manufacturers in the market are Novozymes, DSM/Gist-brocades and Genencor International, together accounting for about 60 per cent of the total turnover. Most players focus on only one or two related end-user segments, such as baking, brewing or juice processing. Smaller enzyme companies can often be characterised as serving emerging and niche markets with high-value speciality enzymes.

The European food enzyme market is witnessing a period of significant change. Change that is taking place as a result of transformations in product portfolios and the overall market structure. As consolidation accelerates, the number of players active in the market will further decrease, with only a few large bulk enzyme suppliers existing in the foreseeable future. Focus on product development, particularly for speciality enzymes, will provide manufacturers with a firm basis on which they can remain competitive. A comprehensive enzyme portfolio and the development of close end-user relationships are two key areas that are expected to generate success over the forecast period.

On the market for industrial enzymes, economies of scale in the production of enzymes play an important role. On the markets for food a considerable number of enzymes and especially enzyme mixtures are produced, but the voluminous quantities are less.

One third of the enzymes for the food market are used in the diary industry. However, the total amount of different types of cheese in Europe is estimated to more than one thousand and the very specific applications of enzymes is apparent: Several enzymes are used in several combinations in several different process circumstances.

#### *2.4.1.2. Biocatalysts*

For thousands of years, man has used naturally occurring micro-organisms, - bacteria, yeasts and moulds -, and the enzymes they produce to make foods such as bread, cheese, beer and wine. For

example in bread-making the enzyme, amylase, is used to break down flour into soluble sugars, which are transformed by yeast into alcohol and carbon dioxide. This makes the bread rise. Today, enzymes are used for an increasing range of applications: Baking, cheese making, starch processing and production of fruit juices and other drinks. Here, they can improve texture, appearance and nutritional value, and may generate desirable flavours and aromas.

**Technological Possibilities**

The relative scarcity of enzyme use within the food industry is brought about by a combination of problems. Concerns over possible adverse effects on product quality, in particular with respect to flavour and texture, the limitations given by the activity of enzymes and their considerable costs make more cost effective methods very attractive to industry.

**Table 21 - Enzymes Used in Food Processing**

| Class | Enzyme | High Value | Major Food Use |
|---|---|---|---|
| **Carbohydrase** | Alpha-amylase | + | + |
| | Beta-amylase | | + |
| | Amyloglucosydase | + | + |
| | Cellulase | | |
| | Pectinase | | + |
| | Invertase | | |
| **Proteases** | Bacterial proteases | | + |
| | Fungal proteases | | |
| | Bromelain | | |
| | Pancreatin | | + |
| | Rennin (chymosin) | + | + |
| | Pepsin | | + |
| | Papain | + | + |
| **Others** | Glucose oxidase | | + |
| | Glucose isomerase | + | |
| | Lipase | | |

The enzymes representing the bulk of industrial use are listed in table 21. The five that are marked as 'high values', make up the major production in value, if not in volume. These enzymes are employed in a wide range of industries in addition to food processing. For example does Novozymes estimate that around 40 per cent of their enzyme sales are used in the production of detergents - mainly proteases (Novozymes, 2001).

Most of the enzymes listed in the table are employed in one way or another within the food industry. However, only ten are used in significant amounts and represent the bulk of commercial use in this area, - these have been marked 'major food use'.

In food production, enzymes have a number of advantages: They are welcomed as alternatives to traditional chemical-based technology, and can replace synthetic chemicals in many processes. This allows real advances in the environmental performance of production processes, through lower energy consumption and biodegradability. They are more specific in their action than synthetic chemicals. Processes, which use enzymes, therefore have fewer side reactions and waste by-

products, give higher quality products and reduce the likelihood of pollution. Furthermore, they allow some processes to be carried out which would otherwise be impossible.

The major applications of enzymes within the food industry are outlined in table 22 below.

**Table 22 - Enzyme Applications, Food Processing Industry**

| | |
|---|---|
| **Amylases and Amyloglucosidase** | Production of fermentable sugars, in baking and brewing<br>Starch liquification<br>Fruit juice clarification |
| **Cellulase** | Fruit liquification<br>Solubilisation of pentosan in baking |
| **Pectinase** | Fruit juice clarification |
| **Invertase** | Hydrolysis of sucrose in confectionary<br>Flavour development in fruit juices |
| **Proteases** | Meat tenderisation<br>Flavour and colour in juices<br>Bread quality in baking<br>Enhanced cheese ripening<br>Brewing |
| **Lipases** | Foam stabilisation in baking<br>Enhanced cheese ripening |
| **Glucose isomerase** | High fructose corn syrup |
| **Glucose oxidase** | Prevention of Malliard browning reactions<br>Bromate replacer in baking<br>Oxygen scavenger in fruit juices |

The major users are the baking, brewing, juice and beverage and dairy industries. Amylases are used to breakdown starch to provide glucose for fermentation, or in the liquefaction of starch as in the production of high fructose corn syrups (HFCS). The glucose produced in the latter case is converted to the sweeter tasting fructose by the action of glucose isomerase. Whilst HFCS production is carried out on a large scale within the USA its application in Europe has been limited by competition with sugar beat based alternatives and arguments over EU quotas. The other carbohydrases-cellulase and pectinases such as polygalacturonase and pectinesterase are used to liquefy fruit by breaking down the cell walls and also to clarify fruit juices by removing the pectin which constitutes 'haze' in these products. The proteases have a wide range of applications: They can influence bread firmness by alteration in gliadin or glutenin proteins in dough; tender meat by breaking down the sarcomere structure muscle; or produce flavour in a variety of products including cheese.

**Current and Future Applications**

Fundamental changes in product portfolios are hitting the food enzyme market, a result of market players shifting their attention away from traditional food enzyme products. As manufacturers move towards speciality products and emerging applications, standard bulk products are seeing their market share dwindle. It appears that lucrative speciality enzymes are providing excellent development opportunities. Market revenues will rise from about €250 million in 1999 to €320 million by 2006, growing at an annual compound growth rate of 3.2 per cent[29]. The major share of the food enzymes market is for starch processing, accounting for 26.7 per cent of the total market, followed by the dairy sector with 25.8 per cent and baking segment with 20.5 per cent.

[29] Food Navigator: *Trends*, http://www.foodnavigator.com/trends5.asp?id=155

Research and development are providing manufacturers with not only an expanding number of enzymes, but also further possible applications for existing products. Product development is an ongoing feature of the European market and a key to maintaining market shares. New product ranges are being marketed as cost-effective solutions, with improved performance and more environmentally friendly characteristics.

