

A simulation program for training in integrated life cycle management

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The concept of integrated life cycle management forms part of the standard tool box of the modern environmentalist. The question for educators is how to make it operational for the student. This question was a major challenge in developing a computer-aided instruction program that simulates the environmental behaviour of life cycles of products. The program makes it possible to approach the (adverse) effects on the environment of the product life cycle in an integrated way and to investigate possibilities for reducing environmental pollution. The product chain is split into many steps. Each step represents a unit operation in the product life cycle. In each step the student can choose an environmental measure from a broad range of measures in order to influence the environmental effects. The effects on the environment are made visible in data matrices for auxiliary products, flow of materials, secondary products, chain losses and emissions. Changes in one or more steps are immediately passed on to effects in the entire product chain. This offers the student the opportunity to manipulate the behaviour of the life cycle system and, hopefully, to achieve a deeper understanding of the concept of integrated life cycle management.

Keywords: life cycle management; simulation program; training

Introduction

Integrated life cycle management involves the premise that local changes in or modifications to the product life cycle system be seen in terms of the adverse environmental effects of the product chain as a whole. However, the complex structure, unpredictable behaviour and strong mutual relationships of product chains are severe barriers to studying the environmental effects from an integrated management point of view.

Production systems have traditionally been considered in terms of specific production branches. Production units or companies are usually unified in branch associations, which form a dimension perpendicular to that of the successive processing units within product chains. This means that, in practice, the production companies involved are primarily concerned with the economic and environmental interests of their own processing unit and can hardly be expected to have an overview of the entire product life cycle. In the worst case, a local reduction of pollution in one step of the product chain will cause an increase in another step of the chain, whereby the net effect of environmental measures is negative.

This approach to environmental problems from a strongly traditional organizational and economic

perspective, together with the complexity of the concept itself, form severe restrictions or barriers to developing effective environmental policy. Education in environmental sciences, which pays attention to the role of integrated life cycle management, may help to solve this problem. Such education involves emphasis on the conceptual aspects of integrated life cycle management as well as on changing the student's attitude towards the subject. Both aspects play a dominant role in the course 'Cleaner production' at the Open University of The Netherlands¹ where a computer program has been developed to simulate the behaviour of product life cycles. The program offers the student the possibility to take environmental measures at various points in the product life cycle. The effects are instantly calculated and presented to the student in terms of emission data in the different environmental compartments.

This paper outlines the model of integrated life cycle management as used in the simulation program and describes the didactic design and the functional design of the computer program, as well as student activities. These descriptions are clarified with examples from the phosphate fertilizer product chain. A brief discussion of the educational framework in which the course 'Cleaner production' functions is given, and the article ends with an enumeration

of advantages and disadvantages of the simulation program.

Educational framework

The Open University of The Netherlands is an institution that provides study programmes in higher, distance education. The open character involves open admission and a great deal of freedom for students to compose their own study programme. The distance aspect implies that students study primarily at home, at their own pace and when they choose. Occasionally the students have to visit a study centre in order to carry out a task which requires viewing a video or using a computer-aided instruction (CAI) program.

The course 'Cleaner production' is a 100 hour graduate-level course and is part of the degree programme 'Environmental sciences' at the Department of Natural Sciences. The content builds upon more basic courses in environmental sciences and chemistry. However, if a student has a preliminary basic knowledge in the natural sciences the course can also be studied independently of other courses. The main goal of the course is to learn how to apply scientific knowledge by analysing, assessing and solving (possible) environmental problems in terms of integrated life cycle management.

The course consists of a textbook, a task booklet and a computer simulation program on integrated life cycle management. The textbook contains the core of the learning material and concentrates on the concepts of sustainable development, integrated life cycle management and clean(er) technology. The first block provides a general introduction to environmental and technological policy making; the second block deals mainly with the concept of technology and its interactions with society; the third and last block describes, in a systematic manner, the technologies in the field of environmental technology. The systematic division runs from intrinsic (prevention) to extrinsic (restoration) use of environmental technologies: preventive technology, recycling technology, purification technology, disposal technology and remedial technology. Because energy is involved in all technologies, a separate chapter is devoted to energy technology.

