Chapter 12
Closing Water Cycles in Industry: Theory and Implementation

Jurgis K. Staniškis

Abstract Sustainable development calls for processes with a closed loop philosophy and recycling becomes thus a normal, rather than exceptional solution. Water reuse and recycling in industry is one of the most important ways enabling absolute and relative decoupling of environmental impact from economic growth. There are more and more corporations focusing development efforts on Cleaner Production (CP) and Pinch analysis methods, i.e. systematic approach to using resource more efficiently, and avoiding the use of hazardous substances where substitutes are available.

Paper deals with water saving, reuse and recycling in industrial companies by preventive strategies, which are achieved by applying know-how, by improving technology and/or by changing attitudes. Preventive strategies included the following prevention methods: good housekeeping, input substitution, better process control, equipment modification, technology change, product modification and on-site recovery/reuse. The key idea is to remove the reasons of problems rather than their symptoms.

Keywords Water saving • Water reuse and recycle in industry • Preventive strategies • Cleaner production • Water pinch study

12.1 Introduction

Natural resources include both the raw materials necessary for most human activities and the different environmental media, such as air, water and soil, which sustain life on our planet. Therefore, careful management of the use of these resources is a basis

J.K. Staniškis (✉)
Institute of Environmental Engineering, Kaunas University of Technology, Kaunas, Lithuania
e-mail: Jurgis.Staniskis@ktu.lt

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for sustainable development. In contrast with raw material, it is their declining quality that causes concern. It is not question of how much there is, but what state they are in.

Resource efficiency or resource productivity can be defined as the efficiency with which we use energy and materials throughout the economy, i.e. the value added per unit of resource input. An example of resource productivity calculation on a national level is total material (water) use divided by the total economic activity by the country, expressed in GDP.

There are many difficulties facing those who have interests both in the natural environment and in the man-made environment together with the problems of their interfacing. The industrial system is the collection of physical, chemical, and technological processes developed by man for the restructuring of materials. The biosystem involves the collection of natural ecosystems in the landscape. There are two main types of interaction between physico-ecological and socio-economical systems. Firstly, there is environmental intervention in which socio-economic systems operate apart from physico-ecological systems to cause them to react in the pre-determined and in advantageous manner. Such intervention systems involve a considerable amount of monitoring and tend to take a rather analytical view of environmental systems. Three main types of intervention could be considered [1]:

1. prediction of outputs,
2. manipulation of storages and
3. control of inputs.

Prediction of outputs may be viewed in a purely passive sense where expected outputs are predicted by the use of forecasting techniques. The classical example of this type of intervention is the model for the Nemunas River which is one dimensional quasi-dynamic, based on the differential equations of the first order with the possibility to analyze conservative materials transport and to predict transport and transformation of non-conservative materials, for instance dissolved oxygen, organics, nutrients [13].

Manipulation of storages is very important method of environmental system interfacing which involves the manipulation of physico-ecological storages by the socio-economic system. Using this method, water quality problem at the hot spot could be solved instead of controlling inputs by spatial distribution of pollution along rivers and estuaries. This creates the ability of the natural processes of stream channels to renew and dissipate pollution. As usual, regional treatment plants are fixed in their location as a result of political and engineering considerations. Using second method of intervention, the problem instead could be solved by means of non-linear programming.

The potentially most important approach is the *control of inputs*. This is very difficult to achieve except over small scales of space and time and requires a considerable input of energy and sophistication of time space application to make such control effective. The simple and very practical case of this type of intervention was designed as a decision support system for the waste management [2].