The use of enzymes within industry in general and the food industry in particular may be extended by the application of genetic engineering and related technologies. Genetic engineering enables the transfer of DNA from one organism to another. Thus, given suitable DNA sequences, the ability to synthesise any enzyme can be transferred between organisms. This technology allows enzymes to be synthesised in large amounts and in systems, which are commercially viable. This technology has already been employed in the production of chymosin. Chymosin is used in the production of cheese, the industry as a whole requiring an estimated 70 000 kg per annum.

Most food production processes are biotechnological processes for which no production alternative is available. These biotechnological processes cannot be indicated as more clean than chemical/physiological processes, by definition. However, biotechnology can contribute to cleaner production in some of these processes.

However, all known examples of environmental savings are spin-offs of economic savings, like the water saving processes in the fruit juice industry leading to less transport and thus less traffic pollution.

The application of enzymes in the food industry is usually carried out in conventional bioreactors. The enzyme is added to the food substrate and is one of the components of the reagent mixture. Alternatively enzymes can be immobilised in carrier materials, excluded from the reagent mixture. This saves costs and efforts for separating the product from the enzymes, for re-use. One of the main advantages is continuous operation whereby the product passes through and the enzymes are contained within the bioreactor. The environmental spin-off is that less waste is produced.

The main application areas for immobilised enzyme technology are in liquid food processing and brewing. The technology also holds some disadvantages, as immobilised enzymes can lose activity in repeated use, adding to the total processing costs. Also, significant investments are required for large-scale continuous reactor systems.

With the use of recombinant DNA technology the production of enzymes is much 'cleaner' compared to the traditional production processes. Enzyme production with rDNA leads to savings in raw materials, water, steam and electricity of approx. 40 and 50 per cent[30].

The environmental savings in the food sector will remain small compared to the potential savings in, say, the detergent and pulp and paper industry. The most interesting example is in the oil industry, where enzymes can be used in the extraction of vegetable oil from seeds. A new enzymatic process still under development, is intended to replace the traditional technology using hexane[31]. Apart from being dangerous to inhale, hexane is highly explosive. It is used to dissolve

[30] Towards sustainable development with genetic engineering, BioTimes 4 - 12/96, Novo Nordisk; http://www.novo.dk/enzymes/biotimes9604/main.htm

[31] Based on interviews carried out in this study.

the oil from the crushed seeds. The enzymatic process will allow extraction to be performed in water.

### *2.4.1.3. Future Potentials*

In the baking process alone, enzymes can be applied in multiple processes. These are shown in Figure 13. This section concentrates on the improvements that the enzyme transglutaminase can have in the baking industry and tries to develop an estimation of future potential of its future impact.

Emulsifiers contained in bread improvers are substances, which promote the homogeneity of dough. Since many emulsifiers are chemical substances, extensive efforts have been made to replace them with natural, biological auxiliaries. The effect of emulsifiers can be substituted by transglutaminase, in combination with other baking enzymes. Particularly noticeable are the favourable dough properties and the baking volume achieved through the dough-stabilising action of transglutaminase. Emulsifiers strengthen the gluten structure so that it is possible to use machines for the kneading. And they keep the bread fresh longer by retarding the starch crystallization. Figure 15 gives and overview.

**Figure 15 - Baking Enzymes, including Transglutaminase**

| Wheat flour | Enzyme | Action in the dough | Improvements |
|---|---|---|---|
| **Starch** | α-Amylase | Dextrins<br>↓ + β-amylase<br>Maltose<br>↓ + yeast<br>$CO_2$ | ► Dough processing<br>► Aroma, crispness<br>► Baking volume |
| **Protein** | Proteinase<br>Transglutaminase | Gluten softening<br>Gluten strenghtening | ► Dough processing<br>► Dough processing |
| **Pentosan** | Xylanase | Degradation of insoluble pentosans | ► Baking volume<br>► Dough processing<br>► Crumb structure |

http://www.roehmenzyme.com/GB/Pages/seltop_e_fs.html

The west European bread industry produces 25 million tonnes of bread per annum, of which the industrial sector‘s share is 8 million tonnes. Germany and the UK are the main operators with 60 per cent of industrial sector production – France, the Netherlands and Spain produce another 20 per cent between them.[32]

Emulsifier consumption at the individual level remains controversial and very little is known about its real intake by the individual, or by different groups of the population. Per capita consumption data represents the apparent consumption (production/number of habitants). Consumption data comprises therefore industrial use, non-food use, use for animal feeding, waste and individual

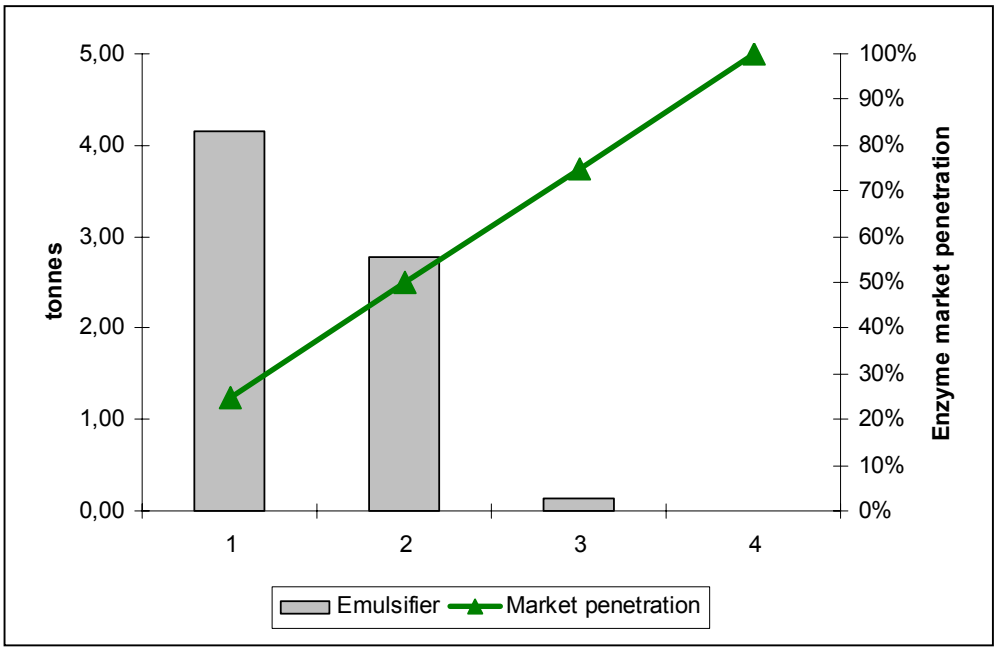
[32] However, the German quality standards („Reinheitsgebot“) for bread do not allow for the addition of neither emulsifiers nor enzymes (clean label). Hence the extrapolation on basis of market data and input recipes is not representative.

consumption. Compared with the apparent consumption (including waste, stocks and industrial consumption) the real consumption might be two to three times lower.