The task booklet is a didactic supplement of the textbook. Not only does the task booklet contain specific learning objectives and exercises with feedback, but it also prepares the student for the final examination of the course, which consists of the solution of problems related to two case studies. In one case study the student is expected to use the simulation program on integrated life cycle management as a tool. Finally, the task booklet contains a detailed description of the phosphate fertilizer and leather product chains and a manual on how to use the simulation program. The data for both product chains have been gathered by Tebodin Engineering², starting from the life cycle analysis model proposed by the

Centre of Environmental Sciences at the University of Leiden³.

A model for integrated life cycle management

A product chain describes a number of successive production steps or stages during the life cycle of a product. It starts with the production of raw materials and ends when the product is disposed of and its residues are returned to the environment. Product chains cannot usually be treated independently of each other. They can, for instance, be related because a secondary product of one product chain may be an input for another chain. Consequently, a product life cycle system should be interpreted as a trajectory within a complex network structure of interrelated production steps. Because of this interrelation, any small disturbance in one step in the network may influence the state of the network as a whole.

To model the product chain a certain degree of simplification is necessary. The computer program, for example, deals with an unbranched, linear chain where spatial and temporal aspects are neglected. Input and output relationships with other product chains are mentioned but are not passed on in the calculations. The calculations are based on the mass balance for each step in the chain: the input for one step in the chain is equal to the output of the preceding step (the flow of materials) and auxiliary products from other product chains (see *Figure 1*). In each production step, the product or its precursor is exported to the next production step. The remainder leaves the chain in the form of useful secondary products or chain losses to the environment.

To understand the model, the reader must understand the concepts used in the model.

Flow of material. Although the flow of phosphate in the case study of phosphate fertilizer is the most important, other materials also play a role. Therefore the flow of phosphate is extended with the additional categories fluoride, cadmium and other remaining compounds.

Raw material. This is the unprocessed (raw) material needed for the production process. Pollution related to the mining of the raw material is part of the product chain. In the product chain of phosphate fertilizer, for example, the phosphate ore forms a part of the so-called matrix that, besides phosphate, contains clay, pebbles and sand.

Auxiliary product. An auxiliary product comes from another chain. Extracting the phosphate from the phosphate ore in the form of phosphoric acid needs, for instance, sulfuric acid as an auxiliary product. One could argue that all environmental effects of producing this auxiliary product have to be added to the environmental load of the product chain. However, waste products from other chains may sometimes be used as auxiliary products in the main chain. Consequently, recycling of such waste materials would even improve the environmental behaviour of the

