MASTER

Modelling and control of product-chains

a meso-economic analysis of paper recycling in the Netherlands

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Award date:
1998

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WFW-Report 98.019

Master's Thesis

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Eindhoven, May 1998

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A Meso-Economic Analysis of Paper Recycling in the Netherlands

Jeroen Blansjaar

15th May 1998

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Preface

Many times during this Master's Thesis project I wondered how many frowns my report was going to cause. Not the frowns over the assertions and conclusions in this report, but frowns from reading the front-page. Reading a mechanical engineering student's Master's Thesis one probably expects any title but the one I gave it. I don't know how many times I wondered about this, probably as many times as I wondered why in Heaven's name I, being a mechanical engineering student, was modelling product-chains and market processes. The answer to this last question actually is quite simple. Solutions to problems in the sustainable development field generally are of an interdisciplinary kind. It is true this can be stated about any other problem as well. It seems to be more true for environmental problems, however. Therefore, the Technology for Sustainable Development Center at the Eindhoven University of Technology is not a Sustainable Development Faculty substitute, but its purpose is the fostering of courses and research-projects on sustainable development at all faculties. A research-project on governments influencing recycling decsions in product-chains therefore, quite naturally, involves a Manufacturing Technology and a System & Control Engineering group.

The project offered the reassurance that System & Control Engineering indeed is a wide applicable art instead of specific knowledge - which was one of the main reasons for majoring in that branch of science. What is more, the project opened possibilites to go beyond the boundaries of the mechanical engingeering field - which was not easy at all times. Therefore I would like to thank Uwe Kleineidam with whom I have had many discussions on economic principles and how to incorporate them in a control engineering model. A special thanks to John Vernooy sharing for with me his knowledge of the Dutch wastepaper industry and letting me experience a wastpaper company for a couple of days. Thanks also to Fred Lambert for his valuable support and to Professor Kok for his swift analysis of my preliminary results at our monthly meetings. In addition I would like to thank Professor Van Heijningen for sharing his knowledge on the environmental analysis of product-chains. Furthermore, I am thankful to Bram de Jager, Han van Kasteren, and Mr. Mostert, for spending some time discussing various aspects of the project.

Jeroen Blansjaar

Eindhoven, May 1998

Abstract

The looping of substance chains has since long been an important aspect of environmental policy. Recovery and recycling (or reuse) of used products is an efficient method of diminishing the discharge of wastes and decreasing the depletion of resources. The growing awareness of the threats man forms to its environment and the consequences that a degraded environment impose on humanity have only increased the appreciation of recycling. With the globalisation of the world economy, however, it is no longer sufficient to establish some static recycling goals for communities or countries. In addition, it is recognised that maximum recycling is not the most sustainable solution in every case. The recycling ratio needs to be optimised constantly.

A methodology is developed for the modelling of product-chains: A flowchart (incorporating some basic processes: production, storage, and a market-process) of the considered economic sector is drawn. By applying materials balances to the storage facilities in the flowchart, dynamic equations for the sector's stock levels can be attained. Production decisions and decisions where to supply or purchase products are substituted in the mentioned balance equations. These decisions are based on market prices which' dynamic equations are added to the system state. The methodology basically foresees in the combination of various micro-economic theories: that of production and of the market process. Policy instruments are modelled as accurately as possible in order to evaluate the influences a government or Integral Chain Management (ICM) might have on the recycling-ratio of a product-chain.

A chain model of the Dutch paper industry is derived applying the mentioned methodology. The Dutch paper industry is chosen since it recently adopted some form of ICM. The so-called Paper Fibre Covenant foresees in mutual sale and purchasse agreements (the Removal System) and a forfeiting institute (the Removal Fund) aiming at a more secure throughput of paper through the chain and an incrementation of household wastepaper recovery. The mathematical model pertains to the Removal Fund primarily. Furthermore, the Dutch governments' environmental policy is taken as a guideline for assessing its influence when trying to control the recycling-ratio of the paper product-chain. However, the little amount of data available for parameter identification caused the model not to attain the objected validity.

Nevertheless, it can be stated that the developed methodology seems to be a reasonable approach to the modelling of a wide range of product-chains. A more thorough identification procedure should be applied to increase the validity of the simulation results. Simulation did show the government to have remarkable little influence on a product-chain, while for gaining high recycling-ratios ICM seems to be a more promising method. Moreover, instituting genuine market mechanisms in the chain showed high ratios to be attained quite easily. Alas, the chain's dynamics are rather slow causing oscillations in the recycling-ratio to last quite long.

Symbols & Abbreviations

Due to the large number of variables and parameters that usually form a mathematical model of an economy some variables or parameters are defined more than once - although it is omitted as much as possible. In many cases some distinction, which parameter or variable is used, is possible from the context. If this is not clear from the context it will be remarked explicitly.

Symbols

a_5	$[Mf/ktonne]$	Removal Fund allowance
α	$[-]$	Recycling-ratio
B	$\in R^{10\times4}$	Input matrix
β	$[-]$	Recovery-ratio
C	$\in R^{3\times10}$	Output equation matrix
C	$[Mf]$	Company capital
C_F	$[Mf]$	Removal Fund capital
CC	$[Mf/year]$	Constant costs
c_d	$[ktonne/Mf]$	Decision constant
c_m	$[-]$	State controllability
c_x	$[-]$	Matrix costs
c_{z1}	$[-]$	Recycled waste-flow controllability
$\underline{c}^T$	$\in R^{1\times10}$	Recycled waste-flow output equation matrix
Γ^m	$\in R^{1\times15}$	Market response weightmatrix
Γ^u	$\in R^{1\times4}$	Input vector weightmatrix
Γ^z	$\in R^{1\times3}$	Weightmatrix of the controlled output
γ	$\in R^3$	Measurement function
D	$\in R^{3\times10}$	Output equation matrix
$D_.$	$[ktonne/year]$	Total market demand to specified market
d	$[1/year]$	Depreciation of capital goods
$d_.$	$[ktonne/year]$	Demand of a single actor
$\underline{d}^T$	$\in R^{1\times4}$	Recycled waste-flow output equation matrix
δ	$[-]$	Dirac delta function
ε	$[1/year]$	Distribution efficiency, of wastes or products
$\varepsilon(.)$	$[-]$	Heaviside step function
E	$[year]$	Enforcement period
F	$\in R^{10\times6}$	Exogenous input matrix
$f(.)$	$[-]$	Factor-function for additional labour costs
$\underline{f}$	$\in R^5$	Mass-flow fractions vector
$\varphi(.)$	$\in R^5$	Mass-flow fractions function

G	$\in R^{3\times 6}$	Output equation matrix
$\underline{g}^T$	$\in R^{1\times 6}$	Recycled waste-flow output equation matrix
H	$[year]$	Planning horizon
I	$[Mf]$	Investments
I_r	$[ktonne/Mf \cdot year]$	Recycling inertia
i	$[1/year]$	Shareholders' interest rate
K	$[Mf]$	Capital goods
K_0	$[Mf]$	Initial capital goods
k	$[Mf/ktonne \cdot year]$	Market sensitivity
L	$[manyear/year]$	Labour
L_0	$[manyear/year]$	Initial labour
l_2	$[Mf/ktonne]$	Removal Fund levy
MC	$[Mf]$	Marginal costs
MR	$[Mf]$	Marginal revenue
$\underline{m}$	$\in R^{15}$	Market response vector
$\mu(.)$	$\in R^{15}$	Market response function
N	$[Mf/year]$	Dividend
n_D	$[-]$	Number of demanders
n_E	$[-]$	Number of simulation intervals per enforcement period
n_H	$[-]$	Number of simulation intervals onto planning horizon
n_S	$[-]$	Number of suppliers
n_U	$[-]$	Number of simulation intervals onto the policy change
PC	$[Mf/ktonne]$	Proportional costs
$P_.$	$[ktonne]$	Product stock
$P_{\underline{x}}$	$\in R^{10\times 40}$	State controllability matrix
p	$[Mf/ktonne]$	Product price
p_D	$[Mf/ktonne]$	Disposal price
p_I	$[Mf/ktonne]$	Incineration price
p_W	$[Mf/ktonne]$	Waste price
π	$[-]$	Productivity of production factor
$q_.$	$[ktonne/year]$	Sales of the specified supplier
r	$[1/year]$	Interest rate
$r_.$	$[ktonne/year]$	Purchases of the specified demander
ρ	$[-]$	Recovery-ratio
S	$[ktonne/year]$	Total market supply to specified market
s	$[ktonne/year]$	Supply of a single actor
T	$[ktonne/year$	Trade at the specified market
TC	$[Mf]$	Total costs
TR	$[Mf]$	Total revenue
T_s	$[1/year]$	Simulation interval (time-step)
$\underline{u}$	$\in R^4$	Controlled input vector
U	$[year]$	Update period
$\underline{v}$	$\in R^6$	Exogenous input vector
w	$[Mf/manyear]$	Wages
X	$[ktonne/year]$	Optimal production or consumption
$\underline{X}$	$\in R^5$	Production rate vector

X_0	$[ktonne/year]$	Initial optimal production rate
$X(.)$	$\in R^5$	Production rate function
$\chi(.)$	$\in R^{10}$	System function
$\underline{x}$	$\in R^{10}$	State vector
Y	$[Mf]$	Venture capital
$\underline{y}$	$\in R^3$	Measured output vector
$\underline{z}$	$\in R^3$	To be controlled output vector
$\zeta(.)$	$\in R^3$	Controlled output measurement function

Abbreviations

DTO	Sustainable Technological Development Committee
ICM	Integral Chain Management
IKP	Integral Chain Management Paper & Board, Foundation
LCA	Life Cycle Analysis
MPC	Model Predictive Control
OR	Operations Research
RHC	Receding Horizon Control
SCM	Supply Chain Management
TDO	Technology for Sustainable Development Center
WCED	United Nations' World Commission on Environment & Development

Chapter 1

Introduction

The challenge of finding sustainable development paths ought to provide the impetus - indeed the imperative - for a renewed search for multilateral solutions and a restructured international economic system of co-operation. These challenges cut across the divides of national sovereignty, of limited strategies for economic gain, and of separated disciplines of science. (Gro Harlem Brundtland [49]).

1.1 Subject Outline

Initiated by the TDO-Center (the Technology for Sustainable Development Center) at the Eindhoven University of Technology the research-project to which this Master's Thesis research resorts was granted to the Control Engineering section of the Physics Department in co-operation with the Manufacturing Technology section of the Technology Management Faculty.

1.1.1 Sustainable Development

Two important landmarks in the increasing concern over the earth's future are the Club of Rome's report *Limits to Growth* (Meadows [31]), published in 1972, and *Our Common Future* (1987) by the Brundtland-Commission (officially the *United Nations' World Commission on Environment & Development*). The WCED defined sustainable development: *"Humanity has the ability to make development sustainable – to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs"* (WCED [49]). Certainly, an environmentally sound future had been advocated before 1972 or 1987, however, the WCED ushered the first *global* effort to challenge the threats of the future. With the WCED the global aspect of the ecological problems therefore was acknowledged - just as the increasing frequency and impact at which ecological hazards seemed to appear.

Environmental Pressure

For a large part the increasing threats to the earth's environment can be ascribed to the present growth rate of the world's population, which has been made quite apparent by the American ecologist Barry Commoner some 25 years ago (Verbong [47]). Commoner introduced a simple formula: $L = P{\cdot}W{\cdot}D$ stating that the load on the environment (L) equals the world population (P) multiplied by the average wealth per person (W) times the degradation of the environment per unit of wealth (D). Knowing the expected world population and the expected wealth per capita by the year 2050, the degradation of the environment per unit of wealth will have to decrease by a factor 20 to 50 in order to maintain the current level of environmental pressure. Thus, by the year 2050, the resource- and energy-efficiency will have to be *at least* 20 times higher than they are now to compensate for the expected growth in wealth and population, *assuming* the current load on the environment is sustainable (DTO-chemie [12]).

Disequilibrium

Recycling of wastes is one way of augmenting resource-efficiency since it decreases the use of primary resources and the production of waste. Apparently a lot of 'environmental-benefits' can be gained from 'looping' substance chains. Logically it became, and still is, an area of increasing research activity to try to define a *steady-state* economy in which current wastes (future resources) and future needs for resources were balanced (Starreveld [40]). During the previous decades however, society has become more individualistic than ever. Many thousands individual decisions nowadays form society. Therefore the paradigm of a sustainable steady-state economy has shifted towards the conviction that the earth's future will not be found in a static equilibrium but will be a process of continuing change. Since closing the substance chains remains of importance it will be increasingly difficult for regional, national, and international governments to control the producers and consumers in their territory towards the right level of production and consumption of goods and recycling of resources. The world-system is continuously out of equilibrium; small actions can have unexpected consequences. A new equilibrium will have to be found continuously (DTO-chemie [12]).

Control of Product-Chains

Concluding from the preceding paragraphs it seems worthwhile to look into the influence of those mentioned governments on product-chains in general and on the controllability of the reuse level of used products or materials in product-chains particular. For that same reason it is surprising the very little literature available on the application of System & Control Engineering principles in the Operations Research (OR) field, except for a revival that took place at the beginning of the 1970s (Vishwakarma [48], English [14], Rademaker [37] & [38], and Brewer [9]). The concurrency of this revival with the crises that, predominantly, struck western societies in early the 1970s seems to be more than just a coincidence. However, control engineering applications in economics are encountered every now and then (Nijmeijer [34], for instance). Comparing, although superficially, the micro-, meso- or macro-economic models, studied in the mentioned control and economic literature, shows them to be of similar structure: lumping all labour, capital goods, resources, etcetera, in the considered economy, into single variables - whether a micro-, meso-, or macro-economy is considered. This approach might be correct, under the right assumptions, for conventional economic modelling - it is not for meso-economic product-chain modelling based on materials balances since its explicit purpose is to model various companies and markets.

Introducing Deciding Actors

In addition to preceding Master's Thesis projects (Eijsink [13]) that were done in this research-project it is tried to improve product-chain models with the economic decisions taken by the actors of such a chain. Production decisions, for instance, taken by companies' management or decisions where to purchase resources or where to supply products. When introducing the economic decisions that influence the flow of materials through a chain various micro-economic theories, namely market-theory and the theory of production and consumption, need to be joined; which seems to be a novelty.

After all, a product-chain consists of companies having markets on the resources and on the product side just as it consists of markets having companies and consumers on the supply and on the demand side.

1.1.2 Paper Production in the Netherlands

It is decided to model the Dutch paper chain for various reasons. First, discussions with the industry and experts on recycling justified the modelling of all companies in life-phase of the chain's product as a single cumulative company. Furthermore, wastepaper has been recovered in the Netherlands for quite a long time increasing the changes of a reasonable amount of data to be available for model validation. Finally, the paper industry is currently adopting some form of Integral Chain Management (ICM) for better adjusting supply and demand among the various actors of the paper chain and increasing recovery and recycling of paper fibres.

A Brief History of the Dutch Paper Industry

Most sources ascribe the invention of paper to a certain Ts'ai Lun a Chinese who discovered the fibre structure about 2000 years ago. Although over the past centuries a lot has changed in the paper and board production process Ts'ai Lun's initial structure of entangled cellulose fibres still is the main component of paper or board. In 1405 Jean 'l Espagnol initiated the Dutch production of paper in the Southern provinces of the Netherlands. In 1428 the world's first double bladed water powered paper-mill was built in Gennep. (Today a paper factory still exists near Gennep.) The world's first wind-paper-mill was built in 1586 in Alkmaar. In those days paper was made out of old fabrics and ropes - any material from which cellulose fibres could be extracted. In 1851 a paper factory was built in Maastricht - this factory would expand and eventually became the Royal Dutch Paper factory (KNP). In 1874, when the American Benjamin Tilghman together with the German Alexander Mitscherlich succeeded in extracting cellulose from wood, wood started to become the dominant resource for paper and board. In the province of Groningen a rather flourishing industry using straw as a resource for board (straw-board) emerges. Nowadays, producing about three million tonnes of paper and board a year, the Dutch Paper & Board Industry belongs to the largest in Europe. Also, it tries to maintain a leading position in researching more efficient and environmentally sound ways of producing paper and board (Informatiecentrum Papier & Karton [23])

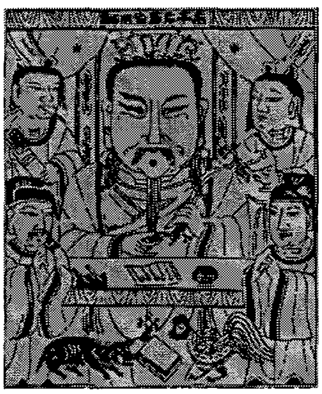


Figure 1.1: *Tsai Lun*

Figure 1.2: *Wind-paper-mill*

Wastepaper Management

Recycling of wastepaper has been an area of interest from the early days of environmental anxiety. Over the past few decades an entire wastepaper industry evolved together with a lively worldwide trade in sorted wastepaper as a resource for paper factories. Throughout the 1980s prices for wastepaper and wasted cardboard were typically cyclic - analog to the economic climate. With the emergence of the worldwide wastepaper market, this decade, fluctuation of the wastepaper prices have become larger and more unpredictable. As a consequence the wastepaper industry has faced serious difficulties in guaranteeing its resource input and product output. These concerns reached their climax in 1993 when the wastepaper price became negative and subsequently boomed to an unprecedented level in the following years. In order to compensate for these insecurities and in anticipation of new government rulings concerning packaging and packaging-wastes (to be effective as of Fall 1997, Stichting-IKP [41]) the Dutch paper industry has signed various agreements promising mutual co-operation between all actors of the paper chain aiming at the regulative legislation to become obsolete.