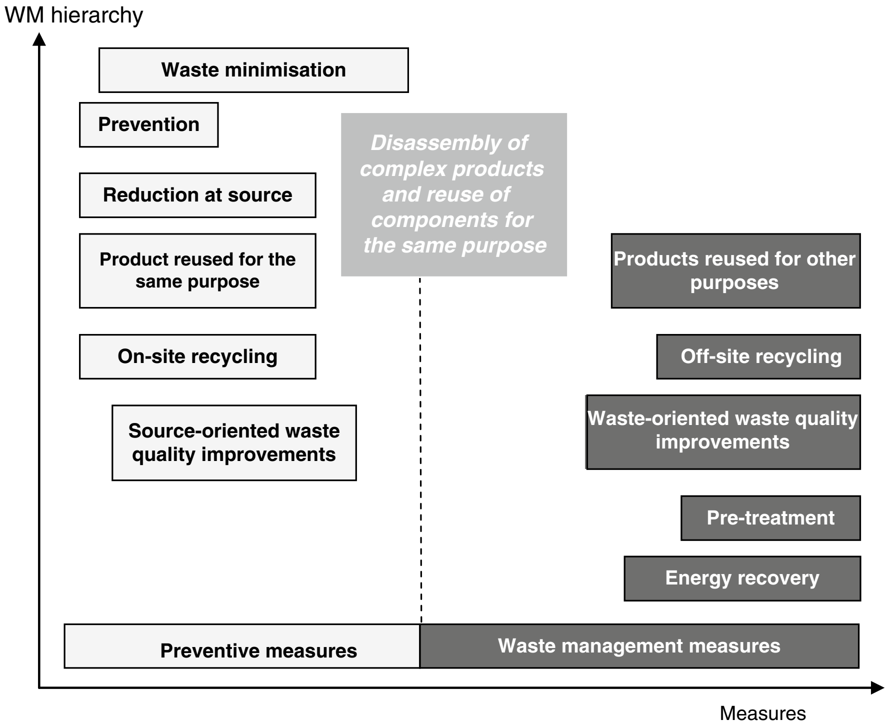

Fig. 12.1 Simple presentation of waste minimization (WM) concept defined by European topic centre on waste

However, it has been widely recognized and practically proved that waste prevention is the most important tool for resource efficiency and for sustainable waste management. The acceptance that waste is there, it always will be and we have just to deal with, it will not lead to waste prevention. To be able to prevent, we need to know the reasons of waste generation. Only after understanding the causes of waste generation we can prevent it. The definition for waste minimization was declared at the task meeting of the European Topic Centre on Waste in 1999 (see Fig. 12.1). Waste preventive measures include [4]:

- reduction of waste by application of more efficient production technologies,
- internal recycling of production waste,
- substitution of hazardous substances,
- more efficient process optimization and control, and
- re-use of products, or parts of products, for the same purpose.

The measures require a proactive attitude and the producer has to implement waste management decisions long before the holder is to dispose an item.

It should be stressed that environmental performance improvement measured through the adoption of waste minimization innovations is regarded as an indicator of business health. Good waste management reflects good management in general. There is also good indicator for financial institution to avoid companies that may face the costs associated with environmental liability [16].

12.2 Waste Prevention and Management: Theory

It has been assumed up to this point that the structure of the system of interest is known together with its inputs and outputs. In most practical environmental instances, however, one or more of the three system elements (input, output, and transformation) may be unknown, or only partially known. The structural properties of a system input, output and transformation, which determine whether all elements of system response can be observed, are usually termed observability and controllability criteria.

Controllability implies the ability of control input to affect any state of the system and observability implies the ability of each state to influence the system output. Figure 12.2 presents four possible system configurations, where system S_1 is controllable and observable, S_2 – controllable but unobservable, S_3 – uncontrollable but observable, and S_4 – uncontrollable and unobservable [1, 5].

The model is an accurate representation of the environmental system if, and only if, the system is controllable and observable. It means:

- A system is to be said to be state controllable if any initial state Y_0 can be transformed to any final state Y_{tf} in a finite time $t_f \geq 0$ for some input X_t.
- A system is set to be observable if every state Y_0 can be exactly determined from measurements on the output Y_t over a finite interval of time $0 \leq t \leq t_f$.

The overall type of control system required in any environment, is dependent not only on the control instruments available, but also upon the nature of the

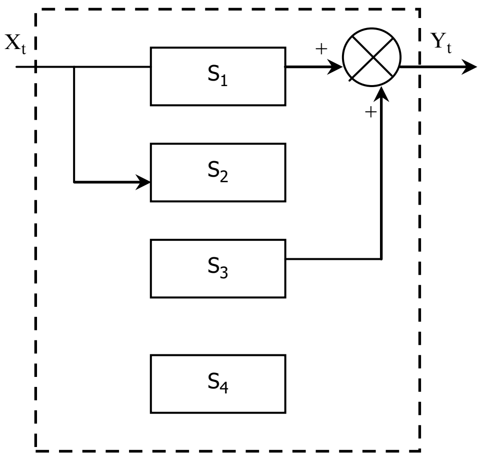

Fig. 12.2 A simple flowchart representing the four possible system configurations

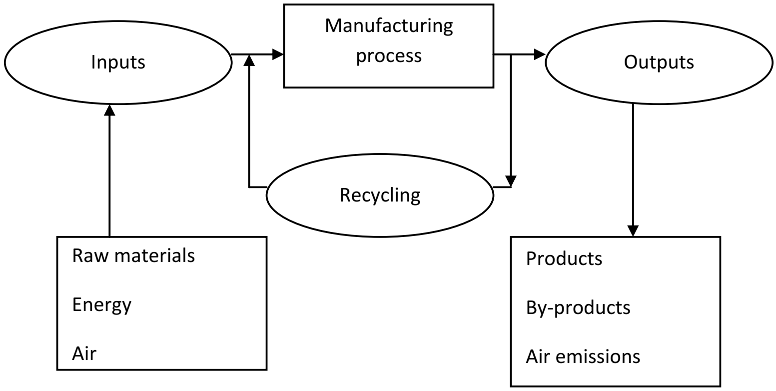

Fig. 12.3 Block flow diagram of typical industrial process

disturbances entering the system. The most common environmental control systems structures are [6]:

- open-loop control systems,
- active closed-loop feedback control systems,
- feedforward control systems, and
- feedback-feedforward control systems.