While the data on emulsifiers is considered for the use by the public domain, the accessibility to data on enzymes is dependent on whether data is considered for the public or proprietary. Unfortunately most of the data on enzymes required in this study is considered to be proprietary. In order to overcome this lack of harmonized statistical information on enzymes for the bakery sector, industry statistics and interviews have been used.

The input relationship between enzyme and emulsifiers in the bakery sector are as follows: For one kg flour, 300 g of the emulsifier is required. This amount can be replaced by only 10g of the enzyme. The cost of one kg emulsifier is about €2.5, while the enzyme price is at €33 per kg.

**Figure 16 - Replacement of Emulsifiers by Enzymes**




Assuming that all 18.5 million tonnes flour consumed annually in Europe were supplemented by an emulsifier with a ration 10/3 (300 grams emulsifier per kg flour) and supposing the technical feasibility of a one-to-one substitution, this results in the hypothetical substitutive relations for the annual European flour consumption depicted in Figure 16.

A 25 per cent substitution of emulsifiers by enzymes would hence lead to a replacement of 4.16 tonnes emulsifier by 46.3 kg enzymes. The cost saving for the manufacturer applying an input ratio of 25 per cent enzymes / 75 per cent emulsifier would be €1 900.

**Feasibility of Future Potential**

It is suggested that the demand for food produced with enzymes (rather than chemical reactions) responds less than proportionately to a change in price, so that a price decrease of „enzyme bread' is not a sufficient incentive for consumers to change their purchasing preferences and consumption habits (Elasticity of Enzyme-Bread Consumption). For this reason, the demand for enzymes from the bakery industry depends entirely on consumer preferences rather than the price of enzymes.

**Table 23 - Drivers in the Baking Industry**

| DRIVERS |
|---|
| • High degree of specificity<br>• Continued growth in the food ingredients markets |

The commercial benefits of high specificity enzymatic products are seen as a major driver of growth within the market. This is coupled with an expected rise in the number of end-user applications and continued growth of the food ingredients markets. Legislative measures on both a national and European scale continue to impact the overall market. The debate surrounding GM foods and organisms has an obvious impact on the development.

The biggest savings at the level of resource consumption can be achieved if the idea of a product is looked at from a different angle. What a consumer wants is in many cases not the material product as such, but rather its performance i.e. the service he or she obtains from it. Thus, one major trend today is that many companies are shifting from selling a product to selling a service and so retaining responsibility for the underlying product throughout its life cycle.

**Table 24 - Barriers in the Baking Industry**

| BARRIERS |
|---|
| • Low public acceptance of enzymes produced by genetically engineers micro-organisms<br>• Legislation regarding enzymes produced by genetically engineers micro-organisms |

The most important bottlenecks for increased enzymes applications in food markets are related to the use of enzymes, which are produced by genetically engineered micro-organisms. These bottlenecks are public acceptance and legislation.

Although EU-regulation should lead to uniform legal systems, the legal situation in the EU member States differs strongly. Whether legislation has to be seen as a hindrance or a stimulant for developments, depends on local factors and actors. The German 'Rheinheitsgebot' concerning beer prohibits the use of novel ingredients in the brewing process. This prompted the German beer industry to develop sophisticated brewing technologies, which had a positive impact on developing new products and processes.

The lack of public acceptance of the use of enzymes produced with genetically modified organisms, is a bottleneck for the use of this specific technology in food processing. The German government did for example deny marketing approval because of the lack of acceptance of the public.

## 2.4.2. Fine Chemicals & Pharmaceuticals

### *2.4.2.1. Biocatalysts*

Biocatalytic methods are used in both the fine chemical and pharmaceutical sectors in the synthesis of a wide variety of compounds. The synthesis of each particular class of molecules requires a unique series of steps, and there is no single bio-transformation process, which can serve as an archetype. Additionally it has proven impossible to gather data on comparative costs of synthetic pathways using a bio-transformation step, compared with a more traditional route. However, examples are described below of a reaction in which biocatalysts have been successfully used, to substitute processes conventionally done by other chemical means, and in reactions that are only really economically viable through the use of a biocatalyst.

It is hard to gauge what the percentage of reactions carried out in the pharmaceutical and fine chemical sectors that could use biocatalysts is. For many simple reactions (such as deproteations) it simply isn't worth using biocatalysts. Perhaps 5 per cent of all chemical reactions in fine chemicals use biocatalysts, but those that do, could not always be done at a commercially reasonable cost by conventional chemical syntheses (e.g. specific stereochemical reactions). Estimates of biocatalysis use in the pharmaceutical sector also vary, but may be as high as 10 per cent.

To illustrate the diversity of the two sectors, three cases are presented in the following. The first is an example of a substitution for a conventional bulk chemical process, the second is an example where use of a biocatalyst is the only commercially viable option, and the third an example of a reaction only possible by the bio-transformation route.

- Production of acrylamide from acrylonitrile

This biotransformation is the first example of successful use of a biocatalyst to produce bulk quantities of a chemical and was pioneered by Nitto (30 000 tonnes per year at one plant)[33]. A French company SNF Floerger has also recently reported uptake of this technology[34]. In comparison with the traditional method that uses a copper catalyst, use of an enzymatic route has several advantages. For example the reaction can be done without heating or high pressure and the waste stream is more easily processed since there is no requirement for heavy metals. Furthermore, the acrylamide produced is of higher quality and therefore will polymerise more readily in subsequent applications. Finally the biotransformation is chemically superior in that it obviates the need to recover unreacted nitrile since the conversion is >99.9 per cent.

- Production of chirally pure 2-chloroproprionic acid (CPA)

If any class of reactions can be considered to be an archetype for use of a biocatalyst in the chemical/pharmaceutical sector, it is the production of a chiral compound that is an intermediate for a single-isomer drug or agrochemical. There are many such reactions that resolve racemic mixtures - most of which rely on hydrolytic enzymes.