1.2 Recycling Control Research-Project

1.2.1 Objective

The objective of the research-project in general is the development of a decision-making support tool for government and industry to analyse the behaviour of a product-chain, including recycling. The ability to control and stabilise the recycling ratio (the amount of recycled goods over the total of used products offered for processing) and the price of secondary (recycled) resources in particular would be an advancement for the recycling industry. Secondly, it would be of interest to know how various governments can influence the recycling ratio. Once the optimal recycling ratio of a particular chain has been assessed the government can then try to attain this value. The assessment of the optimal recycling ratio of a particular product-chain, which could be found through Life Cycle Analysis (LCA), is not the primary goal of this research-project however.

1.2.2 Assignment

Since the development of a tool for decision-making support can only be the scope of a long-term research-project the goal of this particular Master's Thesis will be the modelling of a relevant product-chain that includes recycling: the Dutch paper & board chain. It is the objective to find out more about the dynamics of the Dutch industrial paper sector with respect to the flow of materials. An interesting issue is whether the research activity exposes some kind of chain dynamics that cannot be ascribed to the sum of the dynamics of its actors. Integral Chain Management (ICM) and the instruments governments might have to stabilise recycling loops is another topic of interest. It will be tried to derive a chain model of the Dutch paper industry since this chain recently converted to some form of ICM. The objective is to evaluate the consequences of the so called 'Removal Fund'. (Under the Removal Fund, which is a part of a 'Removal System' the actors in the Dutch paper chain try to adjust supply and demand and redistribute the financial consequences of price insecurities.) Thereto its dynamics will be compared to the dynamics of the chain from before the institution of the Removal Fund. It will be investigated whether the Dutch government's objective recycling percentage 85% can be attained.

1.3 Report Outline

Chapter 2 will explain some basics of System & Control Engineering to those not familiar with that branch of science. In chapter 3 a generally applicable theory for product-chain modelling is developed, whereas chapter 4 will deal with the modelling of the Dutch paper product-chain. In chapter 5 the system and its control properties will be analysed. Chapter 6 will discuss the trials that resulted from simulating the system. Finally, chapter 7 will deal with the conclusions that can be drawn from this research-project in general and the simulations in particular; it will also discuss some perspectives for future research, and some recommendations that subsequently come from this discussion. The appendices will deal with various mathematical details.

Chapter 2

Systems, Models & Control

There probably aren't many people that could not give some definition of a *system*, a *model*, or of *control*. It therefore seems somewhat exaggerated to spend an entire chapter on these phenomena. However, when explaining the *modelling* of the paper-chain-*system* and the *control*-theory that has been applied to it, it is, as it is in any discussion, of importance to agree on what is meant by these terms and explain about some jargon. The fact that systems, models, and controllers are used in everyday life might even trouble the discussion here: Everybody ascribes some meaning to those words, and they probably aren't alike. What *actually* is a system, a model, or control - and what isn't?

2.1 Systems

A system is an abstract presentation of anything - be it real or imaginary. Therefore the best definition of a system probably is the least specific (not referring to anything in particular). "Anything is a system, but a system is nothing." (De Leeuw [11]).

2.1.1 Systems in Perspective

First, a brief historic outline of the notion *system* will be given; then it is tried to put the system into its right context.

A Brief History of System Theory

Modern system theory finds its roots in various branches of science where the notion of how the whole and the parts could be related was developed more or less simultaneously; Shannon (1949), working for Bell Telephone Company, recognised the whole of which language was an element: communication. The *Gestaltpsychologie*, introduced by Wertheimer (1923), in psychology, created insights and solutions to problems that previously could not be solved. Likewise in biology where Ludwig von Bertalanffy (1928) advocated a fundamentally different approach, until then the analysis of organisms was reduced to research on molecules and chemical reactions which, although great achievements were made, left some phenomena unexplained. Around the Second World War a major contribution came from research into firing-control systems. In his book Wiener (1948) introduced concepts as *feedback* and *homeostasis*. In management and industrial sciences System Theory was introduced by Stafford Beer (1959) with his book *Cybernetics & Management*. Considering the topic of this thesis research it might be interesting to mention the fact that an important example of the system approach to current problems is presented in the Club of Rome's *Limits to Growth* (Meadows [31]) focusing on the relation between the environment, population growth, and food problems (Kramer [28]).

Emergence of Systems

In retrospect it can be said that the real breakthrough of the systems approach in science was encountered in the 1960s and 1970s. Two reasons can be given for the new method of holism gaining importance in comparison to the existing paradigm of reductionism. Since the Renaissance analysis had been the primary method of scientists. Memorable achievements were made in explaining the basic principles and fundamental phenomena in various scientific fields by taking objects out of their environment scrutinizing and analysing their behaviour. With the evolvement of science, however, the phenomena that were left to explore became more and more complex, while other occurrences seemed to be inexplicable. The reductionist method of early science taking objects out of their environment disregarding how they were related to other elements or to their environment became increasingly futile. Although analysis was, and still is, an important element of the scientific method, the whole system became equally important. Nowadays elements of the system approach can be found in almost any research area. The second reason for the breakthrough of system theory is that scientists wondered about the possibility of a unifying approach to a subject from any area of research and how theories from multiple disciplines could be related. Although such a general set of notions already existed: mathematics, it was not fit for every area of research, psychotherapy or organisation research for instance (Kramer [28]).

Anything can be a System

Since system theory emerged in various disciplines simultaneously various definitions of a system exist, each taken from the context of its specific field. "A system is a collection of mathematical relations describing an aggregate of physical objects". Or: "A system is a human determined constituency of coherent factors and variables". (Both examples taken from Kramer [28].) According to the first definition any phenomenon without mathematical relations cannot be a system, whereas the second excludes anything that is not determined by humans from being a system (biological systems would therefore be non existent). These definitions not only are too strict, they also go against the general opinion that *a system* attributes to almost anything. One often hears the eco-*system* or even the world-*system* mentioned. Although many scientifically patronizing justifications on the everyday use of the word *system* could be made, the important thing is to realise that when talking about systems one always refers to some kind of context. *Systems* do not exist, but *anything* can be approached as a system (figure 2.1), as can be concluded from the definition at the beginning of this section. Figure 2.1 shows a tripod with its legs being the subsystems. Note the subsystems are not interrelated, they convey external loads on the mounting surface back to the environment. The presented system approach can be used for a force balance analysis of the tripod.

2.1.2 Various System Aspects

Various system aspects can be distinguished: its constituents or subsystems, the relations between the subsystems, and the system structure.

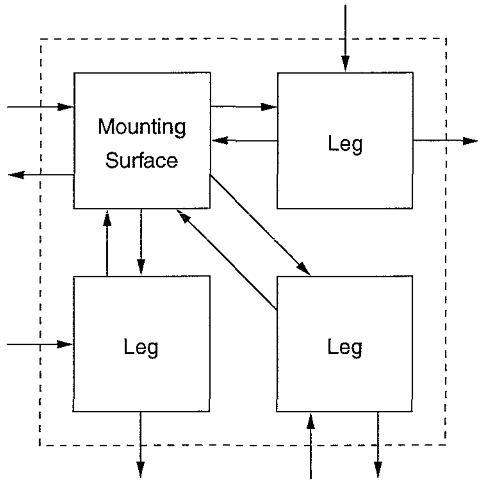


Figure 2.1: *Systems Approach to a Tripod*

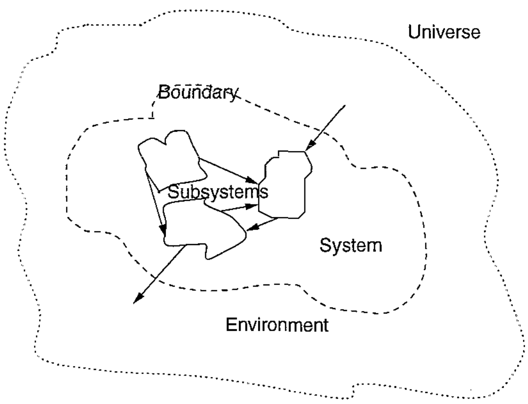


Figure 2.2: *Subsystems, Boundary, Universe*

Constituents

Boulding, a recognised systemtheorist, said: "That what is not chaos, is a system." (In 't Veld [45]). It implies at least one aspect of a system that most scientists seem to agree upon: A system is not chaos, therefore it is ordered. The second aspect of a system that seems to unify most scholars of the systems approach is that what is ordered in the system is also related in some way. Causal relations exist among the various parts of the system that are ordered in the system itself. From here on however the attempts to unify the systems approach among the sciences backfire due to its various backgrounds. The parts constituting a system have been given all sorts of names ranging from elements or components to objects or entities. These notions refer to the undividable parts that form the system a certain professional examines. A sociologist investigating a company as a system would consider the company to be comprised of people and machines as its *elements*; whereas in mathematical system theory one usually speaks of *components*. Note that the very - indivisible - elements of a system for the one scientist might be the entire system that is considered for the other. A biologist studying animals might consider the animals' organs as the basic *objects* in the animal-system. A biochemist, however, would study the organ as a system and take the cells or rather the molecules as its *entities*. The research subject thus determines the level of aggregation.

Subsystems

In addition to the many terms that are used by the various branches of science, control engineers usually refer to the constituents of a system as *subsystems* (figure 2.2). This term better recognises the fact that all those parts that are considered indivisible, indeed are divisible at a lower level of aggregation. It emphasizes the fact that the system approach is a unifying scientific method applicable to a problem of any size. What is more, it acknowledges the fact that any system can be considered as a subsystem of a larger system; and all subsystems can be considered as systems comprised of subsystems. A distinction can be made between subsystems that are solely related to the whole and not interconnected. The logical consequence is that a change in a subsystem will only cause the complexion of the system to change, but not the other subsystems. However, in general, subsystems *are* interrelated causing a perturbation of a subsystem to affect the subsystems it is related to and eventually perturb the whole of the system. System relations are causal, which is a typical aspect of system relations. A subsystem can influence the other but this causal relation cannot be reversed. A government can tax companies but companies cannot tax the government. They might have other means to influence the government, however, this would call for a *new* causal relation from the company to the government. The subsystems in a system and, in particular, how they are related, defines the structure of the system. The system structure therefore determines the behaviour of the system.

The System Boundary and Beyond

Since all systems are subsystems of larger systems one can always expand the approach of a system to include the external influences from neighbouring systems and subsequently consider a larger system. In doing so an unmistakenly better approach will have been attained since the more influences that are considered the better the accordance with the true system will be. However, the new, larger, system that is considered will also be a subsystem of an even larger system, and so on, and so on, until, eventually, the whole universe is considered. Since system theory evolved as a method to abstract rather than involve more reality system theorists introduced the system boundary to exclude reality and relations that are not to be considered. All that is not considered, all that is outside the system boundary, is the system environment. The universe, in system theory, is abstracted to that which encompasses all (figure 2.2). The universe is comprised of the considered system as well as its environment.

2.2 Models

"No substantial part of the universe is so simple that it can be grasped and controlled without abstraction. Abstraction consists in replacing the part of the universe under consideration by a model of similar but simpler structure. Models, formal or intellectual on the one hand, or material on the other, are thus a central necessity of scientific procedure." - Rosenblueth & Wiener (cited by Kramer [28]).

2.2.1 Model Types & Purpose of Modelling

"The sciences do not try to explain, they hardly even try to interpret they, mainly make models. By a model is meant a mathematical construct which, with the addition of certain verbal interpretations, describes the observed phenomena. The justification of such a mathematical construct is solely and precisely that it is expected to work." - John von Neumann (cited by Gleick [17]). Indeed modelling has become a crucial element of the scientific method. By large due to the evolution of the computer the behaviour of many complex systems can now be calculated over large periods of time. Modelling is not restricted to mathematical constructs alone, empiric, conceptual and formal models of either concrete, conceptual or formal systems can be distinguished as well (see table 2.1). Mathematical models solely pertain to the category of formal models.

Model Types

	Empirical Model	Conceptual Model	Formal Model
Concrete Systems	Airplane scale model for windtunnel experiments	Petri-net representing communication between various offices	Formal model of the movement of a car
Conceptual Systems	Gizeh's Pyramid being a realisation of the pyramid from stereometry	Design flowchart of an information system	Differential equations theory
Formal Systems	Ruler as a model of the theory of real numbers	Switching-scheme of the logic AND-function	Analytic geometry enabling the transition from geometry to algebra

Table 2.1: *Model Types* (Kramer [28])

In general the purpose of a model is its relative ease and possibility of repeating analysis of a system under various conditions. An airplane scale model can be exposed to the exact same conditions in repeated experiments while it is possible to change some design parameters of the model - something that would be very difficult to achieve with a real airplane. In some cases however, a model is the only possible method for analysing a system; when experiments on the real system are too expensive or simply impossible. When analysing the Dutch paper chain for instance, it is impossible to evaluate various policy regimes for that chain over a couple of decades. The objective of this thesis project therefore is the development of a formal model of that paper chain - a concrete system.

2.2.2 The Modelling Process

"There exist no recipies for the development of an adequate model in *every* case. Good models, until now, have been derived partly through iteration: Incorporating more aspects of the true system (structure, parameters) in the model, making it less abstract with each step. For the other part they have been brought about by creativity and genius analogies. However, there is no sufficient model for 'creativity' - although some methodology exists modelling is mainly learned through excersising." (In 't Veld [45]). A general distinction that *can* be made is between white- and black-box modelling methods. White-box modelling refers to the development of models from knowledge of the system's internal structure and existing theory, be it of mechanics, physics, electronics, economics, or any other. The black-box modelling techniques, which have been developed over the past decades, try to estimate a system model from input and output time-series, not requiring any prior knowledge of the physical system. When developing a mathematical (formal) model differential equations can be derived applying physical laws. Here, nature is kind and unambiguous: these equations sometimes are of second order but usually first order differential equations are attained. This recognition forms the fundament of system theory bringing together various branches of science. It was developed by mathematicians primarily and manifests itself in the state description. Because of the validity of the existing theoretic concepts varying from the one branch of science to the other the application of first principles for the development of a model might still not lead to a 'white' model in each scientific discipline as can be seen in figure 2.3 (Van den Bosch [7]).

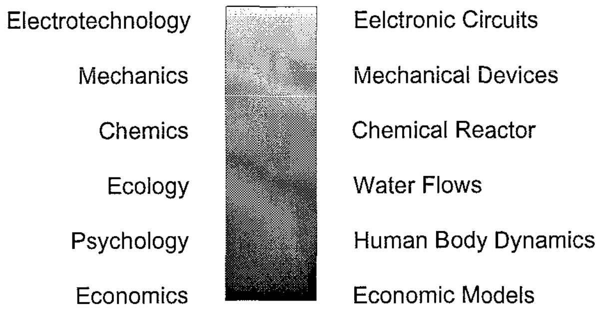


Figure 2.3: *Black & White Modelling*

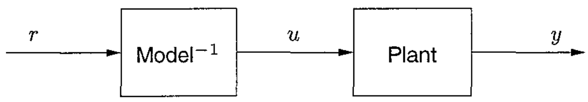


Figure 2.4: *Feedforward Control*

It can be concluded that modelling is an iterative process in which it is tried to develop a better representation of the considered system with each step.

2.3 Control

The term control is not defined unambiguously. In management science it usually means supervision of quality or of a part of the plant or, most common, it refers to the financial stewardship of a company or firm. In control theory, on the other hand, it refers to any action or decision, be it financial, organistational or any other, that influences the evolution of a certain system.

2.3.1 Purpose of Control

The main purpose of control is to meet a certain objective under the condition that the system remains *stable* - a controller's *performance* is considered to be good if it meets the objective. In control theory various definitions and various degrees of stability exist. Generally it can be stated that a system is stable if its outputs remain bounded under the condition that its inputs remain bounded as well; preferably in the face of uncertainties. This is known as *robust stability*. The principal control objective is the tracking of reference path or the attainment of a reference value. The difference between the reference trajectory and the actual value of the system, the tracking error, can be taken proportionally, it can be integrated, or it can be differentiated leading to a corrective action as is done by the well-known PID-controller. Other control laws exist that are based on some criterion (quadratation of the tracking error for instance) that needs to be minimised. Such a control law usually involves an internal model of the considered system and a certain horizon onto which the criterion is evaluated. Finally, dynamic optimal controllers try to attain the optimal value of their objective, be it a minimum or a maximum, which need not be a tracking error.