In practical systems control, it is usually necessary to build up a complex set of feedback, feedforward adaptive and environment control systems capable of representing the whole range of system disturbances and changes, which may occur. This requires the development of hierarchical and nested control systems.

The industrial waste (gas, liquid and solid) is generated in many different processes. The amount and toxicity of waste releases vary with specific industrial processes. Figure 12.3 shows typical industrial processes that produce waste containing different types of pollutants, depending on the input materials and process designs. Thus, process information is critical to make accurate and reliable assessment of the potential for different environmental strategy.

Environmental management has, until recently, developed under the assumption that environmental effects of anthropogenic activities should be addressed by carrying on the "normal" ways of production and adding on control technologies later as needed. This principle has led to attempts to protect the environment by isolation of contaminants from the environment or the use of end-of-pipe technologies. Although these kinds of solutions have undoubtedly led to short term improvements in local pollution problems, there are some significant problems associated with this approach:

- end-of-pipe approach is in one medium risks transferring pollution from that medium to another, where it may either cause equally series environmental problems or even end up as an indirect source of pollution to the same medium,
- end-of-pipe at the abatement contributes significantly to the cost of production processes and products,

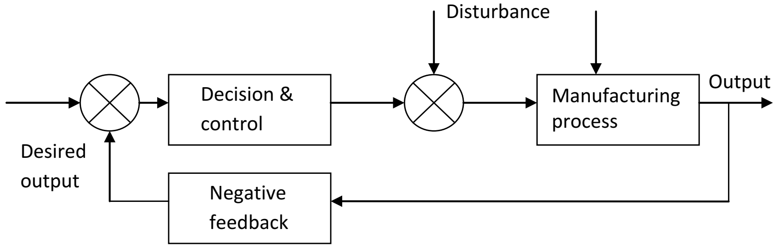

Fig. 12.4 Block diagram representing the structure of environmental control paradigm

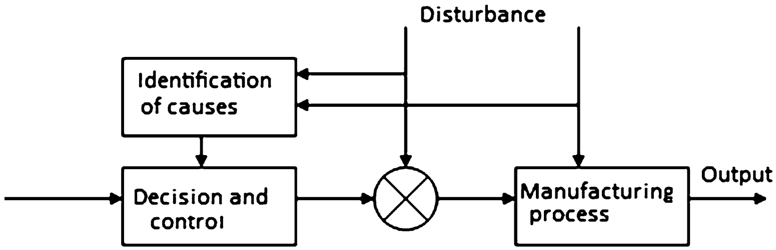

Fig. 12.5 Block diagram representing the structure of preventive paradigm

- end-of-pipe abatement of pollution requires regulation through control legislation which is often costly and cumbersome, leading to potentially inefficient regulatory structures and problems of non-compliance,
- end-of-pipe abatement technology represents a significant technological market with an associated economic inertia which encourages the continued generation of waste and works against any attempt to reduce pollution at the source.

From the systems' theory point of view, this approach is reactive and could be presented as a closed loop feedback control system (Fig. 12.4). Taking corrective measures at the input, when deviations from the standard are recorded in measuring the output is called feedback control.

The structure of environmental control approach shows that this strategy is reactive which refers to actions taken "after the fact" in response to effects. Reactive actions focus on negative impacts and risk reduction through acting on a waste or pollutant, and thus there is an opportunity in space and time to act on what is already a waste or pollutant [6].

The precautionary principle, which is clearly related closely to the concept of prevention, calls for reduction in anthropogenic emissions of potentially hazardous substances in two environmental medium. Preventive actions focus on identification and reduction or elimination of use of materials that could cause harm or damage to the environment. That is, preventive actions are anticipatory by definition, and act not on waste but on conditions and circumstances that have the potential to generate waste. Anticipation and prevention of waste generation is an example of feedforward control in the system development (Fig. 12.5).

The most interesting level, and also the most important in relation to the preventive paradigm, is the internationalization of environmental stewardship thinking and action. The main elements are the following:

- the recognition of the good quality of environment as an integral factor of sustainable industrial activities;
- the recognition of good environmental management as an important factor for the continuity of a company;
- the integration of environmental compatibility within the quality concept of products.

The extensive research and experience from the implementation of cleaner production (CP) proposals in Lithuania and other countries have confirmed the possibility to decrease waste generation by 30% without any investments or with very low cost investments. The further decrease of wastes up to 70% could be achieved by economically viable CP proposals with medium size investments [8, 9].

Currently, company's attitude towards the environment could be characterized by three different levels:

- compliance with regulations,
- anticipation of increasingly stringent regulations, and
- internationalization of environmental stewardship thinking.