[33] Liese, A, Seelbach, K and Wandrey, C. (2000), pp. 362-368.

[34] See http://www.snf-floerger.com/press/pressrel.pdf

In a process developed by Avecia (UK)[35] a bacterial dehalogenase enzyme is used to selectively degrade the R chiral form that is not desired from a racemic mixture. The L-form of CPA can then be used in synthesis of other optically active compounds such as pharmaceuticals[36]. However, the main use of the CPA is in the synthesis of Mecoprop and other phenoxyproprionic acid derived herbicides. Previously many of this class of agrochemicals were sold as racemic mixtures. However, the use of the chirally pure form has significant environmental advantages since less chemical application is required. Most importantly, since the capacities of production plants to generate active product can be doubled, and there also is a 2-fold reduction in costs through raw material savings, there are strong economic incentives to adopt this biotransformation approach. Comparative costings are not available, but 2 000 tonnes a year of 2-CPA are produced each year by this method at a purity of 99 per cent.

- Generation of stereospecific bilactams

One example where a biocatalyst is the only way to carry out a reaction is the Chiroscience lactam/lactamase process in which only one of two forms of a racemic population of bilactam is hydrolysed[37]. The un-hydrolysed stereoisomer can then be converted into a carbocyclic nucleoside such as Carbovir, which is a potent and selective inhibitor of the HIV-1 virus that causes AIDS.

#### *2.4.2.2. Future Potentials*

As discussed in the methodology chapter, not all sectors are open to be analysed using the archetype approach and Fine Chemicals & Pharmaceuticals plus the Food industry are among those. An attempt to assess the potentials in these sectors should however not be dismissed on that ground, as the sectors hold possibilities relevant to the main questions in this study.

Several general trends were reported from the sources consulted in this study. These sources were drawn from both academic and industrial practitioners.

- The predominate trend is a gradual, slow, but increasing acceleration in the uptake of biocatalysis. This is reflected both in increased usage in current processes and in additional processes (there are thousands of processes running which might be amenable to biocatalysis).

- More and better enzymes are becoming available for testing (multigenomic screening and directed evolution approaches), and techniques are evolving for more reliable production and higher-level expression. However, as with most screening approaches, the use of the new techniques for enzyme development relies on having a good assay that is robust and scaleable. As the ability to produce larger volumes of enzymes grow, the unit cost tends to fall and the differential costings begin to look more favourable for biotransformation options. This allows the revisiting of old ideas, where the cost arguments were previously unappealing.

[35] Taylor, S. (1998), pp. 23-25.

[36] Liese, A, Seelbach, K and Wandrey, C. (2000), pp .322-325.

[37] Liese, A, Seelbach, K and Wandrey, C. (2000), pp. 312-313.

- More whole cell rather than isolated enzyme applications are being used. This will be accelerated by the development of sophisticated pathway engineering to do a whole series of reactions within a host cell.

- It takes a long time to take a compound through clinical trials - the compound may have been licensed at a time when production using biocatalytic avenues was not possible. As new drugs come on line we will increasingly see therapeutics produced using processes with biotransformation steps.

The factors deciding the magnitude of biocatalyst use in the chemical/pharmaceutical sector in the next 10 years are presented in table 28. Evidently, these are much the same as for the other sectors.

**Table 25 - Drivers and Barriers, Fine Chemicals/Pharmaceuticals**

| DRIVERS | BARRIERS |
|---|---|
| • Specificity/selectivity<br>• Mild conditions<br>• Simpler processes<br>• Regulatory/safety preferences | • Cost and instability of catalyst<br>• Need for precise control of conditions<br>• Slow rates/ high residence time<br>• Unfamiliarity and high R&D costs |

Again, the biggest barrier to overcome is the inertia in the industry. Though most types of organic reactions can be carried out using enzymes, this is not done due to lack of comfort and familiarity with the processes. The UK Biowise programme, which aims at improving the uptake of biotechnology by industry, has identified three main factors inhibiting greater usage. *First*, few companies have biochemists and microbiologists employed and so most do not have much experience of handling enzymes. However, this situation is improving. *Secondly*, conventional chemical reactions are predictable and represent a quantifiable risk. They have to overcome the fact that if a chemical process goes wrong then they know what to do, but if it's a biological process they might have to call in others. *Thirdly*, chemical companies need to be extremely confident that they can plan and cost the production of fine chemicals from procurement of the reagents to the purity and quantity of the working product. This has to include a detailed plan and cost for waste disposal. Moreover, to compete with global competition chemical manufacturers need to respond to tenders within as little as 10 working days. This last consideration in particular can be a major problem, since there is a perception that it takes longer to establish a biocatalytic process, and a tendency to revert to the familiar under pressure.

Chemical/pharmaceutical companies also face barriers in the form of biocatalyst cost and problems controlling the process. However, these barriers are not particular to this sector. Neither are some of the drivers: The benefits from mild process conditions, the ability to perform tasks which cannot be done by chemistry, and a generally cleaner process, making it easier to meet stricter regulatory standards.

Some drivers are specific to this sector. Notably the ability to make chiral forms: Some stereo-selective, chiral reactions are only possible with enzymes – there are no commercially viable, purely synthetic alternatives. Two trends will make this factor in the use of biocatalysts assume greater prominence. Firstly, the increasingly better understanding of which chiral forms of drugs and agrochemicals are biologically relevant. Secondly, increased selectivity and better processes can be designed and delivered by molecular biology and biochemical engineering.

# 3. Conclusions and Recommendations

This section sums up the results from the different industries studied in the previous chapters. The results are discussed and special attention is given to the feasibility of fulfilling the potentials. *Relevant policy options* are also outlined in connection with the discussion. Finally, a summarizing table of the relevant policy options for each sector is presented.

## *3.1. Concluding on Environmental Effects*

One of the main questions in this study is, what the environmental effects related to process substitution of chemicals for enzymes are, and whether they can be quantified and priced. To address the latter first, these obstacles often stand in the way of reaching certain conclusions regarding exactly how beneficial a new technology is. But this study has put considerable effort into making these estimations, which has entailed identifying both environmental baseline data and appropriate valuation figures.