2.3.2 Feedforward & Feedback Control

When control engineers use the term control these days they usually refer to feedback control since it is the predominant control application. In general by control is meant presenting an input signal to a system such that a certain reference is met. In feedforward control this is done by using some internal model of the system and inverting its dynamics in order to calculate what the input should be

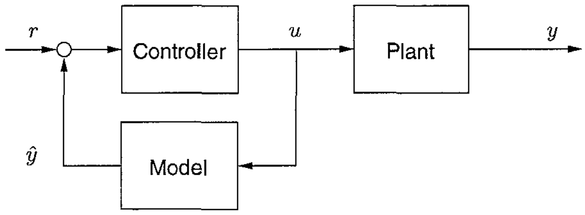


Figure 2.5: *Modelbased Feedforward*

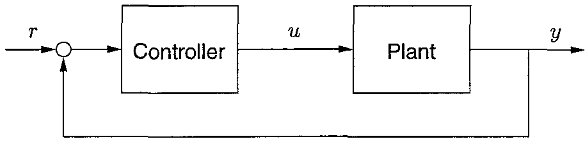


Figure 2.6: *Feedback Control*

(figure 2.4). More complex systems, for instance those of which the dynamics cannot be inverted can be controlled applying the (non-inverted) system model (figure 2.5). In both cases prior knowledge of the controlled system is required. The main advantage of feedback control is that the system itself is used as a model by feeding back the system output. In the face of disturbances the performance of a feedback controlled system is expected to be better since the output of the system itself is known (figure 2.6). The introduction of the feedback loop, however, can give rise to instabilities (Kok [27])

Chapter 3

Modelling Methodology

In this chapter concepts of industrial engineering, econometry, and control engineering will be integrated to attain a first principles model of a product-chain. Since it is objected to complete the process of modelling, system analysis, and controller design rather than elaborate on one of these subjects the methods might seem too straightforward at one instant and farfetched at the other. However, it is believed to be more fruitful to complete the entire process, although shallow at some stages, and devote further studies to various improvements and more in depth analysis of the considered system. In addition to these arguments, for not presenting a method that is beyond discussion, one should remember that the laws in social sciences are not quite as established as physical laws; as Takayama [42] cites Keynes: Economics is "the amalgam of logic, intuition, and wide knowledge of facts, most of which is not precise."

3.1 Introduction

3.1.1 Literature

The modelling of economic or public systems, as any other system, can be approached in various ways. In contrast to physics, the validity of theories in social sciences is much more questioned which may be one of the reasons why control engineers devoted relatively little time to those systems (Rademaker [37], [38], and Vishwakarma [48]). Due to the mathematical fundament of economic theory being less unambiguous than its physical counterparts the concept of white-box modelling, which is frequently encountered in physical system and control engineering, is difficult to apply to economic systems. A first-principles economic model will generally be more 'black' than 'white' (figure 2.3, from Van den Bosch [7]). An extensive overview of black-box models for economic forecasting can be found in Granger's works ([18] & [19]). However, to be able to estimate all the parameters in the chosen model structure the input signal to the estimation needs to contain enough information (Van den Bosch [7]) - it is doubted whether enough data can be acquired for the considered system. Furthermore, little insight can be gained from a black-box model. Therefore it is decided to derive a state space product-chain model based on economic principles. Some suggestions for those principles can be found in economy textbooks like Mansfield [30] and Sher [39]. More specific thoughts on the application of flowcharts and mass-balances to the interdisciplinary field of economy and ecology - although they are static contemplations - can be found in articles by Kandelaars & Van den Bergh [26] and Starreveld & Van Ierland [40]. The work by Ng [33] focuses on the specifics for meso-economic analysis. A more thorough explanation of micro-economic theories of production and exchange can be found in works by Varian [44] or Granger [20].

3.1.2 Outline

In their analysis of industrial systems management scientists and industrial engineers often use a flowchart to visualise the flow of materials through an industrial system (a plant, for instance). Here, the flowchart concept will be applied to a larger system: an industrial sector or 'meso-economic system'. Extracted material flows to various plants and is transformed into products. The products are sold, used, and subsequently disposed of, as will be explained in section 3.2. Besides material flows, flowcharts visualise transformation and other processes, storage for instance. (Note that storage can be regarded as a transformation in time however.) By applying mass-balances to a flowchart, differential equations for its storage locations can be derived. Together with equations for the material in- and outflow as a function of market prices a simulation model is developed. The main reason for pursuing this 'white-box' modelling approach based on economic first-principles is the fact that more insight into the modelled system will be gained from it. In section 3.3 the market processes are explained while the decisions taken by the various actors in the economy are treated in section 3.4.

3.2 Product-Chains, Flowcharts & Mass Balances

3.2.1 Product-Chains & Flowcharts

In accordance with Flapper [15] a flowchart of a life-cycle (figure 3.1) and one of a product-chain including recycling are drawn (figure 3.2). The product-chain consists of the life-phases of a product. The life cycle analysis (LCA), which is frequently encountered in literature on the environment, is also based on these life-phases:

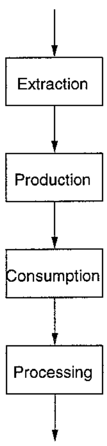


Figure 3.1: *A Product Life-Cycle*

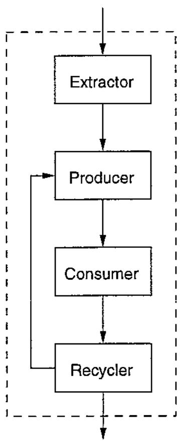


Figure 3.2: *Product-Chain with Recycling*

First, the extractor extracts the resources from the ecosystem (the environment) and sells them to the producer. The producer transforms the resources into products that are sold to the consumers. After consumption the used products are processed (to some extent), and the remainings are offered for disposal into the ecosystem. In the recycling-chain the processor is replaced by a recycler. The recycler recycles some of the used products that are supplied to him and offers the rest for disposal. The amount of used products that is recycled or incinerated depends on the recycler's business decisions and thus on the costs for incineration compared to the price of wasted goods and the price of secondary resources. Basically the recycling-chain is a product-chain allowing the re-flow of used products in any form. When modelling an entire industrial sector, as is done here, various (interacting) actors exist just at each life phase (various extractors, various producers, etcetera). For now, it is assumed that the actors in each phase can be modelled by a single cumulative 'company'; which is encountered in economics more often (Ng [33]).

3.2.2 Flowcharts & Mass-Balances

Figure 3.3 shows a small flowchart of a company including a product storage facility and markets. Note only the boundary of the company subsystem is drawn here - the system boundary is not. The horizontal arrow across the subsystem boundary represents the company's unrecovered. The other horizontal arrows depict supply and demand from the system environment. In abiding by the law of mass conservation the in- and outflow of mass need to balance its accumulation.

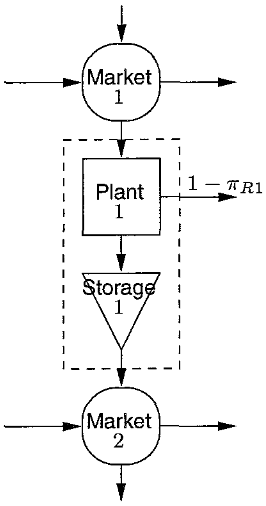


Figure 3.3: *Company Flowchart*

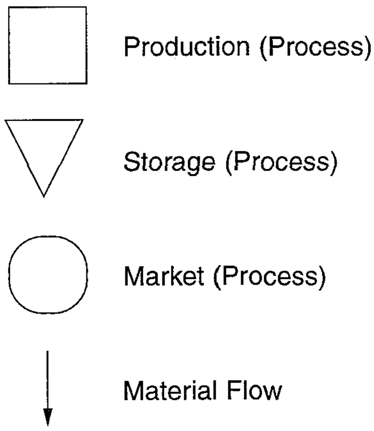


Figure 3.4: *Flowchart Legend*

$$\begin{aligned}\dot{P}_1 &= \underbrace{\frac{T_1}{D_1}\frac{1}{\pi_{R1}}X_1}_{I} - \underbrace{(1-\pi_{R1})\frac{T_1}{D_1}\frac{1}{\pi_{R1}}X_1}_{II} - \frac{T_2}{S_2}\varepsilon_{P1}P_1 \\ &= \frac{T_1}{D_1}\left(\frac{1}{\pi_{R1}}X_1 - (1-\pi_{R1})\frac{1}{\pi_{R1}}X_1\right) - \frac{T_2}{S_2}\varepsilon_{P1}P_1 \\ &= \frac{T_1}{D_1}X_1 - \frac{T_2}{S_2}\varepsilon_{P1}P_1\end{aligned} \tag{3.1}$$

The mass-balance applied to the storage facility in figure 3.3 (equation 3.1) states that the accumulation of products in stock ($\dot{P}_1$) equals the inflow into the storage facility minus the outflow. (Here π_{R1} is the resource productivity, T_1 and D_1 are trade and total demand at the resource market, respectively, X_1 is the plant's optimal production rate, ε is a product distribution efficiency, and T_2 and S_2 are trade and supply at product market, respectively). The inflow to the stock equals the amount of material that flows into the company minus the company's unrecovered losses. In turn, the material inflow into the company (I in equation 3.1) is what it has demanded for ($\frac{1}{\pi_{R1}}X_1$), times the portion of total trade the company acquires ($\frac{T_1}{D_1}$). The unrecovered losses are $1 - \pi_{R1}$ times that inflow (II). Thus, knowing its production losses the company demands for $\frac{1}{\pi_{R1}}X_1$ resources; equation 3.1 then simplifies into a handsome formula. Accordingly, differential equations can be derived for all storage processes in the chain. Furthermore, where flows are divided or added again inflow must equal outflow. (Analogous to Kirchoff's Law in electronics or a force balance in mechanics.)

3.3 A Market Model

The crucial dilemma when deriving some equations describing the market mechanism is how a stable equilibrium is attained between the market price, the quantity supplied, and the demanded quantity (Aoki [1]).

3.3.1 Two Processes

When looking at a trade market two processes can be distinguished. The return of a market price in the face of supply and demand and the distribution of the goods among suppliers and demanders. The ultimate dilemma is which of these processes precedes the other. Logically, two theories exist about adjusting the market variables: the Walrasian theory of price adjustment and the Marshallian theory of quantity adjustment. According to Takayama [42] the price adjustment scheme can also be regarded as the theory of exchange and therefore best suits for modelling a market place - the quantity adjustment theory is referred to as the theory of production. In the chain model, as it is proposed here, that production decision is taken at each plant. Furthermore, Takayama states that since both demand and supply are a function of price, price is most likely to be the final adjustment variable. Subsequently, supply and demand are the inputs to the market. Besides establishing the market price, the market model allocates the exchanged quantities too.

3.3.2 Price Adjustment

The adjustment of price as it is modelled, is based on a simple formula proposed by Walras (Kuhn [29])

$$\dot{p} = k(D - S) \tag{3.2}$$

stating that the time derivative of the market price equals some adjustment parameter k times excess demand. The totals of market demand and supply are attained by summing the supplies and demands of the individual companies.

$$\begin{aligned} S &= \sum_{i=1}^{n_S} s_i \\ D &= \sum_{j=1}^{n_D} d_j \end{aligned} \tag{3.3}$$

With S and D being the totals of demand and supply and n_D, n_S, being the number of demanders and suppliers, respectively. Finally s_i is the quantity supplied by supplier i and d_j the quantity demanded by demander j.

3.3.3 Trade: The Exchange of Goods

A persisting nonlinearity exhibits itself in this area of the economic process: there can only be traded so many goods as are supplied or demanded for. That is, no supplier can sell more goods than his customer is willing to buy, and no demander can require his supplier to sell him more than the supplier has stored. Indeed the market process causes the price to drop when supply exceeds demand causing demand to rise and eventually meet supply. This process develops in time as will be modelled by the proposed market model. At each point in time however it is needed to allocate the supplied goods; each actor needs to know how much it has sold or purchased. The amount of goods that is traded (T) thus depends on total supply (S) and demand (D) to a market according to the following nonlinear relation,

$$T = \min\{S, D\} \tag{3.4}$$

which is also suggested by Granger [20] for the analysis of disequilibrium markets. Among the various actors the allocation of sales and purchases is modelled according to the ratio of their supply or demand over the total supply or demand.

$$q_j = \frac{T_P}{S_P} s_j \tag{3.5}$$

$$r_j = \frac{T_R}{D_R} d_j \tag{3.6}$$

Here q_j are the sales of the jth supplier and r_j are the purchases of the jth demander. The subscripts P and R refer to the product and resources market.

3.4 A Company Model

The division of a company into various levels of production control is encountered frequently in literature but not in a unique way. Giesberts [16] distinguishes four levels; however, another, perhaps more generally accepted, division is (top down): strategic, operational, and instrumental control. Strategic control (top-management) is supposed to be occupied with the long-term decisions primarily - involved in decisions concerning the amounts of capital (K) and labour (L) in the company. Next, operational control (production management) establishes the optimal production rates given the amounts of capital, labour, and the current product and resource prices. The instrumental control pertains to the operation of machines and is done by operators or mechanical and digital controllers. This report will deal with the *operational* control primarily. It is trusted that the *instrumental* control reaches the objectives set out by the operational control while implementation of the *strategic control* decisions is found to be too involved at this stage. For some insights on the mathematical modelling of firms' strategic control is referred to Blok [5]. The model presented by Blok (involving the dynamics of capital and labour due to investments and dividends, see Appendix A) is recommended for application in further studies.

3.4.1 The Production Process

Including the operational production decision in the chain's dynamics involves the introduction of an auxiliary function. It is based on the economic theory concerning production and cost functions.

Production Functions

A production function links the input factors of a company (capital goods, labour, and possibly, resources) to a feasible level of production. A Leontief production function (figure 3.5) is applied for the long-term variations in the production rate ($\bar{X}$) as a function of the input factors capital goods and labour, in reference to their initial values (X_0, K_0, and L_0).

$$\bar{X} = X_0 \min\left\{ \left(\frac{K}{K_0}\right)^{\pi_K}, \left(\frac{L}{L_0}\right)^{\pi_L} \right\} \tag{3.7}$$

With π_K and π_L ($0 < \pi_K, \pi_L < 1$) being productivity factors for capital goods and labour - note they are not analogous to the resources productivity (π_R). In the Leontief production process only one efficient combination of input factors is possible. That is, various combination (K, L) reach the same level of output but only one of them is most efficient. The isoqants in the (K, L)-plane (lines of constant rate of production) are L-shaped. (Note that projecting, on the base, the intersection, of the 'hill' of figure 3.5, with a plane of constant production rate, indeed is of an L-shape.) The Leontief production process therefore often is considered as simplified and non practical. However, the input-output analytical model, for which Leontief was awarded the Nobel Prize, was based on this very production function (Sher [39]). In accordance with Blok [5] the Leontief production function is used to determine the increase of the average (long-term) rate of production ($\bar{X}$) due to investments (established by the company's strategic control). The short-term rate of production (established by the operational control) is based on this average and changes in market price. A smoother production function proposed by Cobb and Douglas (Varian [44], figure 3.6) is used to determine the rate of production around the current set of input factors (K, L).

$$X = \bar{X} \left(\frac{\tilde{K}}{K}\right)^{\pi_K} \left(\frac{\tilde{L}}{L}\right)^{\pi_L} \tag{3.8}$$

Here $\tilde{K}$ and $\tilde{L}$ are the short-term variational amounts of capital goods and labour. It is assumed that the productivities satisfy $\pi_K + \pi_L = 1$ which means that the company exhibits constant return to scales. In such a case the generation of twice as much output requires twice the amount of input from both the input factors.

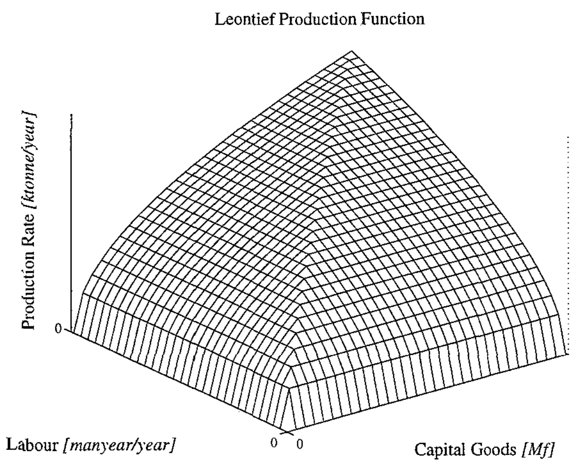


Figure 3.5: *Leontief Production Hill*

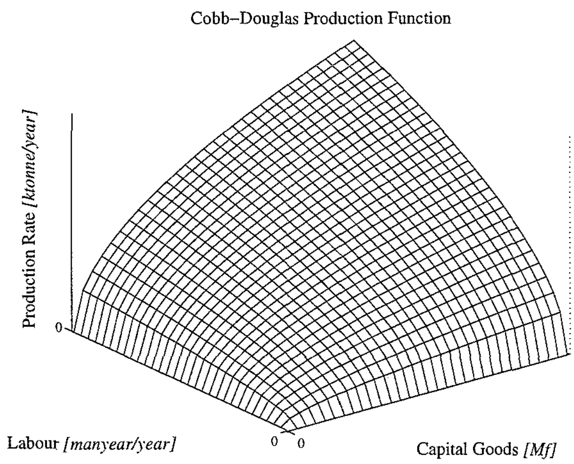


Figure 3.6: *Cobb-Douglas Production Hill*

Due to the 'law' of diminishing marginal revenue or increasing marginal costs, the productivity of each new unit of labour eventually decreases. The Cobb-Douglas production function describes this phenomenon as is shown in figure 3.8. Taking this function (3.8) and realising that capital goods are only variable in the long run (thus $\tilde{K}$ is constant, $\tilde{K} = K$), it is attained that

$$X = \bar{X}\left(\frac{\tilde{L}}{L}\right)^{\pi_L} \quad \Rightarrow \quad \frac{\tilde{L}}{L} = \left(\frac{X}{\bar{X}}\right)^{\frac{1}{\pi_L}} \tag{3.9}$$

3.4.2 Operational Control

To be able to decide about the optimal rate of production with respect to the current market prices, the total costs are required as a function of X only. Then it is possible to find the rate at which profit is maximised by choosing X such that marginal costs equal marginal revenue: $MC = MR$ (Mansfield [30]). The company 'produces to inventory', for the determination of the production rate it is assumed that all produced goods are sold.