The compliance with regulations in most cases is reactive, because measures are taken on an ad-hoc basis after regulations have been developed by the authorities, which is usually done after environmental damages have occurred. The anticipation of increasingly stringent regulations attitude goes further in the pollution control efforts than those strictly required by law. Such approach becomes a corporate strategy since corporate leadership perceives that such activities are positive for their relationship with the authorities and for the environment. The level were preventive paradigm could play extremely important role is internationalization of environmental stewardship thinking.

Therefore, the most effective environmental management should combine both preventive and end-of-pipe strategies (see Fig. 12.6).

Reactive actions focus on explicit use of technology that is manifested as equipment. But preventive actions can be implemented completely through the application of knowledge and changed behavior, or technology that has no apparent linkage to an environmental objective. Prevention means, doing something differently so, that waste is reduced and eliminated.

At the same time, the profitability of pollution prevention measures is clearly critical to the successful implementation. Unless profitability is demonstrable at the level of investment and industrial management decisions, companies will have little incentive to pursue the preventive path. Our broad experience have showed that total cost assessment (TCA) offers an alternative to conventional project analysis approaches by enlarging the inventory of costs and benefits, allocating such costs and benefits more closely to specific processes and products, using multiple profitability indicators to capture indirect, less tangible and longer term pay-offs. Therefore, TCA

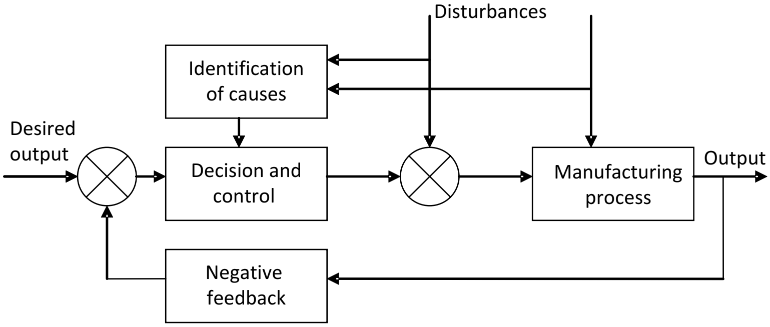

Fig. 12.6 Block diagram representing the structure of closed-loop feedback- feedforward control

is an approach for refining project financial analysis such that prevention investments are treated on the same level in relation to other competing investments [11].

In the early approaches to cleaner production, attention has tended to focus on waste generated during the production processes, and on the need for recycling of raw materials to reduce the environmental burden of product disposal. Developments of the earlier concepts have emphasized the need for attention to be paid both to the general use of materials and to the importance of the design and of the life cycle concept in minimizing subsequent environmental impact.

The life of any product can be divided into five more or less distinct phases as follows:

- conception, design and testing,
- production involving the extraction and transformation of natural resources,
- distribution including packaging, transformation, and marketing,
- the utilization period during which the product provides some useful service, and
- post-utilization period, which involves either the recycling or the treatment and disposal.

The concepts and practices of waste prevention and clean production need to be applied at every stage of the product life-cycle in order to minimize environmental input.

By integrating product life-cycle planning into all product and production considerations, companies could drastically reduce their environmental impacts and increase their efficiency / profits simultaneously [10, 14].

12.3 Implementation

There are two main practical preventive methods for the closing waste and water cycles in industry:

1. Cleaner Production [14],
2. Pinch analysis [17].

The concept of CP was introduced by UNEP in 1989 as a response to the question of how industry could work towards sustainable development.

CP means a continuous application of an integrated preventive environmental strategy to processes, products and services to increase overall efficiency. This leads to improved environmental performance, cost savings, and the reduction of risks to humans and the environment.

- *In production processes*, CP includes conserving raw materials and energy, eliminating toxic raw materials, and reducing the quantity and toxicity of all emissions and waste before they leave the process.
- *In products*, CP focuses on reducing impacts along the entire life cycle of the product – from raw material extraction to the final disposal of the product.
- *In services*, using a preventive approach CP involves design issues, housekeeping improvement, and a better selection of material inputs (in the form of products).

Other concepts such as eco-efficiency, waste minimization and pollution prevention share a common emphasis on pollution/waste elimination/reduction at the source where it is generated. However, CP strategy includes a well-developed procedure for systematic assessment of pollution/waste generation causes and development of practical options aimed at the solution of concrete problems. Additionally, CP strategy includes a clearly defined CP management system, which ensures continuous improvement of environmental and economic performance [7].

CP should not be considered only as an environmental strategy, because it also relates to economic considerations. In this context, waste is considered as a "product" with negative economic value. Each action to reduce consumption of raw materials and energy, and prevent or reduce generation of waste increases productivity and brings financial benefits to the enterprise.