**Table 26 - Overview of Environmental Effects, Archetype Approach**

| | | Chemical Savings | Reduction in Effluents | Energy savings | Water savings |
|---|---|---|---|---|---|
| **Pulp & Paper** | ***Chem. Pulping*** | Bleaching chemicals ($ClO_2$) | AOX (35 per cent) | | |
| | ***Mech. Pulping*** | No | No | 20 per cent in reject step, 2 per cent over all | |
| | ***Deinking*** | Hydrogen peroxide / Sodium hydroxide (EDTA) | Unknown (Heavy metals) | | |
| **Textile** | ***Desizing*** | Caustic (4 mill. t) | TSS | 25 per cent | 50 per cent |
| | ***Scouring*** | Caustic (24 mill. t) Peroxide 14 mill. t) | BOD (30 per cent) COD (40 per cent) | | Yes |
| | ***Bleach clean-up*** | Sulphite (10 mill. t) | Unknown | | Yes |
| **Leather** | ***Soaking*** | Tensides (34 mill. t) | Effect on BOD unknown | | |
| | ***Liming*** | Sodiumsulphide and Calciumhydroxide (14 mill. t) | COD (10 mill. kg) Sulphite (3.5 mill. kg) | Probably | |

So which environmental effects have been identified? The main difficulty in this respect has been to establish the link between chemical input and the resulting effluent levels, - especially quantifying the potential decrease of effluent relative to a decrease in chemical use. In some cases there may also be a change in waste water effluents related to an introduction of enzymes, which have to do with the way enzymes 'work' rather than the chemicals they replace.

Another aspect, which has complicated matters, is that not all the potential environmental gains are as straightforward as direct substitution of chemicals with enzymes. Other weighty environmental effects have been found, namely savings in water and energy consumption.

All these problems aside, it has been possible to assess quite a few potentials as table 29 illustrates. The numbers in parentheses in this table refer to the maximum reduction in the case of complete fulfilment of the identified market potential of enzymatic processing.

This overview shows that very significant potential reductions in both chemical input and environmentally harmful effluents have been found in this study. Not only is it possible to eliminate large amounts of chemicals, but very real savings can also be made with respect to scarce resources like energy and water. The introduction of biocatalysts is all in all a very powerful tool in an overall strategy of greening the European industry.

## 3.2. Concluding on Economic Factors

Different aspects of economic or financial considerations are among the most dominant topics related to assessing the feasibility of process-substitution towards enzymes. These range from strict cost-effectiveness considerations, via issues related to the risk involved in trial processes, problems with estimating future benefits, the need for investment in new production equipment, and to international market concerns. These issues are dealt with separately below.

**Production Cost**

The first and most important factor is the production cost. Clean technologies can be cost saving due to the reduced consumption of resources, reduced costs for safety, cleaning and remediation, etc. These are all factors that have a direct impact on the bottom line of a company. But if the enzymes themselves are significantly more expensive than the traditional chemical alternative, the indirect savings rarely equal the added expense.

In three cases the production costs are lower for the enzyme-aided process, than for the traditional chemical technique, and in one case the price of the enzyme equals the savings on chemicals (see table 27 a few pages ahead). However, in four of the archetypical processes assessed in this study, a change from a chemical to an enzymatic production process does not make economic sense, from the point of view of private companies. This is not surprising as such, but the actual quantification of the magnitude of the price discrepancy is new. An example from the leather industry is the result that the enzyme alternative - proteases -, is 25 per cent more expensive than the traditionally used liming chemicals.

So, more often than not, the numbers do not speak in favour of enzymes. But, in the cases where the use of enzymes makes good economic sense with regard to production costs, it is a matter of somehow informing the companies in the sector that there is money to be saved by converting to biocatalysts. Conversely, where the enzymes are a costlier choice, focus can be switched to the environmental costs, and how to internalise these into the private costs.

*Taxes and subsidies* are the straightforward policy option, when the problem at hand is changing an average cost of a product. Implementation of a tax does have a multitude of consequences, which must be assessed on beforehand. These effects range from deadweight loss, to shutting down or relocating polluting industry and thereby perhaps generating unemployment problems[38]. But, never the less, taxes internalise the environmental costs, and bring the costs into the calculation of the

[38] This is not a problem per se with respect to the environment, but all real policy options must be investigated for distributional effects.

overall productions costs and is therefore the right tool when dealing with this sort of divergence between private and social costs.

**Sunk Cost**

In many cases, the identification of an appropriate enzymatic solution requires considerable effort from a firm, and there might also be sizeable costs related to converting to a new production technology. As the study has shown, there is a range of enzymes which can simply be added to the existing vessels and vats in the production lines in exchange of chemicals, and in these cases the sunk costs does not include new machinery. There are however in all cases expenses related to training of staff, reduced efficiency in a transition period, etc.

Policy tools, which may help to overcome this barrier, can be some sort of *transformation benefit*, aimed at industries with high potential, but low market penetration due to lack of resources to be spent on sunk cost. An example from this study, of where this would be applicable, is the textile mills: They are under considerable pressure on the international market and thus have narrow profit margins and limited free assets, but need to install new machinery in order to convert to enzymatic-aided production. This type of problem can also be addressed through *technology transfers and maturing schemes*.

**Risk**

Risk has two facets in relation to introduction of process-integrated enzymes: Firstly, the risk involved in the initial trials of the process, where considerable raw material can be damaged. Secondly, there is risk related to estimating future marketing possibilities and the situation on the market as such. Concerning the second risk aspect, it is clear that improved quality and added functionality are major advantages of enzymatic production. This is of little benefit to the manufactures however, if the demand side will not pay for this added 'value' to the product.

The risk aspect is difficult to represent in numbers, but it is a barrier in all the considered sectors - with the notable exception of textile laundry, which very illustratively has one of the highest current market penetrations of enzymes. The fact that full-scale trials of enzyme-aided processes are needed for them to be widely accepted, conflicts with the risk involved for the firms. Especially the sectors dominated by SMEs feel this effect. This aspect gains even more weight when it is considered that reducing the risk seems to be able to outweigh an increase in production costs.

In a situation of increasing competitive pressure, a firm with free resources can gain from focussing on production tools, which give them an edge with respect to better quality or functionality of the end product. For the participants in this study, this seemed to be a predominate way of thinking about the future, but a lack of free resources or knowledge often stood in the way of starting the move towards the 'production tools of tomorrow'.

A policy programme of *public funding of full-scale production trials* does therefore look like an appropriate incentive schemes to make industry convert to use of biocatalysts. For such schemes to be successful, it is recommendable to focus on the industries dominated by SMEs, since larger companies are less averse to bearing risks. Such initiatives can at the same time address the problem of lack of knowledge of enzymatic possibilities in some SMEs.