Cost Function

The company's total costs (TC $[Mf]$) are attained by adjusting Blok's [5] formula for the change in the company's capital which, logically, is a subtraction of total costs from the total revenue TR $[Mf]$.

$$TC(K, L, X) = (d + r)K + wL + \left(\frac{p_R}{\pi_R} + PC\right)X \tag{3.10}$$

Here d is the capital goods depreciation, r is the interest rate, w are the wages, π_R is the resource productivity (the amount of resources needed per amount of product), and PC are the proportional costs: Costs proportional to the production rate (energy costs, for instance). The total costs function includes the fixed costs and variable costs. The variable costs of production vary with X, the fixed costs are considered to be fixed over the production planning period but variable with regard to the strategic control horizon. The amounts of capital goods and labour, and therefore their costs ($(d+r)K$ and wL) are fixed. Note, however, that the justification of the assumption that labour is fixed over the planning period is culture dependent. Many economists would argue that labour costs indeed are variable, which they, with the increasing popularity of flexible labour, probably are. Indeed it would be quite restrictive to assume that the amount of labour a company has contracted could not be increased with temporary employees when the product price encourages a company to produce more. In the production function (3.8) labour is therefore considered variable. However, since it is not possible to fire all employees just at once the cost function includes some reduction of costs when littler labour is required, but no more than about a third of the total labour costs. The labour costs thereto are multiplied by a factor $1 + f(x)$, with $f(x) = \frac{1}{3}(x^2 + 2x)$, and $x = (\tilde{L}/L) - 1$; which is drawn in figure 3.7. The dashed line in figure 3.7 is to show that for *increasing* the current production rate, thus hiring more labour, the labour costs increase nearly linear; which is objected since the introduced factor should only be of influence if labour is diminished.

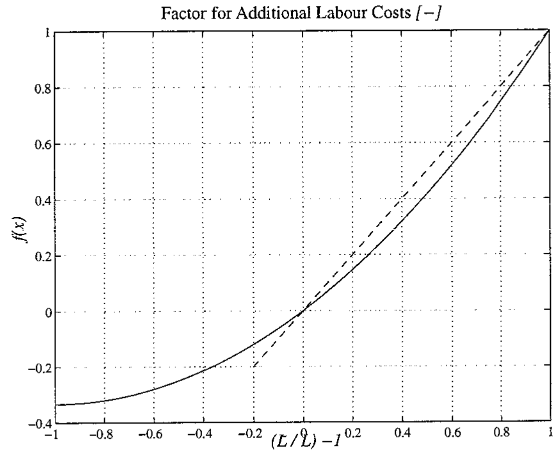


Figure 3.7: *Factor for Adding Labour Costs*

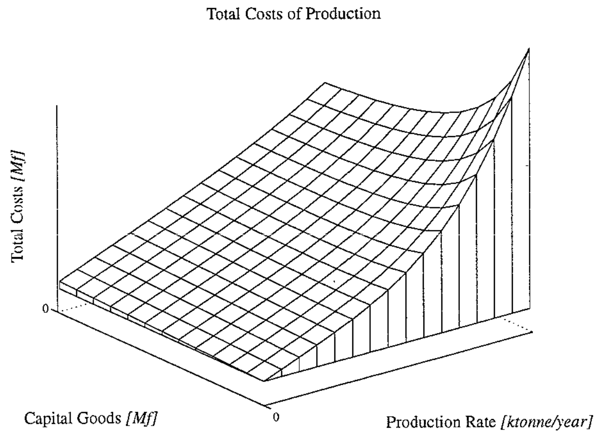


Figure 3.8: *Total Costs with Constant Labour*

Internalising the Operational Control

Given the amounts of capital and labour, the assumption that labour is flexible over the production planning period, but only to some extent, and given the current prices of products and resources the optimal rate of production can be established by solving marginal costs equal marginal revenue ($MC = MR$) for X. The derivation of the equation can be found in Appendix B in detail.

$$X = \left(\frac{p_Q - \frac{p_R}{\pi_R} - PC}{\frac{2}{3}\frac{w}{\pi_L}\left(\frac{K_0}{K}\right)^{\frac{2\pi_K}{\pi_L}}\left(\frac{1}{X_0}\right)^{\frac{2}{\pi_L}} L} \right)^{\frac{\pi_L}{2-\pi_L}} \tag{3.11}$$

Introducing a constant costs variable (CC) it is attained that

$$= \left(\frac{1}{CC}\left(p_Q - \frac{p_R}{\pi_R} - PC\right)\right)^{\frac{\pi_L}{2-\pi_L}} \tag{3.12}$$

Under the assumption that $\pi_K = \pi_L = \frac{1}{2}$ and the practical experience that a company cannot produce a negative amount of products 3.12 is replaced by

$$X = \left(\frac{1}{CC}\left(p_Q - \frac{p_R}{\pi_R} - PC\right)\right)^{\frac{1}{3}} \varepsilon\left(p_Q - \frac{p_R}{\pi_R} - PC\right) \tag{3.13}$$

with the $\varepsilon(x)$ being the Heaviside step function, the primitive of the Dirac delta function $\delta(x)$. The function and its purpose are explained in Appendix C.

3.5 Modelling the Actor's Decisions

The company model presented in the previous section is rather focussed on the production decision taken by a company. The optimal rate of production is established by comparing market prices for resources, products, labour and capital goods. Another decision needs to be modelled however: at which market it should purchase its resources and sell its products or wastes.

3.5.1 Waste Supply Decision

As an example a company recovering the production losses it cannot reuse itself is presented (figure 3.9, note it is an expansion of figure 3.3). The recovered losses are accumulated and need to be disposed of against the lowest possible costs, or preferably sold. As long as it is not prohibited by the proper authorities to dispose of wastes, the company can indeed decide to either dispose of its wastes through landfill or incineration *or* to supply it to some waste processing company. In case of the former option, which used to be the sole option for decades, the company is charged with the governing rate for waste disposal - usually a municipal tax. The charges in the latter option are subject to market conditions. Therefore, if the waste considered here is of some value to any other actor, the company can sell its recovered wastes to the waste processing company. Needless to say any actor is inclined to choose the option from which it will profit most.

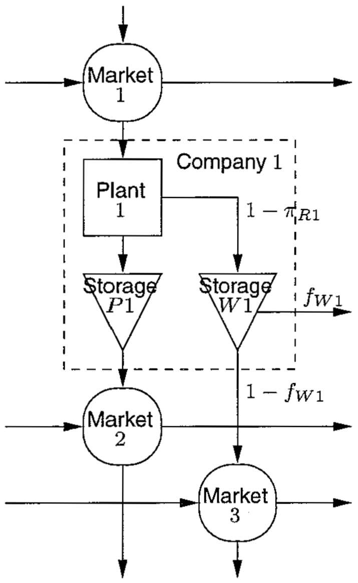


Figure 3.9: *Company Collecting Wastes*

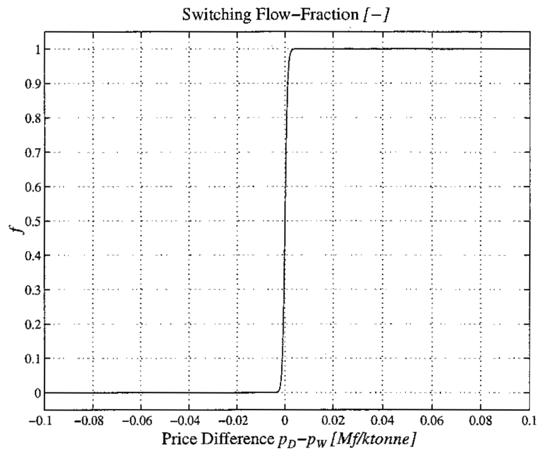


Figure 3.10: *Rather Decisive Company*

Figure 3.9 shows how the company's decision (f_{W1}) influences the mass-flow through this small product-chain. The decision variable is referred to as flow fraction since it determines what fraction of the waste flow is offered for incineration or landfill and what portion is supplied to the waste market (Market 3 in figure 3.9). It therefore follows that $0 \leq f_{W1} \leq 1$ as a function of the waste disposal charge and the current price at market 3.

3.5.2 The Decision Function

Considerations

Many of the decisions modelled in the product-chain in fact are decisions whether or not to recycle. Judging from the numerous debates on a sustainable, more environmentally sound, future and how to achieve it, there seems to be more to this recycling decision than a simple comparison of prices and charges. Increasing pressure has been exerted on companies to increase their efforts for alleviating the environmental burden of their businesses, even when there is no direct financial gain from it. However, since their customers are a part of society, in the end, there is a financial gain for companies to abide by the public opinion. Other considerations involve the investments that are most likely to accompany the adaptation of a plant to recovering its production losses. And consequently the tendency to persist in recycling, even when market prices are not encouraging to do so. These arguments have convinced some authors to propose for recycling to be modelled as an inertia (equation 3.14, Brewer [9]). Although this proposition seems very promising from a mathematical point of view it does inflict some difficulties on the model: model constraints.

$$\dot{f} = \frac{1}{I_r}(p_W - p_D) \tag{3.14}$$

Equation 3.14 states that the time derivative of the mass-flow fraction for recycling a certain amount of recovered material, modelling the decision of the actor wanting to dispose of the material, is reversely proportional to some recycling inertia (I_r) multiplied by the price for wasted goods (p_W) minus the price for disposed goods (p_D). Note that p_D and p_W will probably both be negative since the value of the collection service per unit of material usually is larger than the value of the material itself. Adding the the equation to a model's state vector would necessitate this state variable to be constrained by $0 \leq f \leq 1$. Another possibility would be to model the entire flow of recycled material by an inertia. The flow would then increase with the price for recycled material and vice versa. Unfortunately this method conflicts with the materials or mass balance. Since the amount of recycled material only depends on the mentioned market prices it can reach any level regardless the actual amount of material present in the plant, therefore a situation can arise in which the recycled amount of material is larger than the amount of material in the plant itself.

The Function

It is chosen to model the actor's purchase and sales decisions using a smoothened step function ($\tilde{\varepsilon}(x, c_d)$, see Appendix C). Now if $p_D \gg p_W$ the material will be disposed of ($f = 1$), whereas if $p_D \ll p_W$ the material will be recycled ($f = 0$).

$$f = \tilde{\varepsilon}(p_D - p_W, c_d) \tag{3.15}$$

The function returns a bounded fraction: the fraction of material that is disposed (figure 3.10). The additional argument (c_d) is a decision constant influencing the 'smoothness' of the transition from complete recycling to no recycling at all (a smoother decision function is presented in C.2).

3.6 The Government's Influence

It is intended to model the government as a controller of the considered product-chain. Various policy instruments that might be enforced by the proper authorities are reviewed in this section. For the ones that seem to fit for inclusion in the model it is tried to capture them mathematically

3.6.1 Control Instruments

Naturally the government, in pursuing incrementation of the reuse of paper & board, can consider to execute their policy themselves. That is, the government can consider to establish various wastepaper processing companies by itself. More often, however, the government will try to have others undertake the required activities. In doing so the government generally has two options: persuasion or enforcement. More specifically these options can be categorised in three groups of government regulation instruments (Van Ast [2]). In decreasing vigour of enforcement they are:

1. Direct regulation; a rather traditional means of environmental policy enforcement, the government enforces a law prohibiting a certain type of behaviour.
2. Indirect regulation; a more persuasive measure through which the government tries to influence people's or companies' behaviour. Although they still are relatively free to persist in their habits it now is quite unattractive to do so, mainly through financial or economic interventions.
3. Selfregulation; a quite progressive measure through which the government tries to convince civilians or companies of the necessity of a change in their behaviour. The policy instrument developed over the past decades as a direct consequence of the increasing number of legislative prohibitions making it impossible to enforce them all. Integral Chain Management ICM and covenants emphatically belong to this group of policy measures.

A Regulating Government

In order to direct the level of recycling in a certain product-chain or industrial sector a regulating government can consider a couple of control instruments.

1. Legislative action by the government would involve a prohibition of waste disposal (landfilling or incineration), it therefore is a typical example of direct regulation. A disposal prohibition for a number of wastes (including paper & board) is effective in the Netherlands these days.
2. A levy per produced or purchased product would be an example of indirect regulation and could be used to enforce the supply and demand curves of the various actors to return the same, environmentally, optimal level of production. However, hereto the costs to the environment need to be internalised, which is a very topical but much disputed enterprise (Tietenberg [43]). More important, it would involve a non-uniform taxation policy which conflicts with the principles of taxation (Paulus [36]).
3. One can also assume the government setting the price actors might receive for supplying their wastes for incineration - again an indirect regulating instrument. Normally this price would be negative for the collection and incineration of waste is a service to those who need to dispose of their wastes. For households this negative price is analogous to the municipal taxes for waste collection making it assumable that the government has some influence on this price.

Since product levies are not encountered in the Dutch paper industry they will not be included in the model.

A Selfregulation Stimulating Government

Selfregulation and ICM have been main paradigms of the Dutch national environmental policy for a couple of years now. Co-operation between the members of a product-chain (ICM, Wolters [50]), is believed to be a tremendous opportunity for attaining sustainable production methods. The concurrent development of procedures to have supply and demand correspond better throughout the product-chain (in the Operations Research area): Supply Chain Management (SCM), and of Life Cycle Analysis (in the Sustainable Development field) leaves possibilities that should not be missed (Bloemhof [4]). The government's main task in ICM is not to regulate but to create conditions that foster the emergence of selfregulation. It involves influencing attitudes and activities regarding the environmental threats or goals, bringing parties - the members of a product-chain - together for discussions, and distributing expertise in ICM through investigation of best-practices in selfregulation.

3.6.2 Modelling Regulative Policy Instruments

Two regulative instruments will be discussed: legislation and price establishment.

Legislation

When modelling a product-chain the government's legislative influences manifest themselves through restrictions in the material flows. The disposal prohibition of several wastes, enforced by the Dutch government, bounds the mass-flow fractions. Referring to equation 3.15 a typical actor decision now is modelled by restricting the actor to dispose no more than a maximimum fraction (f_W^{max}) of its total waste flow.

$$f = f_W^{max} \tilde{\varepsilon}(p_D - p_W, c_d) \tag{3.16}$$

Price Establishment

Reconsidering equation 3.16 a price establishing policy measure means the government can decide on the value of p_D. In doing so it will influence the decisions of the actors in the chain.

3.6.3 Modelling Selfregulation Simulating Policies

As was mentioned previously the government's main task in a selfregulation stimulating policy is to create conditions that foster selfregulation in a certain industrial sector. However, the creation of conditions is difficult to capture in mathematical equations and is therefore not modelled. What can be done is the modelling of an industrial sector operating under some kind of selfregulating regime. The Removal Fund, an element of the Paper Fibre Covenant, that is supposed to take some control over the Dutch paper industry these days, is modelled and evaluated.

Chapter 4

The Paper Product-Chain

The previous chapter dealt with the development of a modelling methodology as general as possible. Here it is tried to apply the methodology in deriving a product-chain model of the Dutch paper industry. Section 4.1 will treat the current paper chain as it is, or more appropriate, was, before the effectuation of the Removal System. Section 4.2 goes into the government acting as a dynamic optimal controller for the industrial sector and what its control objective should be. Finally, section 4.3 will discuss the Removal Fund model.