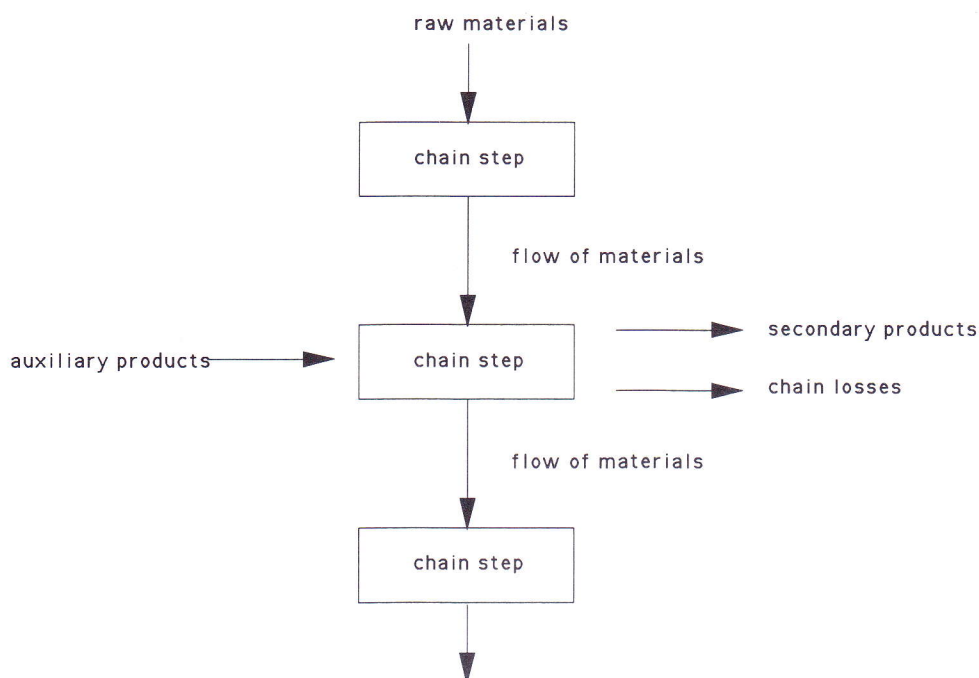


Figure 1 Model of the product chain based on the mass balance for each step in the chain

chain. Taking into account this kind of effect would result in a complex and untransparent model. Therefore, possible environmental effects ensuing from the production of the auxiliary product are neglected and students are asked to discuss the implications of this assumption in a qualitative way.

Secondary product. This is a product or partial product that leaves the product chain and can be used in other product chains. The environmental effects of secondary products that may exist in the long term are left aside. For example, sand and pebbles from the phosphate ore are useful auxiliary products that can be used in the building industry.

Chain loss. A material that leaves the product chain and cannot be used in a useful way, ends up in the environment. The environmental behaviour of the product chain is strongly determined by chain losses. The simulation program records the parts of the flow of materials to which the losses can be ascribed ('source'). Moreover, it can also be interesting to know in which environmental compartment the chain losses are found again ('destination'), namely the compartments air, water, soil and waste.

From an environmental point of view it is important to know not only the destination of the chain losses but also the chemical form of those emissions, since various chemical forms may have quite different effects on the environment. In addition, the nature of the emissions strongly determines the choice of appropriate environmental measures. Consequently, each compartment is split up into a number of emission groups in which the nature of the chain losses is further specified (see Table 1). In the case of the phosphate fertilizer chain, for example, the phosphate ore is polluted with cadmium. The cadmium divides itself, during the

production of phosphoric acid, between the phosphoric acid and the gypsum produced. If the gypsum is discharged into surface water, the water will be polluted. The cadmium emission is then accounted for in the emission group 'metal compounds' of the compartment 'water'.

Energy. Energy consumption has a special place in the model. Not only does energy consumption give direct and quantitative chain losses in terms of combustion emission, but the energy concept itself is also of more fundamental meaning when assessing the product chain: being aware that supplies of raw materials are limited is even more important for energy than for other raw materials. The amount of energy consumed and the related combustion emissions are important factors in assessing a product chain.

Environmental measure. A number of environmental measures are available for each step in the product chain. The broader term of 'environmental measures' is used instead of 'environmental techniques' because the environmental behaviour of the product chain may be changed without applying specific techniques, but with measures such as the introduction of an environmental protection system or the import of phosphate ore from one place instead of another, where less fuel may be necessary for transportation. The environmental techniques included in the environmental measures consist of techniques integrated in the process as well as end-of-pipe techniques. Enacting an environmental measure will affect the mass balance of that step in the product chain. Some chain losses will be reduced while others will be increased. The flow of materials and the amounts of auxiliary products will change too. The consequences for the entire product chain can be calculated because of the model-based linkage of the

Table 1 Emission groups in the compartments air, water, soil and waste

Air	Water	Soil	Waste
sulfur dioxide nitrogen oxides carbon monoxide hydrocarbons carbon dioxide particles fluoride compounds ammonia	phosphoric compounds fluoride compounds nitrous compounds sulfuric compounds metallic compounds chemical oxygen demand compounds diverse (remaining) compounds	phosphoric compounds fluoride compounds metallic compounds diverse (remaining) compounds	non-chemical waste chemical waste

subsequent steps in the product chain through the flow of materials.