A preventive approach means that environmental problems are addressed before they arise when choices are made concerning processes, raw materials, design, transportation, services, etc. Such approach effectively addresses the wasting of natural resources since pollution not only leads to environmental degradation but it is also a sign of inefficient production processes or management. In practice, CP means the following:

- avoiding or reducing the amount of the waste produced,
- using energy and resources more efficiently,
- producing environmentally sounder products and services, and
- generating less waste, reducing costs and increasing profits.

Cleaner production is achieved by applying know-how, by improving technology, and/or by changing attitudes. CP strategy includes the following prevention practices: good housekeeping, input substitution, better process control, equipment modification, technology change, product modification, energy efficiency/reuse.

The method of Cleaner production assessment was developed by the Institute of environmental engineering (APINI) together with World Cleaner Production Society (WCPS, Norway). CP assessment procedure is a closed loop system, consisting of: preparation phase, preliminary assessment, planning and organization,

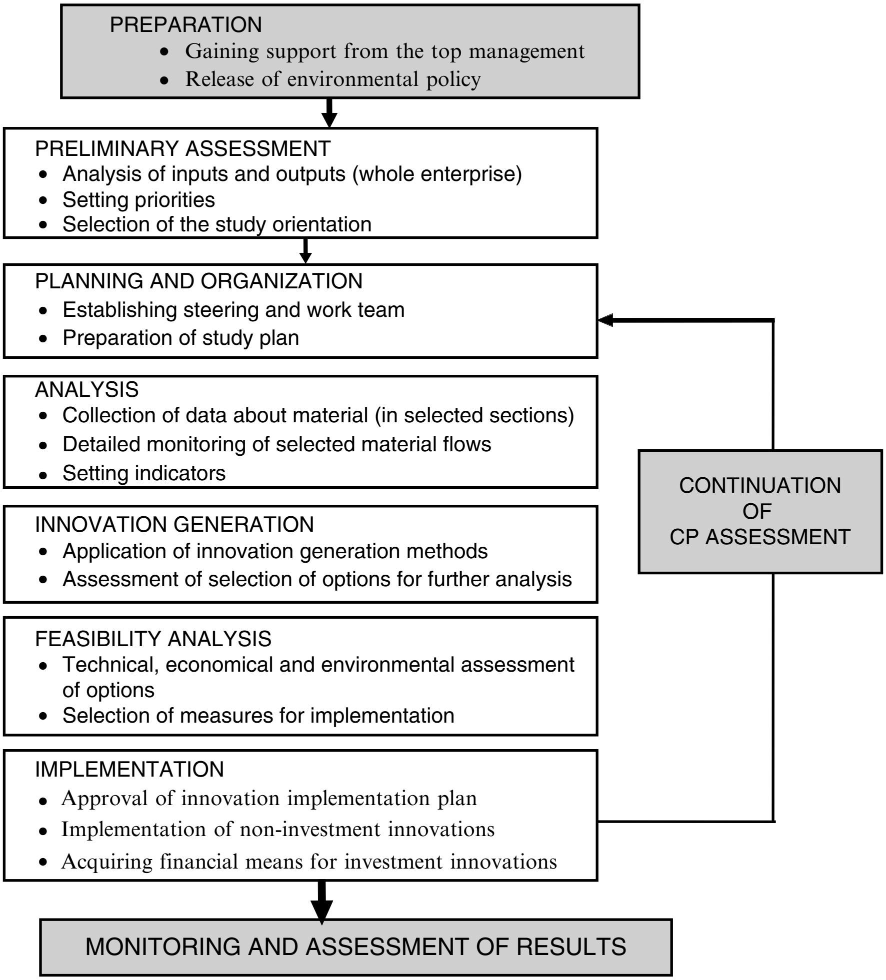

Fig. 12.7 Flowchart of Cleaner production assessment procedure

analysis, innovation generation, feasibility analysis, implementation and monitoring (see Fig. 12.7) [10, 15].

For a number of years, process integration techniques based on pinch analysis have been successfully applied to improving energy efficiency in the process industries. Analogous techniques have been developed for water conservation and wastewater minimization [15].

Water pinch is a systematic technique for analyzing water networks and identifying innovations to increase the efficient use of water in industrial processes. Pinch applications help to identify and to optimize the water system in the plant by application of reuse, recycle and regeneration strategy [17].