4.1 The Paper Chain Model

Discussions with the waste paper industry have led to the development of a flowchart of the paper sector as it is; ignoring the changes that might be imposed by the effectuation of the Paper Fibre Covenant. Figure 4.1 shows the flow of paper, board and their waste as it currently is encountered in the Dutch paper chain: The Paper Industry either buys Pulp or sorted Wastepaper (or a combination of both) at the respective markets. Subsequently, the Paper & Board Industry supplies the crude paper it has produced to the Paper & Board Market (Market 2 in figure 4.1). The Paper & Board Market also experiences supply from outside the chain: foreign suppliers. Some of the bulk paper is bought by the Paper & Board Product Industry, converting the crude paper and board into products of paper and board (printed paper, board boxes for packaging, etcetera). This group of 'converter companies' is considered to belong to the group of 'first users or first recipients' of paper and board which is important for the levying of a removal contribution in the 'Removal System' under the Paper Fibre Covenant. Currently, wastes from the OSSC-sector (Offices, Shops, Services & Companies) are supposed to be transferred to the Wastepaper Market. However, due to a large and entangled network of wastepaper collection done by associations, some of the 'company-wastepaper' is not transferred directly to the wastepaper market. Household wastes are removed by the municipality services completely. Both flows eventually form a supply to the Wastepaper Market where the waste paper factory buys its resources. Depending on the price it might receive for its sorted and processed wastepaper it will either supply sorted waste paper to the market or decide to offer it for incineration.

4.1.1 State, Input, Output & Auxiliary Vectors

The dynamic variables involved in the presented model are included in the system's state vector

$$\underline{x} = [p_1\ p_2\ p_4\ p_5\ P_1\ P_2\ W_2\ W_3\ W_4\ P_5]^T \tag{4.1}$$

With p_j being the respective market prices and P_j and W_j the product and waste stock of actor j. The elements of the input vector $\underline{u}$, the government's influences, have been discussed in the previous chapter. Note that since paper waste-flows are considered here the disposal price p_D now becomes an incineration price p_I.

$$\underline{u} = [p_I \; f_{W2}^{max} \; f_{W3}^{max} \; f_{P5}^{max}]^T \tag{4.2}$$

The control efforts are bounded by

$$\begin{bmatrix} -1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \leq \underline{u} \leq \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \tag{4.3}$$

The uncontrolled input consists of foreign supply and demand to various markets. The subscripts refer to external supply and demand to the respective market number.

$$\begin{aligned} \underline{v} &= [\underline{v}_1{}^T \; \underline{v}_4{}^T \; \underline{v}_5{}^T]^T \\ &= [s_{e1} \; d_{e1} \; s_{e4} \; d_{e4} \; s_{e5} \; d_{e5}]^T \end{aligned} \tag{4.4}$$

The auxiliary vector $\underline{m}$ consists of the total supply, demand, and trade at each market

$$\begin{aligned} \underline{m} &= [\underline{m}_1 \; \underline{m}_2 \ldots \underline{m}_5]^T \\ &= [S_1 \; D_1 \; T_1 \; S_2 \; D_2 \; T_2 \ldots S_5 \; D_5 \; T_5]^T \end{aligned} \tag{4.5}$$

Vector $\underline{X}$ includes the optimal production rates when the particular actor is a company and the deployment of products when end use is considered.

$$\underline{X} = [X_1 \; X_2 \ldots X_5]^T \tag{4.6}$$

The mass-flow fractions vector $\underline{f}$ returns the actors' choices for a particular resource or for where to supply its wastes.

$$\underline{f} = [f_{R1} \; f_{W2} \; f_{W3} \; f_{W4} \; f_{P5}]^T \tag{4.7}$$

The output vector to be controlled, $\underline{z} = \zeta(\underline{x}, \underline{m}, \underline{f})$, is comprised of the recycled paper flow, the reused paper paper flow and the recovered flow. The Dutch paper industry reserves the term recycling for *paper & board* from wastepaper exclusively, here it is assumed that all sorted wastepaper, sold on the respective market (5), indeed will be a resource for paper or board. Recovered wastepaper is all that is collected (flows to the Market for Refuse Collection Services, 4). Reused wastepaper is that part of T_4 that is purchased by the Wastepaper Industry (Actor 5).

$$\underline{z} = \begin{bmatrix} \frac{T_5}{S_5}(1 - f_{P5})\varepsilon_{P5} P_5 \\ \frac{T_4}{D_4}\frac{1}{\pi_{R4}} X_5 \\ T_4 \end{bmatrix} \tag{4.8}$$

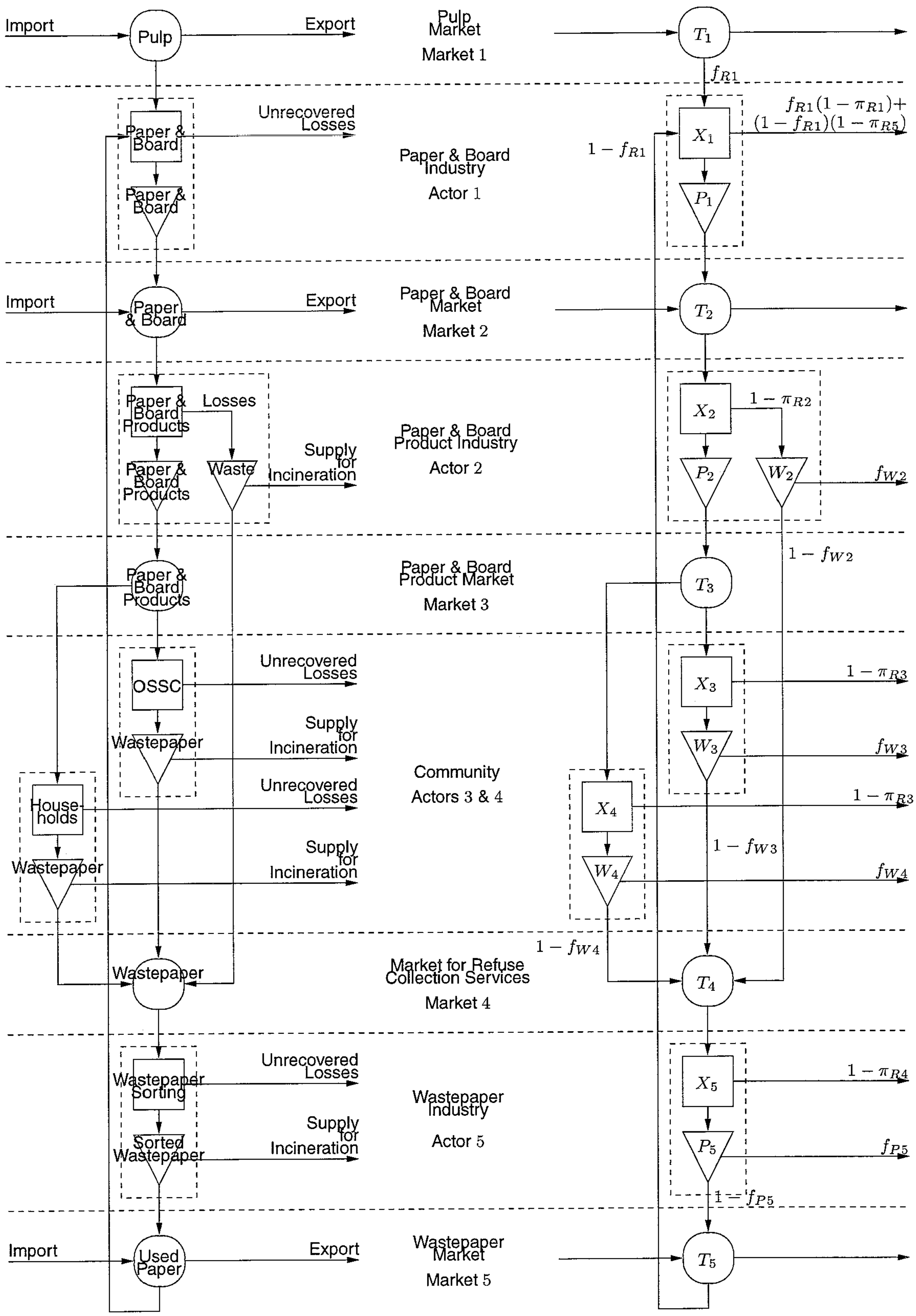


Figure 4.1: *Flowchart of the Paper Chain*

Although it is objected to control a recycling-ratio (α) it is quite difficult to establish the right weighting for a ratio ($0 \leqq \alpha \lessapprox 1$) in comparison to the trade flows of $\underline{m}$ - as is done in the optimisation objective, equation 4.11. It is therefore decided to optimise the recycled flow (z_1). The mentioned ratios α (recycling), β (reuse) and ρ (recovery) then are

$$\begin{bmatrix}\alpha\\ \beta\\ \rho\end{bmatrix} = \frac{1}{\frac{T_3}{D_3}\frac{1}{\pi_{R2}}X_2}\underline{z} \tag{4.9}$$

A measured output vector ($\underline{y} = \gamma(\underline{x})$) containing market prices, is defined also. It will be used for comparisons with data from the actual paper chain and in model parameter identification.

$$\underline{y} = [p_1\ p_2\ p_5] \tag{4.10}$$

4.1.2 Model Parameters

A number of model parameters is established from the *Environmental Action Plan Paper & Board*-report (Stichting-IKP [41]). Losses at various points in the paper industry determine the productivity of the specific resources (table 4.1). The products and waste distribution efficiencies (ε_{Pj}, ε_{Wj}) are set to .99 [−] - it is assumed that virtually all stock can be supplied.

Productivities		
π_{R1}	.99 [−]	Pulp is known to have little losses
π_{R2}	.88 [−]	Quite some paper or board is lost in production (nearly all is recovered)
π_{R3}	.85 [−]	Long-lasting paper use is 15%
π_{R4}	.96 [−]	Recovery losses are about 4%
π_{R5}	.90 [−]	Filling and fibre losses are estimated at 10%

Table 4.1: *Productivities* (Stichting-IKP [41])

Wastepaper & Pulp Shares in Paper		
Paper	Wastepaper	Pulp
Corrugated Board	99%	1%
Massive & Folded Board	85%	15%
Packaging Paper	75%	25%
Sanitary Paper	70%	30%
Newspaper Paper	70%	30%
Print & Writing Paper	2%	98%

Table 4.2: *Shares in Paper* (Castro [10])

Using the table above the minimum and maximum fraction (f_{R1}^{min} and f_{R1}^{max}) of pulp needed for the production of paper and board can be established (Castro [10]). Taking into consideration the weight percentage of each product in the total paper & board flow the fractions are estimated at $f_{R1}^{min} = .2$ [−] and $f_{R1}^{max} = 1$ [−]. The remaining model parameters, the market sensitivities k_j and the proportional and constant costs of the modelled firms (PC_j, CC_j) are estimated in section 5.1.

4.1.3 The Paper Product-Chain Block Diagram

The product-chain model can be classified as meso-economic: describing an industrial sector. It consists of industries, in each of the product's life phases, separated by markets (figure 4.1). As is encountered more often in meso-economic analysis it is assumed that all companies in an industrial sector can be modelled by only one, aggregated, company (Ng [33]). Because of the complexity and nonlinearity of the economic relations involved it has shown infeasible to derive a set of differential equations of a confined number of variables. Therefore a couple of auxiliary functions are introduced. The endogenous output vector $\underline{m} = \mu(\underline{x}, \underline{v}, \underline{X}, \underline{f})$ consists of the market response variables: total supply, demand and trade at the various markets; as is explained in section 3.3. Each actor receives its optimal produced or purchased quantity from an auxiliary function $\underline{X} = X(\underline{x}, \underline{u}, \underline{f})$ that calculates the optimal production rates as is explained in section 3.4; the function $\underline{f} = \varphi(\underline{x}, \underline{u})$ returns the optimal mass-flow fractions based on market prices. Figure 4.2 explains that the system function ($\dot{\underline{x}} = \chi(\underline{x}, \underline{m}, \underline{X}, \underline{f})$) can be written as a function having $\underline{x}$, $\underline{u}$, and $\underline{v}$ as its arguments. Figure 4.3 shows the topology of the controlled chain.

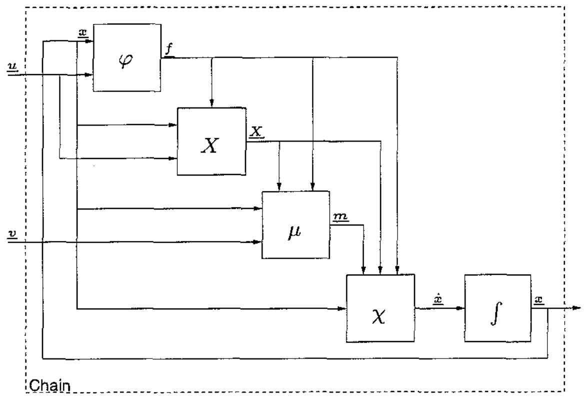


Figure 4.2: *System Topology*

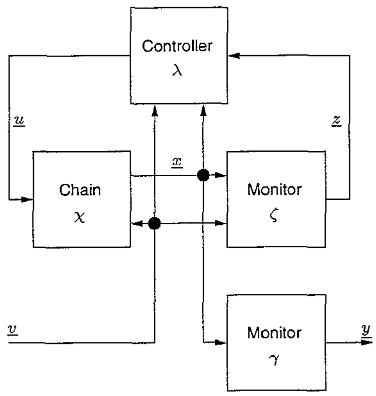


Figure 4.3: *Controlled Chain*

4.2 Dynamic Optimal Control

For pursuing the objective of a sustainable society it is required to balance economy and ecology (WCED [49]). The national government controlling the paper industry in a sustainable manner will have to consider both aspects in its control objective.

4.2.1 The Chain Control Objective

A straightforward objective function for the government would be the trade in Paper & Board Products (T_3, figure 4.1) as a measure for the state of the economy combined with the recycled wastepaper flow from the Wastepaper Industry (5) as a measure for ecologically responsible behaviour (equation 4.8). Producing sustainably, in the correct sense, would require both the trade and the wastepaper flow to be maximised. Note that for a thorough analysis of the product-chain the ecological consequences of the supplying industries should be considered too, as is advocated by the LCA (Wolters [50]) and Boustead [8] (figure 4.4). When including all the consequences of production and consumption (depletion of resources and disposal of wastes) in a single objective function it is required to establish the relative impact of those consequences on environment in order to establish how they should be weighted in relation to each other. If the production of a *ktonne* of paper from wastepaper involved a substantially larger amount of CO_2 to be emitted compared to producing that same *ktonne* of paper from pulp it would have to be weighted in the objective function. Establishing sustainable levels of extraction for particular resources is a field of research in itself (Van Heijningen [21], see also figure 4.5) and is therefore omitted in this study.

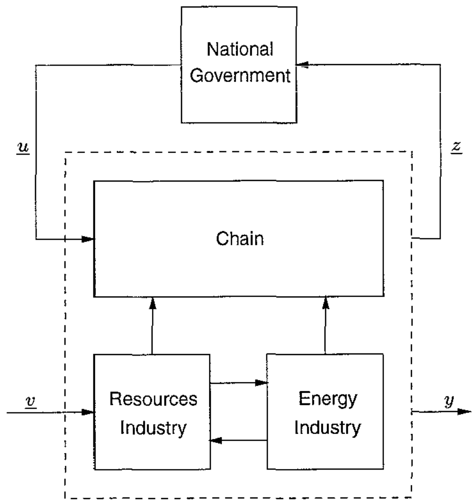


Figure 4.4: *Chain including Suppliers* (Boustead [8])

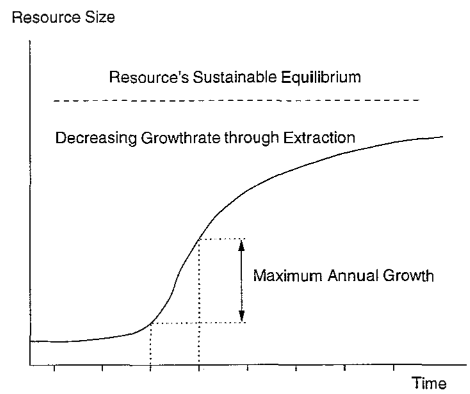


Figure 4.5: *Growthcurve Biotic System* (Heijningen [21])

4.2.2 Applied Optimisation

In addition, when assessing the government's control objective, it can be stated that controlling a society requires a gradual change of policy. Citizens and businesses alike need to be given some confidence that today's legislation will govern tomorrow as well. It is necessary for them to optimise their activity under the legislative conditions. A minimum policy change is attained by incorporating weightmatrix Γ^u in the controller's objective. Weightmatrix Γ^m is large when the government favours economic growth. - The market response vector $\underline{m}$ contains trade at various markets (T_j) which was proposed as a measure for the the economic situation. - Likewise Γ^z weights the recovery and reuse of materials, a government favouring environmental issues would increase this weightmatrix. (The weightmatrices all are row-matrices.) The controller's objective function then becomes

$$J(t) = \Gamma^m \underline{m}(t) + \Gamma^z \underline{z}(t) + \Gamma^u \Delta \underline{u}(t) \tag{4.11}$$

A linear criterion is proposed since no predefined reference value or trajectory is available making it impossible to define a quadratic criterion. The *Environmental Action Plan Paper & Board* does state recovering 85% of the recoverable paper (which again is 85% of all paper use) is one of its objectives. The objective implies a recovery ratio of $\beta = .85 \cdot .85 = .72$ which could be considered as a setpoint for the paper chain system. However, it is not known at all whether this value is an optimum or a mere infringed target that could just as well be too restrictive. It therefore is decided to implement a linear criterion in the system's dynamic optimal controller and see what optimal recycling- and recovery-ratios can be attained. Negative entries in the weightmatrices cause the corresponding vector values to be optimised - the objective function is minimised. Due to the summation of the positively and negatively weighted vectors entries of these vectors might balance one another. This does not have to be a problem however since a particular government can decided that a certain sudden policy change is worth the expected environmental benefits.