Optimizing the product chain in an environmental sense demands the balancing of many possible environmental measures from the perspective of integrated life cycle management. Economic, social and practical aspects must also be weighed. This weighing is complicated since these aspects are often qualitative in nature and of a different character, and consequently are strongly judged by individual preferences. This complication makes the necessity of sufficient insight into the quantitative functioning of the product chain no less urgent. It is still important, therefore, to create a good overview of the adverse environmental aspects of the product chain as a whole in a quantitative way. If we are to reduce, for example, cadmium losses during the production of phosphoric acid, a variety of environmental measures are available: switching to another production process for the production of phosphoric acid (process integrated technique), separating the cadmium from the gypsum through an ion-exchange column, liquid extraction or sulfide precipitation (end-of-pipe techniques). However, new problems may arise, such as the generation of chemical waste that has to be dumped. *Figure 2* shows an outline of the product chain of phosphate fertilizer with the different steps in the product chain, the secondary products and the chain losses.

Didactic design

The main objective of the computer program is to provide students with a tool that supports the operation and manipulation of the concept 'integrated life cycle management' introduced in the textbook. The primary goal of this tool is to assist the student in gaining insight into the way the application of some specific environmental measure in one local step of the product chain influences the behaviour of the life cycle system as a whole. An important point of departure for the didactic design of the simulation program is the fact that intuitive or heuristic solutions on a local level can sometimes reduce the overall performance of the production chain in unexpected ways. If students are presumed to play an active role in the learning process, they have to be provided with opportunities to develop and explore intuitive initiatives in a way which provides

immediate confrontation with the consequences of their actions. This implies that the computer program must have an open structure with a great deal of student control, along with a feedback mechanism that instantly shows the calculated effects of the measures applied.

This didactic approach is strongly based on theories of problem-based learning⁴. The problem-based approach assumes that learning is an active and constructive process that is facilitated by supplying students with a proper learning environment, i.e. an adequate problem or case study. This problem-based approach is seen as being highly motivating in that it reflects a natural way of learning. Theory and practice are directly linked, and students themselves have responsibility for attaining the learning objectives. In addition, higher level academic skills, such as critical thinking, creative thinking, evaluating the chosen approach, developing a flexible attitude and making effective use of available or prior knowledge, form part of this approach. A necessary condition for the students to successfully tackle the problems posed is the availability of a sufficient body of knowledge to carry out the study task. For this purpose simple exercises can be found in the task booklet. After working with the simulation program the students are asked to make a small report (four pages) to present their conclusions.

Functional performance of the computer program⁵

With the help of exercises, the student learns to identify the vulnerable parts of the product chain, to select appropriate environmental measures, to interpret the effects of these measures, and to make explicit and balance the qualitative and quantitative aspects, such as environmental aspects, costs, feasibility and social aspects, when optimizing the product chain. To these ends, the program fulfils two main instructional functions:

- (1) *Presentation of data from the product chain.* The flow of materials, the use of auxiliary products, secondary products, consumption of energy and chain losses are given for the entire product chain. The chain losses are specified with respect to source