**Industrial Organisation**
Another economic consideration for the firms is the international competition on the market. For the food industry, continued growth of the food-ingredient market in general has excelled the use of enzymes. Many of the bulk industries investigated in this report conversely feel the pressure from market forces pulling production to low-wage countries in Asia, Latin America and the former USSR republics.

The macroeconomic effect on employment, turnover and profitability in the sector will no doubt assert significant influence on the companies' desire for - and possibility of - adapting biotechnology. But the inclination to embrace new production processes is not automatically negative. As it follows from the above discussion of sunk costs, it depends a lot on the company's size and the average profit margin in the sector[39].

Looking at a sector as a whole, growing market shares for enzymatic processes might occur through new firms breaking into the market rather than old ones updating their production technology.

There are no specific policy tools identified in this study in relation to these factors, other than the usual macroeconomic kit.

## *3.3. Concluding on Institutional Factors*

**Environment**
This study has presented some images of possible benefits to the environment from the adaptation of biocatalysts in industrial processes. Among the results of this report, a potential of reducing the use of tensides with more than 34 million tonnes a year from tanneries in the European leather industry alone, was detected.

There are two main policy options to discuss in relation to the environmental factors: *green taxes or legislation on pollution levels*. They both work towards the same aim, namely making the companies *internalise the external costs*, which otherwise are born by society as a whole. Another relevant instrument is *(tradable) pollution permits*, which are already implemented within the pulp & paper industry. There are many arguments against or in favour these instruments, but here the focus will solely be on how they can benefit the introduction of more enzymes into industrial use.

**Table 27 - Overview of Economic, Environmental and Socio-economic Costs**

| | Pulp & Paper | | | Textile | | | Leather | |
|---|---|---|---|---|---|---|---|---|
| | Chem. pulping | Mech. pulping | Deinking | Desizing | Scouring | Bleach clean-up | Soaking | Liming |
| Economic costs | + | - | 0 | - | + | + | - | - |
| Environmental costs | + | + | (+) | + | + | + | +/- | + |
| Total socio-economic costs | + | Indeter-minate | Indeter-minate | Indeter-minate | + | + | Indeter-minate | + |

[39] The profit margins in Fine Chemicals, Pharmaceuticals and Textile laundries are considerably higher than in the Pulp & Paper and Textile mills.

Table 27 below gives an overview of the economic and environmental costs estimations made for all the selected sectors. It is remarkable that none of the total socio-economic costs of substitutions toward biotechnology are negative. The archetype examples were selected on the grounds of promise, but the actual calculations use quite low valuation of the environmental effects.

It is obvious from the previous chapters that the environmental legislation in Europe plays a mayor role in the feasibility of reducing the use of chemicals in industrial processes. New, stronger standards for affluent contents of pollutants force the companies to either invest in abatement technology or convert to technologies that generate less harmful effluent.

Another possibility for the companies in reaction to stronger environmental legislation is to convert to a production process, which creates less emission. This can be achieved in several different ways: closing material flows inside and outside of the company, better logistics, improved energy efficiency, redesigning production processes and products, better process control, use of fewer toxic chemicals and substituting raw materials and replacing old by new production processes. This has again lead many companies to develop tools such as indicators that help them to link design changes, environmental impact and cost. Although these initiatives have only been started recently, they contribute to include environmental factors to a set of other business factors.

A good example of this, is the pulp and paper industry's move away from the use of elemental chlorine due to public focus on the damaging effects. This is supported by the interviews in the textile sector, where environmental regulation and enforcement is seen by respondents in the interviews as the main external factor in aiding market penetration.

There is a row of environmental services, which have already been partly internalised in the prices, and the line between private and social costs is not always clean-cut. This goes for energy, water and some chemical inputs, which are the targets of various green taxes. Many of the prospective enzyme processes have the capability of reducing the use of especially water and energy, so an increase in the price on these input factors would make the enzyme technology significantly more attractive. Bearing in mind that some of the potential reduction of these two factors is as high as 50 per cent, even a small increase in price would be very notable.

In order to make new environmental legislation or taxes as effective as possible there is a need for *more research on the enzyme related environmental effects and reduced clean-up costs*. Also, *case studies determining which the environmental costs are currently born by the companies and which are not*, can help guide environmental policies.

It is often argued, that stricter environmental control and lower limit values is effective in making companies 'clean up their act'. However, it is a fact that regulations may in fact not reduce pollution problems, but merely displace them. In a global economy production can be moved overseas, if it is more cost-effective to produce a particular product in a country with more lax environmental laws, than to adopt a new less polluting production technique. This is a very relevant point in relation to many of the bulk industries in this study.

**Management**

The implementation of biocatalytic processes as 'cleaner technology' may require rearrangement of strategies inside and outside a company. Despite the fact that the changes are not necessarily complex, especially SMEs face difficulties in realizing biocatalyst technology concepts. While

many large companies are systematically integrating their processes, SMEs lag behind in this development in part due to ill-informed management.

This sort of inertia in the sectors can be counteracted through *information campaigns, practical demonstrations, conferences, workshop* etc. to generate awareness and motivation of high-level staff. In an area like biotechnology, there is an inclination to secrecy and exclusive patent rights, which to some extent stand in the way of knowledge sharing between companies in the same sector. Policy options that are very recommendable for overcoming this problem are *management networks* and *R&D networks between similar size (smaller) companies in different sectors*. Though a particular enzymatic process might not be relevant for the other members of the group, experiences and lessons learnt can be shared for mutual benefit. These experiences include important factors like training of staff, management of risk, implementation of green accounting etc.

The more operational and realistic the information is, the better, in the sense that SMEs need to have outlined not just the potentials of biocatalysts use, but also the costs and practical problems in order for them to asses the possible gains and risks.

**Demand**
Public awareness of - and demand for - ecological goods can be listed both as an institutional factor and an economic factor, and it is an interesting issue in this study.

Many of the bulk industries are very much demand driven industries, as opposed to R&D-driven, and if the consumers start demanding eco-friendly products from these industries, it might significantly alter the market penetration of industrial enzymes. Some interviewees pointed to the lack of demand for eco-friendly products within their sector as a barrier and others name it as a pulling force. In economic terms this relates to the price-elasticity on enzymatically produced products: Is the consumer (of both intermediate and end products) willing to pay the extra costs associated with the production of a greener product? If they are; it serves as a driving force, if not; like a barrier.

From this simple deduction it follows that a *time-limited subsidy* might help bridge this price gap until the green technology has increased the efficiency in production and the manufacturing costs drops sufficiently.