4.3 The Paper Fibre Covenant Model

4.3.1 Legislation

Integral Chain Management has been a major aspect of the Dutch government's environmental policy; it was introduced as a main focal point in the National Environmental Policy Plan (VROM [32]). As a consequence the nationally binding Packaging Covenant I has been effective as of 1991 for the whole of the Dutch packaging industry. By signing the covenant all of the chain members agreed to put effort into recycling, reuse and prevention of packaging wastes. The recently effectuated Government Ruling Packaging & Packaging-wastes transforms the European Guideline 94/63/EC of December 1994 into national law and, in fact, intensifies the current policy. The ruling explicitly mentions the possibility for a Packaging Covenant II. In reaction, the Dutch paper and board industry, the graphic industry, the newspaper and magazine publishers, together with the national and local authorities have been studying the possibility of a Paper Fibre Covenant as of 1995. The Paper Fibre Covenant completely complies with the new ruling and would function as an executive covenant with the framework of a possible Packaging Covenant II. The two main objectives of the covenant, as it is stated in the *Environmental Action Plan Paper & Board* (Stichting-IKP [41]), are an increase in the wastepaper collection at households and a secure and more tranquil flow of material through the paper chain. (In the past, from time to time, this flow has not been tranquil at all.) The Paper Fibre Covenant has recently been approved by the various Dutch national authorities and is now under scrutiny from the European Commission (Stichting-IKP [41]).

4.3.2 The Paper Fibre Covenant

The Removal System

The discharge of wastepaper & board into the environment, in any form, has been prohibited since recently, which has been another incentive for the Paper Fibre Covenant. The nationally binding Agreement Removal Contribution Paper & Board, which is a part of the covenant, will install a system of guaranteed supply and purchase among the chain's actors. The so called 'Removal System' will only be applied in extraordinary situations - a genuine market situation is supposed to exist between the actors as long as possible. In extraordinary situations (scarcity or surplus) a supply and purchase guarantee between the municipal and the waste paper factory and between the waste paper factory and the paper factory will be effective. This trade will still be according to market prices however. In case of a surplus the Surplus Management will buy waste paper from the waste paper factory and stock it, sell on the paper market, or have it incinerated - it is the only actor allowed to do so.

The Removal Fund

When the waste paper prices soar a situation can emerge in which the waste paper factory cannot generate enough money from trading its processed waste paper. In such cases it will request for a removal payment by the municipal to compensate for its costs, the removal system will then be active, meaning that the municipality can receive a compensation for the payment to the waste paper industry from this Removal Fund. During the Removal Fund paying the allowances to the municipalites the fund is replenished by the group of 'first users'. It would be of interest to know whether indeed this removal system is robust to external disturbances: mainly price fluctuations due to international trade. In order to analyse the flow of money and goods through the chain it is transformed into a control system using the actor and market block that were introduced in the previous sections.

4.3.3 The Covenant Model

It needs to be realised that not all aspects of the ICM-controlled chain that are aimed by the Paper Fibre Covenant can be evaluated. The objected increase in household wastepaper collection for instance is not controllable by financial-economic factors alone but will involve many social and psychological aspects as well. In this study the households' decisions are modelled by a simple comparison of the refuse collection service duty and the collected wastepaper price. The model that is derived will predominantly describe the Removal Fund of the Paper Fibre Covenant.

Adapting the Chain Model

Under the Removal Fund the dynamic optimal controller (the government) is no longer applied to the system. The control law is adapted to the guidelines that were agreed upon in the Paper Fibre Covenant (Stichting-IKP [41]). The Removal Fund secures the recovery of Household (Actor 4, figure 4.1) wastepaper by forfeiting the municipalities' payments to the Wastepaper Industry (Actor 5) since it is anticipated that the municipalities' eager for collecting wastepaper might drop in case of the wastepaper price at the collection market (Market 4) becoming low or negative. Such a situation would endanger a secured material flow through the paper industry. The Removal Fund (C_F) is replenished by a levy (l_2) from the 'first recipient' or 'first user' of paper (Actor 2) per *ktonne* of paper it processes (equation 4.12). The presented agreement is modelled somewhat differently but will return equal results: The Removal Fund pays an allowance to the Wastepaper Industry (a_5) influencing its production decision while receiving (a possibly negative) price (p_4) from the municipalities or Households (Actor 4).

$$\dot{C}_F = l_2 \frac{T_3}{D_3} \frac{1}{\pi_{R2}} X_2 - a_5 \frac{T_4}{S_4} \varepsilon_{W4} W_4 \tag{4.12}$$

The Wastepaper Industry's production decision then becomes

$$X_5 = \left(\frac{1}{CC_5} \left((1 - f_{P5}) p_5 + \frac{W_4}{W_2 + W_3 + W_4} a_5 - \frac{1}{\pi_{R4}} p_4 - PC_5 \right) \right)^{\frac{1}{3}} \varepsilon \left((1 - f_{P5}) p_5 + \frac{W_4}{W_2 + W_3 + W_4} a_5 - \frac{1}{\pi_{R4}} p_4 - PC_5 \right) \tag{4.13}$$

Removal Fund Control Law

Under the Removal Fund the input vector becomes $\underline{u} = [l_2 \; a_5]^T$. From the preceding paragraphs it can be concluded that the Removal Fund control algorithm is

$$\underline{u} = \begin{cases} \begin{bmatrix} .013\ [Mf/ktonne] \\ p_S - c_m p_5 \end{bmatrix} & if\ p_5 < p_S \\ \\ \begin{bmatrix} 0 \\ 0 \end{bmatrix} & if\ p_5 \geq p_S \end{cases} \tag{4.14}$$

with p_S being the standard price for collecting and processing of wastepaper. The 'matrix' constant (c_m) defines the multiplication factor for the market price based on the quality of the wastepaper flow. On January 1st, 1997, the Removal Fund Board has established the basic price for wastepaper to be .055 $[Mf/ktonne]$ plus .03 $[Mf/ktonne]$ for sorting. Assuming a $50/50$ coloured/de-inking flow of paper in the chain, as is done by the Stichting-IKP [41] as well, the standard price is $p_S = .5 \cdot .055 + .5 \cdot (.055 + .03) = .07\ [Mf/ktonne]$. Under that same condition the matrix constant (c_m), weighting the market price, is $c_m = \frac{1}{2}\ [-]$. The removal levy value $l_2 = .013\ [Mf/ktonne]$ is based on a $\frac{1}{3}$ household and $\frac{2}{3}$ OSSC wasteflow under the "average" scenario as described in the *Environmental Action Plan Paper & Board* from the Stichting-IKP ([41]).

Chapter 5

Identification, Analysis & Controller Design

From a System & Control Engineering point of view a rather hard to handle nonlinear model emerges from the merged economic theories. In retrospect it seems by large this is due to the fundaments of the economic theory not being developed further and in an unambiguous way as they were in physics - it seems the economic sciences cannot yet oversee the field as the physical sciences can. This does not necessarily have to come as a surprise since in comparison with physics, in economics "...*we* are the molecules..." as is stated by English [14].

5.1 Identification

Besides the parameters that were established first hand in section 4.1 a number of parameters remain to be determined, two methods are applied to attain their values. Due to the little amount of data (time-series) available, a number of publications (Stichting-IKP [41] & Blaauwendraat [3]) were used to establish them manually. Next some data supplied by the Dutch Central Bureau for Statistics (CBS) together with a guiding publication ([3]) is used to identify the remaining system parameters ($\underline{\theta}$, equation 5.1). Available for estimation are average annual market prices of three products (p_1, p_2 & p_5) for eight years together with the average foreign and domestic sales and purchases each year. It is assumed the sales and purchases give a reasonable indication of supply and demand and that the system parameters are constant over the identification interval ($\dot{\underline{\hat{\theta}}} = \underline{0}$).

$$\underline{\theta} = [k_1\ k_2\ k_4\ k_5\ PC_1\ CC_1\ PC_5\ CC_5]^T \tag{5.1}$$

A numerical nonlinear optimisation routine as mentioned by Veldpaus [46] is used for minimising a quadratic criterion

$$J = \sum_{j=1}^{8} (\underline{\bar{y}}_j - \underline{\hat{\bar{y}}}_j)^T (\underline{\bar{y}}_j - \underline{\hat{\bar{y}}}_j) \tag{5.2}$$

with

$$\underline{\hat{\bar{y}}}_j = \gamma(\underline{\hat{\bar{x}}}_j) \tag{5.3}$$

and $\underline{\hat{\bar{x}}}_j$, being the average system state over a year, and $\underline{\hat{\dot{x}}} = \chi(\underline{\hat{x}}, \underline{u}, \underline{v}, \underline{\hat{\theta}})$. All measurements are considered of equal importance therefore no weighting is applied. Thus, the values of $\underline{\theta}$ are attained for which the model output best agrees with the supplied data from the actual Dutch paper chain. The estimations returned rather remarkable results.

Estimated Parameters

	Manual	Routine
k_1 $[Mf/ktonne \cdot year]$	$1.0 \cdot 10^{-3}$	$1.3 \cdot 10^{-6}$
k_2 $[Mf/ktonne \cdot year]$	$2.0 \cdot 10^{-4}$	$8.2 \cdot 10^{-9}$
k_4 $[Mf/ktonne \cdot year]$	$1.0 \cdot 10^{-4}$	$1.2 \cdot 10^{-6}$
k_5 $[Mf/ktonne \cdot year]$	$4.0 \cdot 10^{-3}$	$.98 \cdot 10^{-6}$
PC_1 $[Mf/ktonne]$	$1.0 \cdot 10^{-3}$	$.91 \cdot 10^{-3}$
CC_1 $[Mf]$	$2.4 \cdot 10^{-10}$	$1.0 \cdot 10^{-6}$
PC_5 $[Mf/ktonne]$	$1.0 \cdot 10^{-2}$	$1.1 \cdot 10^{-3}$
CC_5 $[Mf]$	$2.0 \cdot 10^{-11}$	$1.1 \cdot 10^{-6}$

Table 5.1: *Parameter Estimation, Manually & by a Routine*

According to the identification routine the Paper Market (2) is much less sensitive to surpluses in supply or demand than the other markets are. Together with the estimation procedure's standard deviation ($\sigma_{\hat{y}} = .15$ $[Mf/ktonne]$) being rather large, one needs to be quite skeptical about these results. Moreover, simulations showed the chain's behaviour with the manually determined parameters to expose some features that are known to occur in the actual paper chain as well. Although the values of these parameters are quite different from those determined by the estimation routine, the manually determined parameters are applied in simulation. Still, with the current parameter set, the model should be regarded as a trend analysis tool rather than a prediction model.

5.2 System Analysis

The persisting nonlinearities in the considered system obstruct an indepth analysis of the paper chain. Moreover, the theoretic approaches that are currently being developed for various types of nonlinear systems do not seem to apply to the considered system either. Due to the five switching actors' decisions ($\underline{f}$) the promising local state space models approach would have involved the introduction of 2^5 different local models. Most of the insights with respect to the system behaviour will therefore, as usually is the case with nonlinear systems (De Jager [24]), need to be gained from simulation trials. Some traditional methods of system analysis will be applied to the linearised system in each operating point. What is more, the system returns results which are in good accordance with intuition.

5.2.1 System Function

Reconsidering the system function (from section 4.1)

$$\underline{\dot{x}} = \chi(\underline{x}, \underline{m}, \underline{X}, \underline{f}) \tag{5.4}$$

and substituting the auxiliary functions in the system function, it is attained that

$$= \chi(\underline{x}, \mu(\underline{x}, \underline{v}, X(\underline{x}, \underline{u}, \varphi(\underline{x}, \underline{u})), \varphi(\underline{x}, \underline{u})), X(\underline{x}, \underline{u}, \varphi(\underline{x}, \underline{u})), \varphi(\underline{x}, \underline{u})) \tag{5.5}$$

as is shown in figure 4.2. Simplifying the above equation indeed proves that the system can be written as a function of the system state $\underline{x}$, the controlled input $\underline{u}$, and the uncontrolled (exogenous) input $\underline{v}$.

$$\dot{\underline{x}} = \chi(\underline{x}, \underline{u}, \underline{v}) \tag{5.6}$$

Note that strictly these function ($\chi(\underline{x}, \underline{m}, \underline{X}, \underline{f})$ and $\chi(\underline{x}, \underline{u}, \underline{v})$) cannot be the same since they have different arguments and therefore are of different structure.

5.2.2 Linearisation

Some traditional system analysis methods require the system matrices. Linearisation of the system around the current operating point ($\underline{x}_0$,$\underline{u}_0$,$\underline{v}_0$) returns these matrices. For small variations $\delta\underline{x}$, $\delta\underline{u}$ and $\delta\underline{v}$ around the current operating point, the system can be linearised, attaining

$$\delta\dot{\underline{x}} = A(\underline{x}_0, \underline{u}_0, \underline{v}_0)\delta\underline{x} + B(\underline{x}_0, \underline{u}_0, \underline{v}_0)\delta\underline{u} + F(\underline{x}_0, \underline{u}_0, \underline{v}_0)\delta\underline{v} \tag{5.7}$$

However, since the substitution of the auxiliary functions in the nonlinear system function and computing its derivatives would require quite some work it is tried to compute the systemmatrices differently.

$$A = \frac{d\chi}{d\underline{x}}|_{\underline{x}_0,\underline{u}_0,\underline{v}_0} \tag{5.8}$$

$$= \frac{\partial\chi}{\partial\underline{x}} + \frac{\partial\chi}{\partial\underline{m}}\left(\frac{\partial\mu}{\partial\underline{x}} + \frac{\partial\mu}{\partial\underline{X}}\left(\frac{\partial X}{\partial\underline{x}} + \frac{\partial X}{\partial\underline{f}}\frac{\partial\varphi}{\partial\underline{x}}\right) + \frac{\partial\mu}{\partial\underline{f}}\frac{\partial\varphi}{\partial\underline{x}}\right) + \frac{\partial\chi}{\partial\underline{X}}\left(\frac{\partial X}{\partial\underline{x}} + \frac{\partial X}{\partial\underline{f}}\frac{\partial\varphi}{\partial\underline{x}}\right) + \frac{\partial\chi}{\partial\underline{f}}\frac{\partial\varphi}{\partial\underline{x}} \tag{5.9}$$

Which can be rewritten into

$$A = \chi_{\underline{x}} + \chi_{\underline{m}}(\mu_{\underline{x}} + \mu_{\underline{X}}(X_{\underline{x}} + X_{\underline{f}}\varphi_{\underline{x}}) + \mu_{\underline{f}}\varphi_{\underline{x}}) + \chi_{\underline{X}}(X_{\underline{x}} + X_{\underline{f}}\varphi_{\underline{x}}) + \chi_{\underline{f}}\varphi_{\underline{x}} \tag{5.10}$$

likewise

$$B = \frac{d\chi}{d\underline{u}}|_{\underline{x}_0,\underline{u}_0,\underline{v}_0} \tag{5.11}$$

$$= \chi_{\underline{m}}(\mu_{\underline{X}}(X_{\underline{u}} + X_{\underline{f}}\varphi_{\underline{u}}) + \mu_{\underline{f}}\varphi_{\underline{u}}) + \chi_{\underline{X}}(X_{\underline{u}} + X_{\underline{f}}\varphi_{\underline{u}}) + \chi_{\underline{f}}\varphi_{\underline{u}}$$

and also

$$F = \frac{d\chi}{d\underline{v}}|_{\underline{x}_0,\underline{u}_0,\underline{v}_0} \tag{5.12}$$

$$= \chi_{\underline{m}}\mu_{\underline{v}}$$

Applying the linearised system in discrete simulation indeed returns the exact same results as do simulations with the nonlinear system function.

5.2.3 Some Remarks Concerning Stability

Although no conclusive analysis concerning the system's stability can be given, it is possible to state some useful remarks. Under the assumption that the uncontrolled inputs are bounded it is plausible that the system state is bounded since the production rates are bounded as well. Due to the decreasing incrementation of the production rates as a function of product prices it is unlikely for the production rates to rise unboundedly. What is more, increasing production rates boost supply which in turn causes prices and thus production to drop, a natural damping exhibits itself here. The lower bounds on the production rates are set to 0 (see equation 3.13). However, no restrictions exist on prices to rise or fall maintaining their relative differences. More important, due to the storage of products a lead-time exists between the actual production and market supply, leaving the possibility for the infamous hog-cycle to emerge. (The hog-cycle is principly no different than the, among control engineers well-known, example of controlling a system with dead-time). The market sensitivities (k_j), quite logically, have a major influence on the occurrence of a hog-cycle. The value of the market sensitivities quite possibly are related to the existence of additional merchants in between the Wastepaper Industry and the Paper & Board Industry. Those intervening merchants, having their own storage facilities, might dampen the oscillations in the wastepaper price. A large storage capacity of intermediate trade would then cause the market sensitivities to be low.