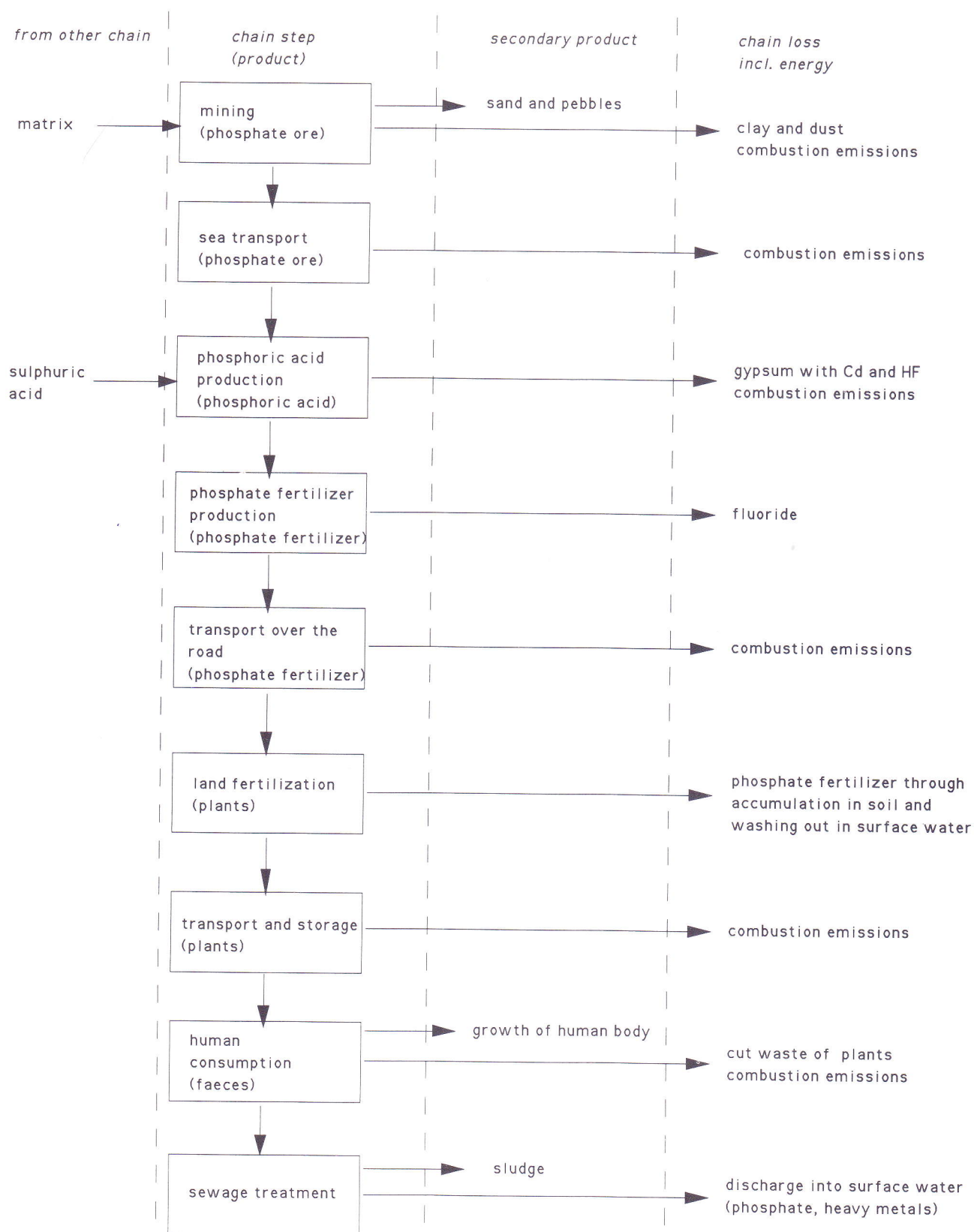


Figure 2 Model of the product chain of phosphate fertilizer

(flow of materials), destination (environmental compartment) and nature of the emissions (emission groups). All data within the model are standardized per unit end product (e.g. 1 kg

phosphate fertilizer). This standard is arbitrary, but of substantial importance for interpretation.
 (2) *Calculation of effects of environmental measures.* A number of competitive environmental measures