During the water pinch study in an industrial facility, several types of water reuse solutions, with or without water treatment, are possible [3]:

1. A water pinch study starts with the assumption that existing input concentrations are at their maximum acceptable limits for all processes and equipment. This shows the minimum acceptable usage under currently imposed constraints on the inlet concentrations. Innovations, identified at this stage will be low-cost proposal, generally allowing only small water reuse possibilities.
2. Larger water savings are possible by increasing upper concentration limits to selected inputs. This type of innovation should be carefully discussed between plant operators and engineers in order to evaluate the risk of quality. In most cases external process experts, data from manufacturers and feasibility studies are required.
3. The next water reuse potential is different combinations of regeneration and reuse. These innovations comprise partially treated some process water streams before their reuse. First, the key streams for possible treatment in regeneration are identified. Then existing and new treatment units are evaluated in terms of reducing overall water consumption. Innovations identified at this stage usually involve capital investments for local treatment facilities.
4. The final possibility is the assessment of distributed effluent treatment options. Instead of mixing all waste streams together and treating them in a single treatment plant, streams are segregated according contaminants they contain and appropriately treated. In this case, several small-scale treatments units will operate on undiluted effluent streams. Distributed treatment systems are interesting innovations as they often offer better removal efficiency at reduced cost.

Water pinch typical assessment procedure consists of three main phases:

1. *Planning and water balance.* It is essential to construct water and pollutant balance, as well as industrial company future plans and objectives for the site. The balances should be validated and conflicts in available data should be resolved. If required, additional measurements for water flows and contaminant concentrations should be performed. The location of main effluent streams should be identified together with their associated problems and key contaminants.
2. *Water pinch analysis*. The main objective is to identify the areas for water savings and innovations. For this freshwater target for fixed operating conditions, the maximum acceptable input concentrations, water stream regeneration and distributed wastewater treatment possibilities have to be identified. Besides that, detailed analysis of wastewater treatment options and appropriate technologies, such as membranes or biological treatment has to be performed.
3. *Innovation identification and implementation.* The objective of this phase is full evaluation (technical, economical, environmental) of innovations identified in the previous phases, and the development of an investment projects with their associated costs.

The structure of the typical water pinch assessment procedure is very close to cleaner production assessment (see Fig. 12.7). Therefore, it looks rational to combine both procedures into one model, especially when it comes to low-cost innovations (see Fig. 12.8).

The integrated Cleaner Production and Process integration assessment scheme was successfully used for many innovations identification, financing and implementation in different industrial sectors. One of real and simple case is presented below.

First of all, the Cleaner production assessment method was used for the wastewater recirculation in sheep skins tannery. Initially, all water used in beamhouse operations was fresh water supplied directly from the river Nemunas. All waste water from the beamhouse (663 m^3 per day) became sewage. This waste water contained detergents and other chemicals (formalin, sodium carbonate). The working temperature was about 35°C. Great losses of water, steam energy and chemicals occurred because of inefficient technology and operations [12].

The following improvement steps based on the detailed assessment of process material balance have been made in the tannery:

Step 1: Wastewater from degreasing and rinsing (60 m^3) operations is used in the soaking operation.
Step 2: Wastewater from squeezing operations after first and second washings (140 m^3) is used for squeezing after soaking.
Step 3: Wastewater from degreasing and rinsing operations (70 m^3) is used for squeezing after the first washing.
Step 4: Wastewater from the second washing (53 m^3) is used for the first washing. Wastewater from a degreasing operation (17 m^3) is used for the first washing.
Step 5: Wastewater from degreasing and rinsing operations (53 m^3) is used for the second washing (Fig. 12.9).

Main advantage of the innovation
This innovation enabled recirculation of the wastewater and has clear economic and environmental benefits.

Environmental benefit:

- reduction in water consumption,
- reduction in chemicals consumption,
- energy savings, and
- decrease in pollution load to wastewater.

Economic benefit
Investment in the modification of production processes (reuse of waste water) – 50 000 USD. Because of reduced costs for chemicals and more efficient use of water, the annual savings at this facility – 100 000 USD. Pay-back of the investment – 6 months.

It is important to mention, that very close results of economical and environmental benefits have been achieved by pinch analysis method too.