**Lack of Transparency**
In a more nuanced look at the 'lack-of-demand' problem, one must include the aspect of transparency - or in this case; low degree thereof. It is this problem that makes the question of demand for bio-produced goods an institutional one. It is a fact, that demand for similar products like organic food is seriously weakened, if the buyers are not certain that the label is trustworthy. There has simply been to many cases of plagiarised free-riding on the wave of political consumerism.

The debate surrounding GM foods and the effect this has had on the demand for food produce with the use of enzymes, should also be brought up. Enzymes produced by genetically engineered organisms raise concern among some consumers, even though there is a sharp differentiation between the close-circuit, process-integrated use of GM enzymes and actual use of GM enzymes as additive to food or animal feed. This crucial difference should be highlighted for consumers.

The respondents in this study pointed at *environmental accounting standards* or other forms of *environmental performance indicators*, as possible policy tools to overcome the lack of transparency of environmental effects in production. Good examples in this area are the successful 'ISO 14.001' and 'EMAS 2' *environmental management schemes*. It can even be suggested to enforce a *mandatory environmental certification* of companies, which would make it possible for the buyers to favour companies using biotechnology, as they would have a more attractive environmental profile.

## 3.4. Concluding on Technological Factors (R&D)

The subtitle on this chapter could be: What influence does public and private R&D have on the development towards increased use of process-integrated enzymes? This question has not been dealt with in depth in this study, as the archetype approach focuses on readily applicable biocatalysts, which have already been developed for industrial use. Manufacturing and runnability of the enzymes as well as industry support have however been shown to be lacking in some areas. Furthermore, the development of new enzymes remains crucial to the continued expansion of process-integrated enzyme use.

**Manufacturing Cost of Biocatalysts**

A large producer of enzymes has been quoted for saying that the total price of introduction of a new enzyme at industrial scale will be about the same, whether the quantity is 10 kg or 10 tonnes per annum: The total cost for the buyer is about $1 million per year, regardless. Since enzymes often have to be adapted to a specific use, they are rarely produced in large amount. The average price is therefore high, as the development costs have to be recovered. This study has identified a need for reducing these manufacturing costs of the enzymes to increase competitiveness on the market.

So, how can manufacturing and development costs be reduced? The specification, discovery, and modification of enzymes for industrial or pharmaceutical applications are time and resource consuming tasks, and there is a need for technologies that would further automate and quicken the search phase, screening tests, and modification procedures. It can be expected that methods will be developed to make *direct DNA screening of enzymes* more feasible. Similarly it can be expected that methods of *rational modification* will become more important for well-characterised enzyme-substrate pairs. At present new enzymes are searched for in nature by applying computerised methods based on databases, robotic systems, and miniaturised high-throughput screening methods. In the future, it may become feasible to design enzymes for special purposes by using *combinatorial and molecular modelling techniques*. Efforts are being made to develop and apply de novo design and synthesis of catalysts from organic molecules, such as macrocyclic compounds, polymers, cyclodextrins, and peptides.

The promise of high-throughput screening and combinatorial chemistry is strengthened by the emerging *microreactor technology*. The former two methods are useful in locating new enzymes and in improving their properties; microreactors can be used to test the viability of new enzymatic processes. In microreactors miniaturised mixers, catalytic reaction chambers, and separation devices are integrated for the performance of test runs that approximate what could happen in full-scale systems. Microreactors may have a particular relevance for companies that lack pilot plant resources.

**Runnability of Biocatalysts**
The main issues relating to runnability of enzymes is the need to reduce the risk for companies involved in transferring to biocatalytic processes. This study has clearly shown that this risk is a major barrier. Developing hardier and possibly faster working enzymes, whereby improving the predictability and sensitivity of the biocatalysts, could help overcome this obstacle.

Methods have to be developed to modify the properties of biocatalyst technologies so that they will meet future requirements of the industry. Many of the *natural enzymes have to be made more efficient and stable* in wider temperature ranges, at high pressures, or even in non-aqueous environments, such as organic solvents.

Methods used to modify existing (natural or man-made) biocatalysts include *standard chemistry, recombination techniques* (standard cloning, expression cloning, DNA shuffling), *rational design methods* (usually involving computerised methods and databases) and *directed evolution* (multiple cycles of mutation, selection, and amplification). With modification some enzymes can be made resistant to inhibitors that usually restrict their use. Finally, enzymes intended for the market have to be supplemented with bulking, coating, and preservative compounds.

Improving catalysts and catalysis processes promises several important payoffs downstream in manufacturing. New catalysts that are more precisely designed than present ones can maximise output of desired products while minimising by-products. New catalysts will enable engineers to produce the same products using less expensive feed stocks or even to replace feed stocks based on non-renewable and depletable resources, - such as oil - with renewable ones, such as grains or switch grass. Another payoff, predicted to grow in relative importance in the future, will come from catalysis technologies that reduce pollution by obviating the need for organic solvents, eliminating troublesome by-products that subsequently need to be disposed of.

**Industry Support**
Customers from all segments of the biocatalyst user community require services related to biocatalyst technologies. Yet there are wide differences between the frequency and quality of services required by bulk commodity producers, fine chemicals manufacturers and research laboratories. While industry may need support mainly in process design, research laboratories can require detailed information on even the most improbable aspects of the products they use. Industry is likely to seek advice from third parties for economical reasons, but in research settings users want to be reassured about the characteristics of the products in absolute detail, and it is the manufacturers of enzymes who are expected to supply all of the required information. Producers of fine chemicals have to be able to combine various areas of expertise and may be willing to use consultant services relatively frequently.

The difficulty experienced in this study, related to getting information on real production costs and environmental effects, clearly illustrate the need for more specific studies – and making the economic results available to the potential user companies. *Technology foresights* of this kind have two advantages: Firstly, estimations of actual potential in different industries and mapping of the barriers and drivers can form the basis for better policy intervention. Secondly, such studies may proactively promote research and development in socially desirable and serviceable directions.

**Development of New Biocatalysts**
At the bottom of every catalytic process are complex physical and chemical dramas playing out on tiny scales, often at arresting speeds and under surveillance-unfriendly conditions common in industrial processes. These factors have traditionally made scientific study and design of catalysis technologies extremely challenging, costly, or technically impossible. Yet it is precisely this sort of knowledge and investigation that harbours the greatest potential payoffs. Those who know more about catalysis and harness that knowledge into new and better catalysis technology will be the ones with the right stuff in tomorrow‘s commercial and environmental context.