Case Help Qu End

Integrated life cycle management

a

☐ auxiliary products

☐ flow of materials

☐ chain losses

☒ emissions

☐ secondary products

origin

☐ phosphate ☒ energy

☐ fluoride ☐ everything

☐ cadmium

☐ other

destination

☒ air ☐ everywhere

☐ water

☐ soil

☐ waste

emissions into the air due to energy consumption

	S02	NOx	CO	CCmp	CO2	Part.	FCmp
1	5.16E-7	7.50E-6	2.97E-5	2.29E-5	4.22E-4	1.22E-6	0.0
2	3.19E-5	1.83E-6	1.10E-5	3.39E-9	1.51E-3	1.10E-6	0.0
3	5.81E-6	1.08E-5	0.0	0.0	4.25E-3	6.01E-7	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	5.57E-6	8.09E-5	3.21E-4	2.47E-8	4.55E-3	1.31E-5	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	1.56E-7	2.26E-6	8.95E-6	6.9E-10	1.27E-4	3.66E-7	0.0
8	0.0	3.12E-9	0.0	0.0	1.25E-6	0.0	0.0
9	2.7E-10	0.0	0.0	0.0	2.92E-8	0.0	0.0

☒ without measures

☐ measures included

☐ ratio included/without

Figure 3 Screen lay-out showing examples of (a) emissions to the compartment 'air' due to energy consumption (per kg fertilizer), and (b) available environmental measures for the sixth step in the production chain: land fertilization

Case Help Ou End

Integrated life cycle management

b

☐ auxiliary products

☐ flow of materials

☐ chain losses

☐ emissions

☐ secondary products

Land fertilizing

closed-system culture

crop improvement

+ substitution by animal manure

substitution by compost

substitution by sludge from a sewage treatment plant

☐ add

☐ remove

☐ overview

closed-system culture

Water recirculation systems are particularly used in greenhouse cultivation. Heavy metals are extracted from the return flow of water by carbon and sand filters. The purified water can be reused for irrigation. As a result of this measure, less phosphate fertilizer is needed because of the re-use of phosphates in the return flow of water. The contaminated filters, however, have to be treated as chemical waste. The extra costs of this measure are negligible.









	1	2	3	4	5	6	7	8	9
       	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	2.7E-10	0.0	0.0	0.0	0.0	2.92E-8	0.0	0.0	0.0

Figure 3 Continued

are available for each step in the product chain. The description of the environmental measures contains both a brief technical description as well as certain qualitative considerations. Environmental measures can be selected and applied into the product chain according to the student's needs. The program then automatically recalculates the entire product chain. Moreover, it is possible to apply more than one measure at a time.

The program runs on a DOS-PC (386) under Windows and with a mouse. (The program has been developed with an object oriented method in Toolbook under Windows; the calculation core has been written in Pascal. The program works on a DOS-PC under Windows-3.1 with a 80386 processor and with a minimum of 4 MB internal memory⁶.) On the left-hand side of the screen the successive steps of the product chain (nine in the two case studies) are shown and indicated with icons (see *Figure 3*). Beside the icons there is a window for showing the data requested. The student can select the data to be represented by clicking the appropriate buttons (auxiliary products, secondary products, flow of materials, energy, chain losses with origin and destination, or emission groups with origin and destination).

As an extra facility, the computer program enables comparison of the adapted product chain with the original one and allows all measures applied by the student to be reviewed. Finally, the program has an extended 'help' facility for supporting the operation of the simulation program and information about environmental measures, environmental concepts and production steps. The 'help' function corresponds to the standard Windows 'help'. Hypertext linkages offer fast access to the appropriate information. Help regarding the objects on the screen can also be activated directly by clicking the right-hand button of the mouse while the cursor is positioned on the object.

The program is technically divided into two parts: a processing unit which performs the calculations, and a set of datafiles which contain case-specific information. In this way, editing of data is easily performed and extension with other case studies is also possible. However, the number of chain steps is limited to nine as a consequence of the screen layout. So far, the program has not been equipped with a data-entry or editing utility.

Student activities

The student carries out a number of exercises with the computer program in two sessions of 2 hours each. To prepare for these exercises, the student must first read a chapter in the task booklet about the applied model for integrated life cycle management and the two case studies. In the first session the student learns how to retrieve and interpret data. The complexity of the exercises gradually increases. In order to teach the student a more or less systematic approach to the problem, the first case study is divided into a number

of sub-problems. The task booklet gives detailed feedback to these sub-problems. After the first session, it is expected that students are able to solve a similar problem for the other case study in the second session. Students have to report their findings, arguments and conclusions for this problem in a report not exceeding four pages. The grade given to the report is based upon the quality of the argument and the qualitative and quantitative reasoning.