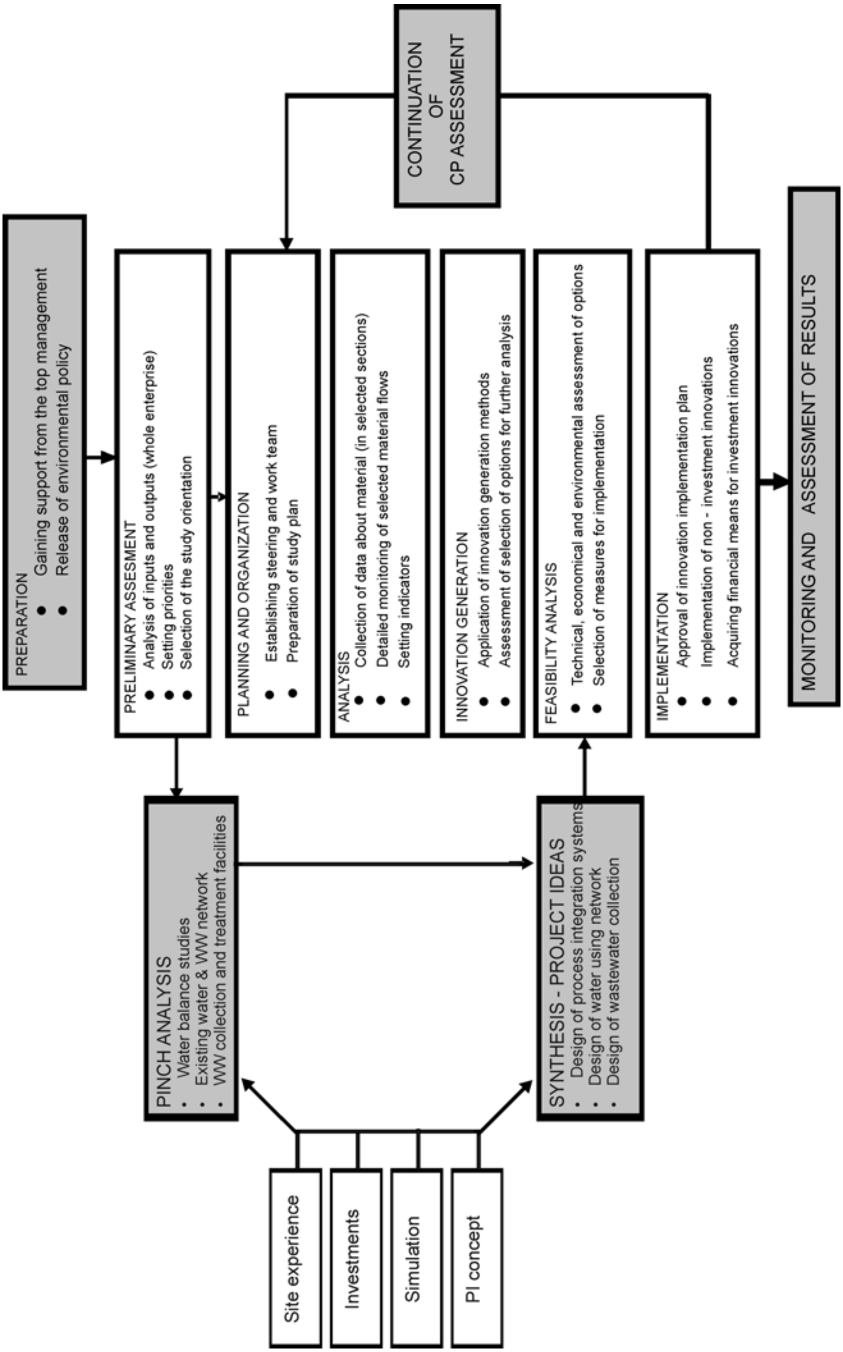

Fig. 12.8 Flowchart of integrated CP and water pinch assessment scheme

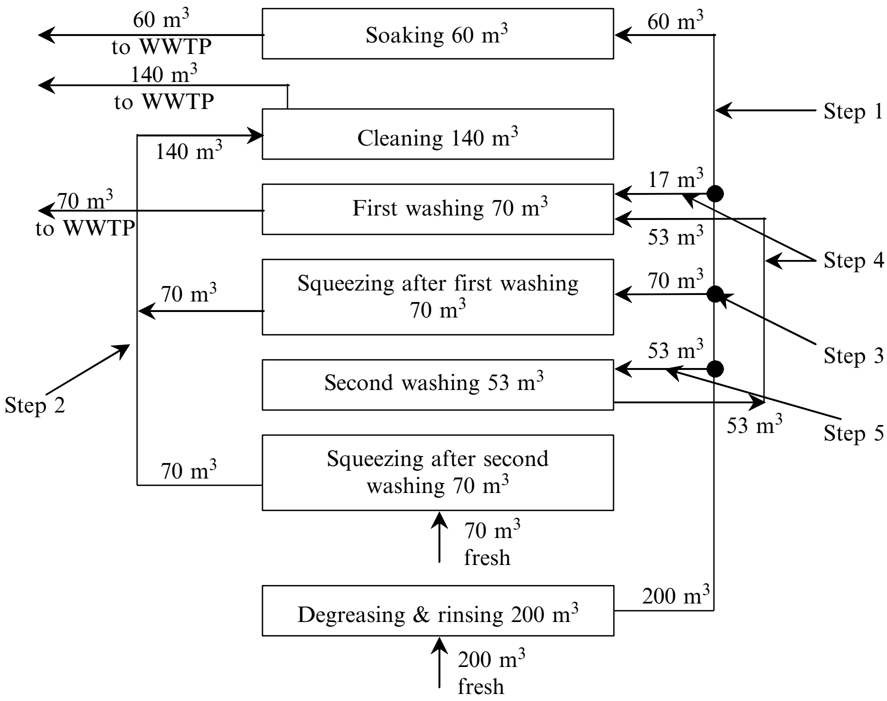

Fig. 12.9 Flow sheet presentation of water recycling in beamhouse operations (WWTP – wastewater treatment plant)

The Cleaner Production and Process Integration concept has been widely implemented in Lithuanian industries during the last decade. The experts of the Institute of Environmental Engineering (APINI) have played the crucial role in waste minimization innovations identification, evaluation, implementation and reporting. 85 industrial companies have implemented 177 waste minimization innovations. The impact of implemented waste minimization methods to the environmental performance improvement is summarized in Table 12.1.