A very small percentage of industry‘s research goes into high-risk catalysis work. The bulk of industrial catalysis research aims at incremental improvements in existing catalysis technologies. There is a need to *improve the balance between high- and low-risk research*. The goal is a generic strategy for more cost-effective and efficient R&D for arriving at good catalysis solutions to any particular industrial problem.

This is also where the significance of EU Research Funding comes into play: *A EU biocatalysis programme* could accelerate and leverage industry's investment in higher risk research, which harbours greater payoffs in the form of sustained competitiveness than the shorter term research that now predominates. Such a program may enable a notable growth in industry's high-risk catalysis research, an area that now receives very limited government support beyond the basic sciences, despite increased vulnerability to technology breakthroughs in other countries.

## 3.5. Recommendations

The previous sections in this chapter have looked at the relevant policy recommendations in different problem areas, and what remains is an overview of policy recommendations.

Table 28 summarises the policy recommendations and indicates whether they are relevant in the three main sectors assessed in this report and the subsidiary archetype processes which where identified. This overview gives a good indication of which policies are recommendable on a broad scale, and which are relevant in relation to specific sectors.

Policies involving a direct transfer of money - taxes, subsidies, transformation benefits, and time-limited subsidies - are not always applicable. As the overview shows, regular taxes/subsidies are recommended in the cases where an unfavourable price stands in the way of a wide application of an enzyme technology.

Green taxes, lower limit values or pollution permits is however suggested in nearly all cases in this study. The reason is that not all external environmental costs accruing to society as a whole are covered by the responsible companies at present. The assessment of social costs summarized in table 30 supports this fact, and it is not even a full account of all environmental effects, but limited to the ones it has been possible to identify in relation to the chemical substitution. More research on the enzyme related environmental effects and reduced clean-up costs is clearly needed. This is an essential policy recommendation, which can be neatly combined with technology foresights.

The lack of reliable environmental data reflects the low degree of transparency of production processes, which in turn make it hard for demanders of both finished and intermediate products to make the eco-friendly choice. It is important to support consumer power by enforcing green

accounting standards, environmental performance indicators, environmental management schemes, environmental certification etc.

Technology transfers and maturing schemes are a noteworthy way of approaching the issues of sunk cost and the risks associated with introduction of process-integrated biocatalysts. This goes hand in hand with information campaigns, practical demonstrations and R&D networks targeting management and other high-level staff in smaller companies, where limited awareness of / risk aversion towards new biotechnology has been identified as a considerable impediment.

Public funding of full-scale trials deserves special attention, since this step seemed to be a considerable obstacle in many of the investigated sectors. The risk associated with testing a new biocatalytic aided productions technique is a significant barrier for many companies, as the uncertain costs are a major deterrent.

A very clear point is that the problems in relation to technological factors are common to all sectors, and that the policy options concerning industry support, lower manufacturing cost, improved runnability and development of new enzymes therefore are very recommendable. Of these, technology foresight and lowering manufacturing costs are extremely important, as they both can assist in the crucial process of getting the enzymes from the lab test tubes into the industrial processes on a large scale.

# 4. References

CIRFS (International Rayon and Synthetic Fibres Committee):
Data, www.cirfs.org

European Commission: *Sixth Environment Action Programme,*
http://www.europa.eu.int/comm/environment/enveco/priority_study/index.htm

Euratex: Statistics CITH, www.euratex.org

European Biotech (1997): *A new Economy*, Ernst & Young 1997.

Etschmann/Gebhardt/Sell (2000), in: BioWorld 1/2000

FAO: *FAOStat Forestry Data*, www.fao.org

FFIF/CEPI: *Finnish Forest Industries Federation:* www.forestindustries.fi and *CEPI:*
www.cepi.org

Food Navigator: *Trends*, http://www.foodnavigator.com/

JRC/IPTS (1998): *Biocatalysis: State of the art in Europe* (eur 18680), 1998

JRC/IPTS (January 2000): *The Introduction of Process-integrated Biocatalysts in Companies – Effects of Dynamics in Internal and External Networks,*(eur 19582 EN), January 2000

JRC/IPTS (February, 2001): *Integrated Pollution Prevention and Control (IPPC) Reference Document on Best Available Techniques for the Textiles Industry*, Draft February 2001

JRC/IPTS (May, 2001): *Integrated Pollution Prevention and Control (IPPC) Reference Document on Best Available Techniques*
*for the Tanning of Hides and Skins*, May 2001

JRC/IPTS (July, 2000): *Integrated Pollution Prevention and Control (IPPC)*
*Reference Document on Best Available Techniques in the Pulp and Paper Industry*, July 2000

Liese, A, Seelbach, K and Wandrey, C. (2000). *Industrial Biotransformations* ,Wiley-VCH 2000

Novo Nordisk (1996): *Towards sustainable development with genetic engineering*, BioTimes 4 - 12/96, http://www.novo.dk/enzymes/biotimes9604/main.htm

Novozymes (2001): *2001 Annual Report*, 2001

OECD IEA statistics: http://www.iea.org/

OECD (1994): *Biotechnology for a Clean Environment: Prevention, Detection, Remediation,* OECD 1994.

OECD (1998): *Biotechnology for Clean Industrial Products and Processes*, draft 1998

OECD (2001): *The Application of Biotechnology to Industrial Sustainability*, 2001

Pere, Jaakko; Siika-aho, Matti; Viikari, Liisa (2000): *Biomechanical pulping with enzymes: Response of coarse mechanical pulp to enzymatic modification and secondary refining,* Tappi Journal . Vol. 83 (2000) No: 5

SNF Floeger: http://www.snf-floerger.com/press/pressrel.pdf

Taylor, S. (1998): *Singled out for success,* Chemistry in Britain, May 1998

UBA (1998): *Stand der Möglichkeiten von prozessintegrierten biotechnischen Präventivtechniken zur Vermeidung oder zur Verminderung von Umweltbelastungen*, 69/98, Umwelt Bundes Amt (UBA)

UBA (1996): *Stand und Perspektiven der Katalysatoren- und Enzymtechnik, Sachstandsbericht des Büros für Technikfolgenabschätzung beim Deutschen Bundestag,* Umwelt Bundes Amt 1996.

Viikari et al.(2002): *Ullmann's Encyclopedia of Industrial Chemistry Enzymes, 6.3.6. Enzymes in pulp and paper processing,* Wiley 2002