5.2.4 Controllability

The derived system matrices are used for a traditional investigation of the system's controllability. Hereto the controlled output equation $\underline{z} = \zeta(\underline{x}, \underline{m}, \underline{f})$ needs to be linearised too. Again, for small variations around the current operating point it can written that

$$\delta\underline{z} = C(\underline{x}_0, \underline{u}_0, \underline{v}_0)\delta\underline{x} + D(\underline{x}_0, \underline{u}_0, \underline{v}_0)\delta\underline{u} + G(\underline{x}_0, \underline{u}_0, \underline{v}_0)\delta\underline{v} \tag{5.13}$$

Since the recycled waste-flow (z_1, determining the recycling-ratio α) is of interest primarily, equation 5.13 is rewritten in

$$\delta\underline{z}_1 = \underline{c}^T\delta\underline{x} + \underline{d}^T\delta\underline{u} + \underline{g}^T\delta\underline{v} \tag{5.14}$$

The output controllability is attained by multiplying the state controllability matrix $P_{\underline{x}}$ by C (Rosenbrock [22]); likewise the recycled waste-flow controllability is determined by $\underline{c}^T P_{\underline{x}}$. Thus, only $\underline{c}^T$ needs to be derived.

$$\begin{aligned} \underline{c}^T &= \frac{d\zeta_1}{d\underline{x}}|_{\underline{x}_0,\underline{u}_0,\underline{v}_0} \\ &= \zeta_{1\underline{x}} + \zeta_{1\underline{m}}(\mu_{\underline{x}} + \mu_{\underline{X}}(X_{\underline{x}} + X_{\underline{f}}\varphi_{\underline{x}})) + \zeta_{1\underline{f}}\varphi_{\underline{x}} \end{aligned} \tag{5.15}$$

The system is controllable when the controllability matrix $P_{\underline{x}}$ has full rank, likewise the recycled waste-flow is controllable when

$$c_{z_1} = rank(\underline{c}^T P_{\underline{x}}) = 1 \tag{5.16}$$

The rank of the state controllability matrix is given by $c_x = rank(P_{\underline{x}})$. Using a symbolic manipulative software package it is tried but shown infeasible to derive an analytic relation for the controllability of α.

5.3 Controller Design

Taking the system analysis into consideration a controller algorithm computing the optimal government input to the paper product-chain is derived.

5.3.1 Dynamic Optimal Control

The system is controllable under certain conditions only (as is shown in simulation, chapter 6). It is therefore not possible to derive an optimal time path for the system-state and the controlled input for any, arbitrary, recycling-ratio (or recycled waste-flow) reference trajectory. The currently much applied modelbased nonlinear control algorithms like Model Predictive Control (MPC) or Receding Horizon Control (RHC), applying a quadratic optimization objective, cannot be used in this case. An optimisation algorithm maximising the recycled waste-flow, and thus the recycling-ratio, over the planning interval (H) is applied to calculate the optimal input $\underline{u}^*(t)$.

$$\min_{\underline{u}^*(t)} \int_t^{t+H} J(\tau) d\tau \tag{5.17}$$

with $J(t)$ being the objective function defined in equation 4.11 and the weightmatrices being

$$\begin{aligned} \Gamma^m &= [0\ 0\ 0 \ldots 0] \\ \Gamma^z &= [-1\ 0\ 0] \\ \Gamma^u &= [0\ 0\ 0\ 0] \end{aligned} \tag{5.18}$$

Combining this objective with a policy change minimising and, possibly, an economy optimising term (changing the 0 entries in Γ^m and Γ^u) is recommended for further studies. Only a limited interval (E) of the optimised input is enforced. Moreover, policy updates are allowed after a certain period (U) only - with $U \leq E \leq H$.

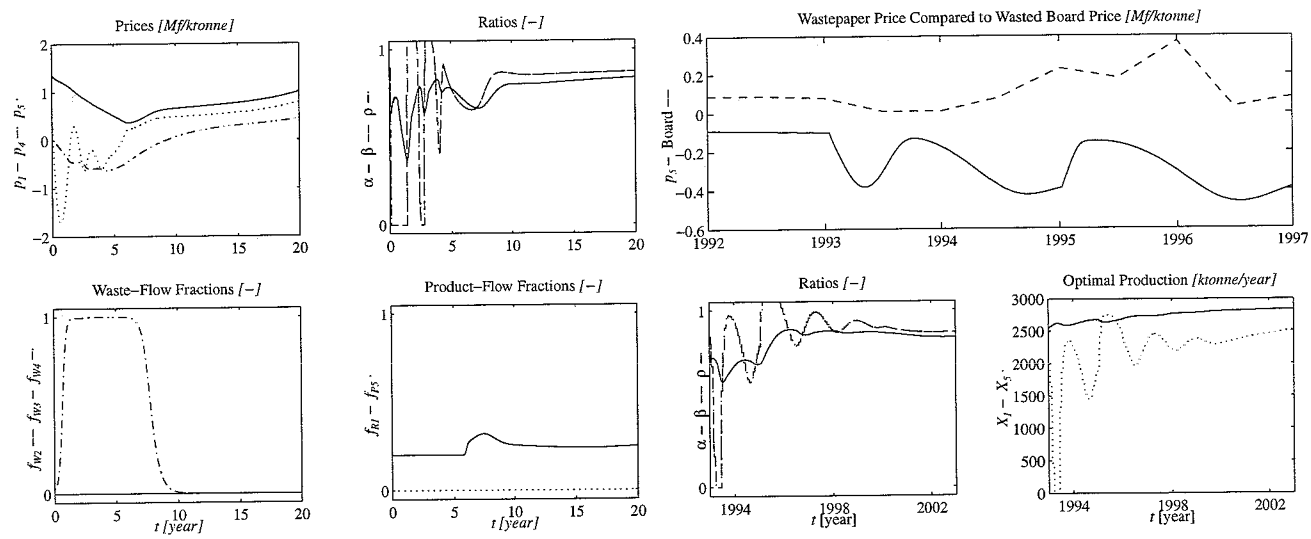
Chapter 6

Simulation & Interpretation

All simulation and identification routines are executed with discrete-time steps $T_s = \frac{1}{52}$ $[year]$, thus $T_s \approx 1$ $[week]$. Simulations are run in MATLAB versions 4.0 and 4.2c.

6.1 Comparative Simulations

An initial simulation is run to assess the system's uncontrolled behaviour. The plots in figure 6.1.a show a transient preceding a relatively steady state of constant recycling ratio and constant price differences. Note this is, strictly spoken, not a stable point in the state space since the prices are not constant but rise with constant difference.



(a) (b)

Figure 6.1: *The left four plots show the uncontrolled behaviour as it will function under disposal prohibition $f_{W2} = f_{W3} = 0$ [−]. The paper product price (p_2) is not shown. The right three plots compare the system's reaction to the actual situation that emerged from the institution of the* DSD

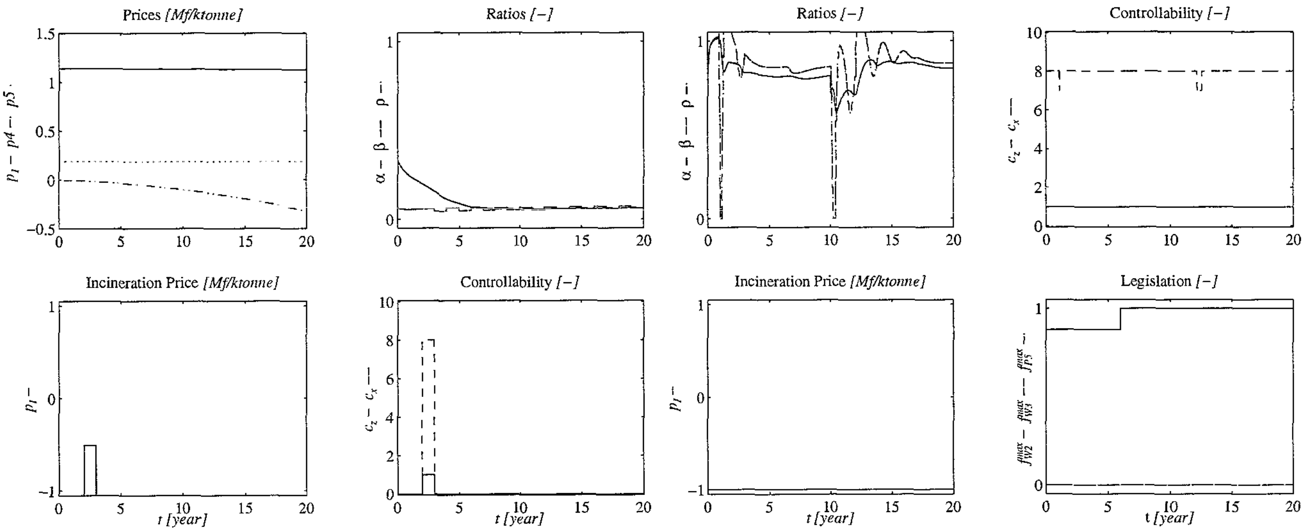
The time-serie's mean of the exogenous input ($\underline{v}$), supplied by the CBS, is taken to be the uncontrolled input vector. A reuse-ratio of $\rho = .87$ and a recycling-ratio of $\alpha = .84$ are attained quite easily - although it takes quite a long time (upper right plot, figure 6.1). The bottom left plot in figure 6.1.a shows household wastes remain to be recovered due to the price mechanism. Initially the wastepaper price, of wastepaper supplied *to* the Wastepaper Industry (p_4), is negative, causing the households to no longer supply their wastes to the Wastepaper Industry. As a consequence wastepaper supply diminishes causing the price to rise again and the municipalities, who are responsible for collecting the households' wastes, to redirect their supplies to the Wastepaper Industry. However, this process lasts about 10 years (from $t \approx 0$ until $t \approx 10$ $[year]$).

Duales System Deutschland

The plots in figure 6.1.b compare the model's response to an actual situation that occurred with the institution of the *Duales System Deutschland* (DSD) in 1993 (Boos [6]). The DSD established a system for centralised collection of household and industrial (OSSC) wastes enforcing considerable levies. As a consequence wastepaper markets in Germany's neighbouring countries faced surpluses leading to price oscillations. In the top plot the model's Wastepaper Price (p_5), which is an average of the price of all wasted paper & board, is compared to the development of the actual price of wasted board - the data was supplied by the Stichting-IKP. The model not returning the exact same results is not surprising since two different prices are compared - a better agreement would be reassuring with respect to the model's validity however. Nevertheless the trend of oscillating prices is returned by the model as well. The bottom right plot shows the modelled Wastepaper Industry to temporarily stop production (in the year 1993) as was encountered in the actual industry as well. The price insecurity has been one of the reasons for setting up the Removal System (section 4.3). The model asserts the oscillations to last until the year 2000 if no intervention takes place.

6.2 Intervention

Sections 4.2 & 5.3 explained what means of intervention (controlled input) is applied to the chain system. It is tried to use the same control variables an actual government might have and to model them as accurately as possible. A simulation trial is run with the parameters from the estimation routine (figure 6.2). The markets have become quite insensitive causing the prices to adapt quite slowly. The optimal production rate for the Wastepaper Industry (5) therefore remains low causing the recycling-ratio to soar. Note no transient oscillations are encountered now, as is predicted in section 5.2. The bounds on the controlled input $u_1 = p_I$ are set less restrictive; the extremes are not shown in the plot since they are not of interest. The bottom left and right plots in figure 6.2.a show the system is uncontrollable as long as p_I is much smaller than p_4. (When incineration is no alternative for supplying the Wastepaper Industry.) The recycled flow controllability (c_z) equals 1 only for the temporary rise of the incineration price (p_I). This phenomenon is understandable since the actors that need to dispose of their wastes will only consider incineration in case of the price they might receive (p_I) being competitive with the price for wastes supplied to the Wastepaper Industry (p_4). In that case, however, they might be restricted by a government prohibiting incineration, therefore, in that case only, the government gains some control over the recycling-ratio (α). Since the ratio is controllable in certain situations only it is uncontrollable in general.



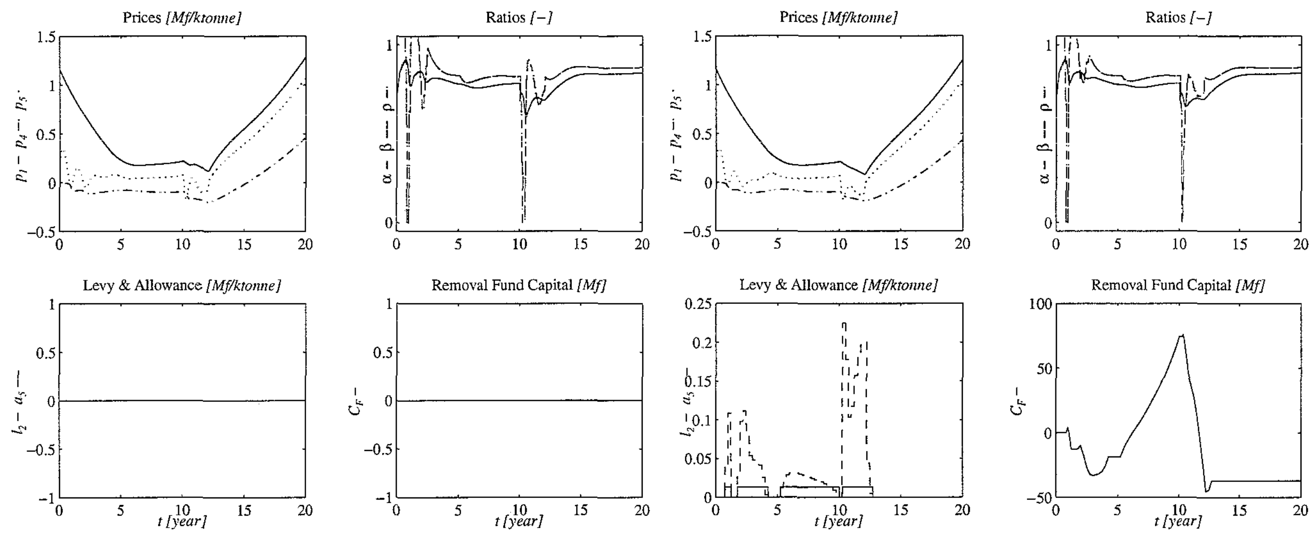
(a) (b)

Figure 6.2: *The left four plots show the system's conditional controllability modelled with the parameters from the estimation routine. Here* $n_U = 52$ $[-]$ *meaning that* $U = 52 \cdot T_s = 52 \cdot \frac{1}{52} = 1$ $[year]$, *with* n_U *being the number of simulation periods per update interval. Likewise,* $E = H = 2$ $[year]$, *thus* $n_E = n_H = 104$ $[-]$. *The right four plots show the system's optimal controlled input; here* $U = E = H = 2$ $[year]$

It is of interest to know whether the control objectives can be attained despite the recycled waste-flow (and its ratio) being controllable under certain conditions only. Can a government taking the optimal policy decisions control the recycling, reuse and recovery of wastes? Figure 6.1.a shows the chain reaches a quite considerable level of recycling without any controlled input. However, the wastepaper surpluses caused by the DSD did upset the paper chain, what is more, it remains rather uneasy until this day. The controlling government should therefore intervene if oscillations cause the chain to drift from its recycling objective too much. The trials in figure 6.2.b, however, show the controller seems not capable of doing so. Understandably the optimal controller sets the incineration price (p_I) to its minimum bound making incineration unattractive and hoping recycling will gain interest. The controller's intervention is comparable to the DSD that was discussed in the previous section. The simulation results show the government acting as a dynamic optimal controller, having the disposition over the modelled instruments, is not appropriate for controlling the modelled Dutch paper industries.

6.3 Simulating the Removal Fund

Besides simulating a policy optimising government some simulations are performed on a model of the Removal System that currently is being established in the Dutch Paper Industry under the Paper Fibre Covenant. The Fund is exposed to conditions that are supposed to be imposed on the actual chain as well. As of 1996 the 'Prohibition Waste Disposal' is in effect aiming at minimising the disposal and incineration of wastes. The prohibition applies to all disposable wastes but cannot be enforced directly to households: their wastes are not monitored. This is situation is modelled by setting all but the waste-flow fraction for households (f_{W4}) to zero. Again a sudden wastepaper surplus is applied to the system at $t = 10$ $[year]$ to analyse its behaviour.