12.4 Conclusion

As it was mentioned in the article, in most case of environmental systems there is incomplete and partial knowledge of the system, which has to be understood and controlled. The nature of knowledge is often incremental and greater insight is gained as analysis and control continues. The consequence of the way we view a system, and hence of the way we observe and measure it, is that our understanding of the system is limited by that view of measurement. In this paper it was demonstrated how systems analysis method can be applied to environmental problems to push

Table 12.1 Environmental benefits from preventive innovations implemented in 1994–2010 in different sectors of Lithuanian economy

	Environmental areas	Environmental benefits	Unit per year
1	Reduction in resource consumption/losses:		
1.1	Electricity	29,940	MWh
1.2	Heat energy	237,205	MWh
1.3	Chemicals and additives	2,289	t
1.4	Water	811.1	1,000 m^3
1.5	Oil	89.9	t
1.6	Fuel	448.1	t
1.7	Fuel consumption, etc. from heat energy saving or from reduction in heat energy losses in production and supply	22,071.61	toe
2	Reduced impact on the environment:		
2.1	Emissions to the atmosphere from stationary pollution sources	3,093.95	t
2.2	Emissions of greenhouse gasses (CO2)	79,759.53	t
2.3	Emissions to the atmosphere from mobile pollution sources	183.98	t
2.4	Wastewater volume	774	1,000 m^3
2.5	Wastewater pollution	521.21	t
2.6	Hazardous waste	621.5	t
2.7	Non-hazardous waste (or waste transformed into raw material for production of other products)	116,108	t
3	Indirect impact on the environment from electricity and heat energy saving (energy produced elsewhere):		
	Reduction in greenhouse gas emissions (CO2): In accordance to natural gas emission factor (in accordance to fuel oil emission factor)	7,107.46 (22,616.36)	t

back information accuracy constraints, to increase the degree of understanding of environmental systems and increase the possibilities of management. It could be concluded:

1. The most environmental problems dealing with interface between physico-ecological and socio-economic systems can be formulated from the systems theory point of view. This allows using modern systems theory methods to solve environmental problems. At the same time, two points must be clearly grasped. Firstly, that the understanding of the system does not necessarily imply that we can control it, and, secondly, that control has a meaning in terms of some stated goal.
2. The structured environmental management clearly shows, that emerging preventive environmental management paradigm differs significantly from the control paradigm of earlier management strategies and calls for new attitudes, not only to the development of production processes and the design of products, but also

to the relationships between consumer and the environment. It must be stated, that for sustainable economic growth and development, the environmental prevention paradigm as a technological and cultural means to achieve the desired compatibility between environmental and economical goals should be used.

3. As long as the material components of products are largely based on the use of virgin resources (including water), while energy is derived from fossil fuels, there is no way to reduce the output of wastes and pollutants below a certain minimum point using preventive management. Unless, the product cycle and materials cycle are (very nearly) closed, the system as a whole will continue to be unsustainable. In this case, preventive and reactive environmental strategies have to be used as a feedforward – feedback management structure.
4. The systems approach relies heavily on large amounts of accurate data, i.e. material and energy balances, which are used both to construct and test environmental models and in their manipulation. The more complex the system, the more data is required, both in space and time. At the same time, in most cases, there is a lack of basic environmental data, existing administrative fragmentation resulting in interfacing and compatibility difficulties, lack of interdisciplinary integration and well defined social goals. One of the main problems is the divorce of the data collector and the systems modeller.
5. Cleaner Production and Pinch analysis proved to be appropriate proactive methods to source/water consumption reduction and has to be included into corporate decision making process. Unlike the command and control regulations to ensure proper management of waste already created, the role of authorities and top management in promoting prevention might therefore be more appropriately viewed as catalytic – pressing manufacturing companies to identify prevention innovations that serve their own and public interest.
6. The integrated assessment model, comprising cleaner production and Pinch analysis methods, allows optimizing the environmental review, material and energy balance construction and feasibility analysis procedures. At the same time, integrated model opens more possibilities for closing water cycles in industry by preventive innovations, including their generation, financing and implementation.

The systems approach and modern systems theory provides a powerful vehicle for the estimation of environmental situation of ever-growing temporal and spatial magnitude and for reducing the areas of uncertainty in our increasingly complex decision-making and management situations based on feedforward – feedback closed loop systems.

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