Students seem to arrive at very diverse results. Most of them succeed in selecting adequate measures to improve the product chain behaviour, including appropriate reasoning and supporting data. Some of them even present various scenarios and discuss them in a comparative way. However, in some cases, a single alternative is proposed consisting of a large number of measures without discussing the priorities of the measures. Furthermore, we have found that students rarely suggest measures that presume severe changes in social and cultural attitudes and behaviour (for example recollecting waste leather products to avoid emissions of chromium). After two simulation sessions a substantial proportion of the students still appear not to adopt the integral life cycle management perspective. In these cases, a major advantage of working with this program seems to be that it makes explicit the students' deficiencies in manipulating and analysing concepts and data on product chains.

Conclusions

Two important aims of the course 'Cleaner production' are the development of a positive attitude with regard to the product life cycle concept and the acquisition of analysis and application skills in this area. These aims are difficult to attain solely through written material. The computer program 'Integrated life cycle management' offers the student a concrete instrument to manipulate within a product chain. The student will have to make choices and weigh them repeatedly based on estimations, expectations and outcomes of their effects. Finally, they have to present and defend possible solutions in a report. Carrying out the exercises associated with the simulation program will give students a deeper understanding of the concept of integrated life cycle management. In fact this has already been found to be the case with the first group of students.

The advantages of the computer program are:

- Provision of an adequate and concrete representation of a product chain. The open structure linked to the online help facility of the program gives the students the opportunity to individually determine the route through the program. There is not one fixed, preprogrammed route.
- The instantaneous availability of the (re)calculated results when environmental measures are applied.
- The flexibility reached by having all data of the case studies, including those of the environmental

measures, stored in separate databases, which facilitates maintenance and adaptation.

Disadvantages are:

- The program is based on a model of unbranched, linear product chains, while reality is often more complex. The program has been designed to serve as a simple and pragmatic educational tool. It presents behavioural changes of the product chain even though it sometimes uses incomplete or imprecise data. Discussion on accuracy of the outcomes would be interesting but is avoided as it would interfere with the main educational aims. The written course material heavily emphasizes this point.
- Although the case studies have been strongly simplified, the program generates a great deal of data. These data are desirable and necessary when regarding content, but may, however, hamper learning.
- The available data for the case studies may show some inaccuracies. In some cases accumulation of uncertainties may lead to strange results. Moreover, there is often no information available on the accuracy of the data used; these points should be used in the criteria for the argument in the report.
- The effects on the environment are expressed within the model in quantitative data. Uneconomic use of materials, environmental degradation (such as mining raw materials) and disturbances of the environment (such as noise nuisance) are, at best, qualitative and lack supporting data.
- All data are standardized per kilogram phosphate fertilizer (or per kilogram leather). Therefore no effects are presented when measures are taken that aim at the reduction of the absolute use.
- Students are asked to weigh very different considerations against each other, such as environmental effects in water against air pollution or negative

effects on soil, just as they are asked to weigh environmental effects against economic and social aspects. This is a difficult, maybe even impossible, task. From the point of view of the course it is important that students use their results for plausible, well reasoned and explicit argument of the measures taken. The question of what weights have to be attributed to what factors is not explicitly presented and can, more or less, be determined by personal insight. Students will have to estimate the validity of the outcomes themselves.

The concept of integrated life cycle management is very complex. The computer program endeavours to make the concept clearer to the students, who will certainly need to use this concept in their professional lives. A simulation model for integrated life cycle management, in which different environmental measures can be applied and weighed, is a useful and necessary educational tool. It is expected that the opinions and thoughts of students with regard to integrated life cycle management will be positively influenced.

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