(a) (b)

Figure 6.3: *The left four plots show the chain's uncontrolled behaviour under the prohibition of incineration. The right four plots show the results of an intervening Removal Fund.*

The upper right plot of figure 6.3.b, which resulted from simulating the Removal Fund, shows the amplitude of the ratio's oscillations to be smaller than those in figure 6.3.a. It seems the Removal Fund does have some influence on the wastepaper recovery. Although the gains from the Removal Fund's intervention might seem relatively small, srutinising the ratio plots shows the Fund to decrease oscillations in the recovery-ratio (β) up to 10%. Which is quite considerable, particularly since the oscillations last for more than two years. Moreover, it is a whole lot of an improvement compared to the government's intervention. Note that the relatively small amount of money that is levied by the Fund in this simulation trial (see also section 4.3) is not enough to cover all costs - some cash-flow problems will be encountered also (bottom right plot of figure 6.3.b). However, simulations with the larger "worst-case scenario"-levy (not presented) show the Fund would gain money. Therefore it is assumed the Fund will eventually do what it is supposed to: levy enough money to cover the costs of allowances and its own costs of operation. Adaption of the Removal Fund's intervention allowances and levies is not modelled however.

Concluding Remark

Simulations on all systems adding the exogenous input vector's standard deviation. multiplied by a normal-distributed random signal, to the exogenous input itself - to simulate the uncertainty in supply and demand - showed the results to be more diffuse but not different essentially. For tutorial reasons the more diffuse results are not presented.

Chapter 7

Conclusions, Perspectives & Recommendations

7.1 Conclusions

Conclusions are drawn with respect to the developed modelling methodology and concerning the behavior of the Dutch paper product-chain.

7.1.1 The Modelling Methodology

The method for the modelling of product-chains as it is proposed in this report basically comes down to the application of mass balances to a material flowchart of the considered industrial sector. Its constitutive relations primarily are the market process and producers' and consumers' decisions (chapter 3).

- Judging from the intuitively reasonable results that were attained in simulation the modelling methodology presented in the beginning of this report is considered to be a promising approach to the modelling of a wide range of product-chains.
- Due to the application of economic theory, and the absence of an unambiguous method for the coupling of various micro-economic theories to form a meso-economic model, the derived models will be rather difficult to analyse from a control engineering perspective. Currently, the attained models are useful for simulation and interpretation of the simulation results, primarily.
- It is particularly difficult to establish the government's influences and how they should be modelled. Moreover, the only influences that seem to be fit for modelling are regulative policy instruments. Social or psychological instruments, which seems to be of major importance in environmental policies, are quite difficult to model mathematically.

It is believed that better simulation results will be returned if more data - time-series, preferably with monthly updates - would be available enabling a better identification of the system parameters.

7.1.2 The Dutch Paper Product-Chain

Government control as well as ICM, a self-control configuration, are applied to the dynamic product-chain model of the Dutch paper industries. The product-chain model consists of a Pulp Market, Paper

& Board Industry, Paper & Board Market, processes in all life-phases of a paper product, onto the Wastepaper Market (figure 4.1).

- Simulations show the paper chain system under government control to be uncontrollable. What is more, the government's control efforts are few and become saturated causing the government to have little influence on the system even though the recycled waste-flow *is* controllable at some instances. The government's indirect regulation policy instruments, which remain unmodelled, should be applied to enforce the ICM installed by the paper chain. Simulations show ICM is a reasonable alternative. An explanation might be the fact that a government cannot discriminate between companies. Taxation and legislation must be equal for all. For controlling the recycling-ratio, however, it might be very useful to only favor the Wastepaper Industry every now and then. In ICM it is tried to do so at the right moment. To add to this conclusion, it is anticipated that the mutual supply and purchase agreements between the members of the paper chain - which are a part of the unmodelled Removal System that is to function together with the Removal Fund - will secure a constant throughput even more.

- Initial simulations show the maximum recycling-ratio ($\alpha = .85$) to be attained, or approximated, quite easily. By large, this is due to the fact that the model only incorporates, economic actor decisions. In other words, simulations assert that if (pure) price mechanisms are introduced to the paper chain the recycling-ratio will rise. (In fact, this is no different than applying a 'polluter pays'-principle. Note the polluter now pays market prices however.

- Parameter identification showed the wastepaper markets to be significantly more sensitive to supply and demand than the other markets that were modelled which, in addition to unexpected surpluses in supply and demand, might be another explanation for the intranquillity of the wastepaper price.

It is quite remarkable of how little influence a, reasonable, government's direct regulation instruments are.

7.2 Perspectives

In general two main directions for future research can be assigned. Continuing the assertions done in this report: the development of product-chain models by applying materials balances to flowcharts of industrial sectors, and trying to apply more control engineering principles to analyse the model. Another promising, although insecure, direction might be the development of bondgraph theory applied to economic systems.

7.2.1 Materials Balances & Control Engineering

A structured approach to a product-chain in the 'materials balance method' would involve

1. draw a flowchart of the considered product's life-cycle
2. apply materials balances and model the resulting equations
3. model the constitutive relations: the companies' production decisions and the consumers' purchase decisions
4. substitute both mathematical constructs to arrive at a single model.

To gain more insights in the behaviour of product-chains either the outlined approach can be applied for the development of a new product-chain model or the paper chain model can be used. However, it might be sensible to simplify the companies' production decisions in the model used for further research. A linear- or root-function relating the difference in resource and product price to the production rate is proposed - ample of nonlinearities remain however. In spite of the conditional controllability it should be tried to derive an optimal development path for the reuse-ratio. With that reference trajectory a quadratic criterion can be defined persuading the recycling control problem into a more general Control Engineering format. Subsequently, various control strategies can be evaluated.

7.2.2 Bondgraph Method

Many scientists assert bondgraphs are a universal approach to the modelling of systems (Van den Bosch [7]) which is exactly - as is stated many times in this report - what seems to undeveloped in economic theory in comparison with physics. The shortcoming might remain unnoticed when modelling single markets or firms but manifests itself when trying to combine them. From a physics point of view it is rather strange economists distinguish between supply *and* demand rather than allowing either supply *or* demand to be positive *and* negative - in mechanics no 'pull' *or* 'push' force is known, just force. Generalised variables need to be defined comparable to physical systems (table 7.1).

Physical & Economical Phenomena

	Electrical	Mechanical	Hydraulic	Economic
effort e	voltage u	force F	pressure p	*demand D*
flow f	current i	velocity v	flow φ	value/cash-flow ...

Table 7.1: *Physics & Economy* (based on Van den Bosch [7])

What is more the bondgraph method deals with causality in a very neat manner. In the initial outline of a modelled system no causality is assigned yet. For electronic systems this helps in solving the question whether a current (i) is caused by a voltage (u) or if the voltage is caused by a current over a resistance (R). In economics a similar question arises when dealing with prices in relation to supply and demand, or rather: demand. Does a change in price cause consumers' demand for that product to change or is it a change in demand for a product that causes the price to change. The answer probably is: both - but which is more suitable for the perceived model. Although the application of bondgraph theory to economic systems can hardly be considered a main field of interest, some references can be made to articles by Brewer [9] and English [14].

7.3 Recommendations

Following from the conclusions and perspectives, quite logically, the following is recommended.

- Further develop the materials balance method in particular the establishment of an (optimal) reference trajectory for the recycled waste-flow (or its ratio) and define a quadratic criterion to be used as control objective. A more thorough identification of the system's parameters is recommended as well. In particular the incorporation of various decision constants (c_d) in the estimation algorithm is expected to improve the model's validity.

- Evaluate the opportunities of applying the bondgraph theory to economic systems. It is expected that systems of larger state-space, but more handsome systemmatrices, will emerge from it; possibly linear models can be derived.

- The development of a validated and generally accepted model requires more than just accidental discussions with the industry or government. It is therefore recommended to initiate more secure co-operation with partners in the modelled product-chain since their experiences are of value and their willingness to supply data is of crucial importance to parameter identification and model validation

Appendix A

Optimal Strategic Control of a Company

It is assumed that the companies in the chain take optimal planning decisions based on some kind of business philosophy. Although this optimal planning decision (strategic control) is not implemented in the presented model - only the operational control is applied - some suggestions for expansion of the model are outlined. In accordance with the systems approach a company can be divided in a plant- and a management-subsystem; with the management subsystem acting as a controller for the plant. A modelbased control algotrithm, optimising its input to the plant based on some internal model and a certain criterion, seems suitable for such a controller. The internal model then is required to return a valid prediction of the plant's behaviour onto a certain prediction horizon which is larger than the company's strategic control horizon (H_C) for which it has to compute the optimum. Blok [5] presents a quite promising approach using a reasonably validated method of maximum dividend over the planning period together with maximum company capital at the planning horizon ($t + H_C$) as its criteria. As is explained in section 3.4 the company's operational control is modelled by internalising the production decision for the coming production planning period (h). In both optimisations it is assumed that all that is supplied or demanded for indeed is sold or purchased.

A.1 A Company's Dynamics

State & Input Vector

Based on the model proposed by Blok [5] the company's state variables include the company's capital (C), the capital goods (K), and its product stock (P) of produced goods. The input to the company include the strategic control variables investments I and dividends N.

Capital Goods & Labour

Assuming the company applies its means of production efficiently - meaning that with the current set of input factors no higher rate of production can be attained - and in accordance with [35], equation 3.7 can be rearranged to

$$\left(\frac{L}{L_0}\right)^{\pi_L} = \left(\frac{K}{K_0}\right)^{\pi_K} \tag{A.1}$$

and thus

$$L = \left(\frac{K}{K_0}\right)^{\frac{\pi_K}{\pi_L}} L_0 \tag{A.2}$$

Over the strategic planning period capital is a dynamic variable while labour is assumed to be hired in relation to it.

State Dynamics

The dynamics of the company's own capital is defined by

$$\begin{aligned} \dot{C} = {} & (1-f)\left(rC + p_Q \frac{T_Q}{S_Q}\varepsilon_P P\right) - \\ & (1-f)\left((d+r)K - w\left(\frac{2}{3} + \frac{1}{3}\left(\frac{K_0}{K}\right)^{\frac{2\pi_K}{\pi_L}}\left(\frac{\frac{T_R}{D_R}X}{X_0}\right)^{\frac{2}{\pi_L}}\right) L - \left(\frac{p_R}{\pi_R} + PC\right)\frac{T_R}{D_R}X\right) - \\ & N \end{aligned} \tag{A.3}$$

the capital goods changes with depreciation d and investments

$$\dot{K} = -dK + I \tag{A.4}$$

and its product stock level by

$$\dot{P} = \frac{T_R}{D_R}\frac{1}{\pi_R}X - \frac{T_Q}{S_Q}\varepsilon_P P \tag{A.5}$$

A linear relation is assumed for the efficiency of the company's distribution involving ε_P, a measure for this efficiency.

A.2 Strategic Control

The management of the company plans ahead and tries to establish the optimal input to the plant. The control algorithm is comparable to the one that was presented in section 5.3.

A.2.1 The Optimisation Objective

Considering a company (C), the management is assumed to operate in a manner comparable to a modelbased controller, maximising an objective function

$$\max_{\underline{u}_C(t)} \int_t^{t+H_C} e^{-i\tau} N(\tau) d\tau + e^{-i(t+H_C)} C(t+H_C) \tag{A.6}$$

with $\underline{u}_C = [I \; N]^T$, the input to the plant. The controller optimises its input using an internal model of the plant $\dot{\underline{x}}_C = \chi_C(\underline{x}_C, \underline{u}_C)$. The internal model is of a smaller dimension than the actual plant model ($\underline{x}_C = [C \; K]^T$). Under the assumption that all projected sales are met, the product stock variable is no longer needed.

Appendix B

The Production Decision

Assuming an efficient Leontief technology, it is attained that

$$\bar{X} = X_0 \left(\frac{K}{K_0}\right)^{\pi_K} \tag{B.1}$$

Combining equation 3.9, the total costs (3.10), B.1, and the multiplication factor for labour costs, given a certain set of input factors (K, L), the total costs as a function of the required rate of production (X) then becomes (figure 3.8)

$$TC(X) = (d+r)K + w\left(\frac{2}{3} + \frac{1}{3}\left(\frac{K_0}{K}\right)^{\frac{2\pi_K}{\pi_L}} \left(\frac{X}{X_0}\right)^{\frac{2}{\pi_L}}\right) L + \left(\frac{p_R}{\pi_R} + PC\right) X$$

The profit maximizing rate of production (X) is attained by solving marginal costs equal marginal revenue $(MC = MR)$ for X

$$\frac{2}{3}\frac{w}{\pi_L}\left(\frac{K_0}{K}\right)^{\frac{2\pi_K}{\pi_L}} \left(\frac{1}{X_0}\right)^{\frac{2}{\pi_L}} X^{\frac{2-\pi_L}{\pi_L}} L + \frac{p_R}{\pi_R} + PC = p_Q \tag{B.2}$$

$$X = \left(\frac{p_Q - \frac{p_R}{\pi_R} - PC}{\frac{2}{3}\frac{w}{\pi_L}\left(\frac{K_0}{K}\right)^{\frac{2\pi_K}{\pi_L}}\left(\frac{1}{X_0}\right)^{\frac{2}{\pi_L}} L}\right)^{\frac{\pi_L}{2-\pi_L}} \tag{B.3}$$

Appendix C

The Heaviside Step Function

In the modelling process the Heaviside step function (ε) is applied for the omission of impossibilities (negative values of $\underline{X}$) and to be able to differentiate a minimum function ($a = \min\{b, c\}$). The step function is defined as

$$\varepsilon(x) = \begin{cases} 0 & \text{if } x < 0 \\ 1 & \text{if } x \geq 0 \end{cases} \tag{C.1}$$

and is the primitive of the Dirac delta function, which is defined as

$$\begin{aligned} \delta(x) &= 0 \quad \text{if } x = 0 \\ \int_{-\infty}^{\infty} \delta(x) &= 1 \end{aligned} \tag{C.2}$$

(Jeffrey [25]). Figure C.1 shows the Heaviside step function. The application in the production decision function is not explained further since it is quite trivial (equation 3.13); the other application deserves better attention however. The market trade function introduced in equation 3.4 involves a min-function. However, during the analysis of section 5.2 the system function χ is differentiated and so is the market-function (μ) including several min-functions. The min-function can be differentiated using the Heaviside function as follows

$$\begin{aligned} a &= \min\{b, c\} \\ &= b - (b - c)\varepsilon(b - c) \end{aligned} \tag{C.3}$$

and thus

$$\begin{aligned} \frac{\partial a}{\partial b} &= 1 - \varepsilon(b - c) - (b - c)\delta(b - c) \\ &= 1 - \varepsilon(b - c) \end{aligned} \tag{C.4}$$

likewise

$$\begin{aligned} \frac{\partial a}{\partial c} &= \varepsilon(b - c) + (b - c)\delta(b - c) \\ &= \varepsilon(b - c) \end{aligned} \tag{C.5}$$

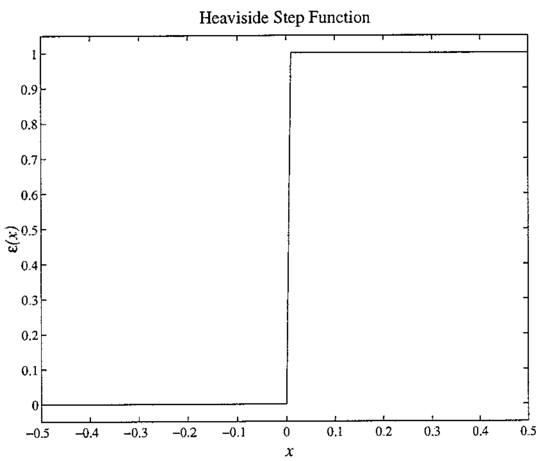


Figure C.1: *Heaviside Step Function*

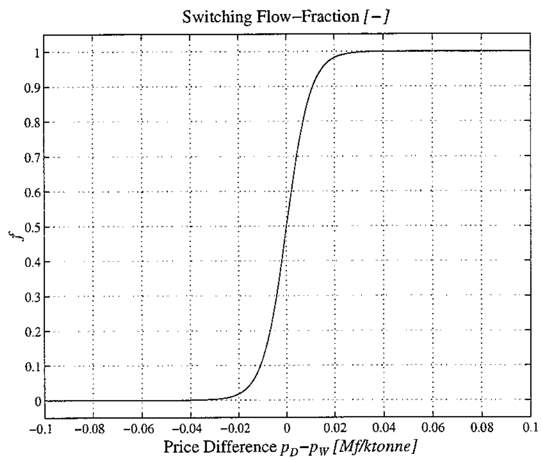


Figure C.2: *Decision Function*

An approximated or smoothed Heaviside ($\tilde{\varepsilon}$) function is applied when modelling the actor's decisions (equation 3.15). To smoothen the transition from the one to the other result of the decision a tanh function is used (figure C.2)

$$\tilde{\varepsilon}(x, c_d) = \frac{1}{2} + \frac{1}{2}\tanh(c_d x) \tag{C.6}$$

with c_d a decision constant influencing the smoothness of the decision. The major advantage of this function is that it can be differentiated quite easily. Note that for large c_d the approximated Heaviside function transfers into the exact Heaviside function

$$\lim_{c_d \to \infty} \tilde{\varepsilon}(x, c_d) = \varepsilon(x) \tag{C.7}$$

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