Entropy, Water and Resources

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An Essay in Natural Sciences-Consistent Economics

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Preface

This book lies at the intersection of natural sciences, economics, and water engineering and is in line with the long tradition of environmental economics at the University of Heidelberg. In the 1970s, the Neo-Austrian Capital Theory was developed using the fundamental laws of thermodynamics as a common language between the natural and social sciences. Niemes (1981) integrated the dynamic and irreversibility characteristics of the natural environment into the Neo-Austrian capital theory. Faber et al. (1983, 1987, 1995) then extended this interdisciplinary approach further to create a comprehensive, dynamic, environmental resource model.

Over the last 3 decades, the theoretical foundations of environmental economics have been modified and there have been an impressive variety of applications. This book aims to reduce the gaps between economic theory, natural sciences, and engineering practice. One of the reasons these gaps exist is because economic assumptions are used to construct dynamic environmental and resource models, which are not consistent with the fundamental laws of the natural sciences. Another reason for the gap might be the distance between academic theory and real world situations.

Based on an extended thermodynamic approach, the authors explain which economic assumptions are acceptable for constructing a dynamic model that is consistent with the natural sciences. In particular, the special role of water in the production and reproduction activities will be considered as an integral component. Water is generated in a separate water treatment process and is used to transport the unavoidable by-products of production and reproduction activities to a wastewater sector. In this respect, not only environmental protection aspects, but also the interrelation between the water requirements and the use of non-renewable resources for producing desired consumption goods will be highlighted. Special attention is given to show that the economies of developed countries, which still rely on the use of non-renewable natural resources, will be confronted with closely connected crises. The inter-temporal marginal costs of using the non-renewable resources also cause an increase in the costs of water and energy.

We will demonstrate how natural sciences consistent economic models are beneficial to the long-term study and realization of water supply and wastewater infrastructure projects and hydro-geological investigations. We use two case studies to develop an enhanced water infrastructure model. As part of the model, we introduce capital stocks for water use, water infrastructure, water treatment, water distribution, as well as wastewater collection and wastewater treatment. Although it takes serious effort to derive the optimal conditions for the extended dynamic model, the derived results confirm that close cooperation between theoretical work and practical experience can deliver a surplus of inside information that would otherwise not be achievable.

Special thanks are given to the UFZ-Helmholtz-Centre for Environmental Research – and Eawag-Swiss Institute of Aquatic Science and Technology – for financial support of our endeavor over a 3-year period, without which it could not have been realized. We also thank Mrs. Leslie Ferre (Arizona, USA) for her carefully proof-reading of this book, and Malte Faber and Frank Jöst (University of Heidelberg) and Gunter Stephan (University of Bern) for fruitful discussions and comments.

Last but not least, we emphasize their patience, assistance, and motivation and dedicate this book to Ingrid Niemes and Kristin Schirmer.

Leipzig Horst Niemes
Zurich Mario Schirmer
April 2010

Contents

Chapter 1
Introduction

An Essay in Natural Sciences Consistent Economics

Abstract This book at the intersection of natural sciences, economics, and water engineering aims to reduce the gaps between economic theory, natural sciences, and engineering practice. Based on an extended thermodynamic approach, the authors explain which economic assumptions are acceptable for constructing a dynamic model that is consistent with the natural sciences. In particular, the special role of water in the production and reproduction activities will be considered as an integral component. Water is generated in a separate water treatment process and is used to transport the unavoidable by-products of production and reproduction activities to a wastewater sector. In this respect, not only environmental protection aspects, but also the interrelation between the water requirements and the use of non-renewable resources for producing desired consumption goods will be highlighted.

Environmental and Ecological Economics might be considered unique multi-disciplinary scientific fields, for which the two headings are used synonymously because both disciplines deal with resource and environmental problems from an economics perspective. Faber (2007:18) reflected on and characterized both his own work as well as the scientific work of the impressive number of scientists dealing with environmental and resource problems at the University of Heidelberg over a period of 3 decades, and drew a clear dividing line between ecological and environmental economics as follows:

> While the representatives of ecology have few, if any difficulties with Ecological Economics, the relationship between mainstream Economics and Ecological Economics is not quite so harmonious. Why is this? The answer is: the mainstream economist views nature as a subsystem of the economy, whereas the ecological economist takes quite the opposite view.

This differentiation should be examined in the context of the development of the scientific work of Faber and his colleagues at the University of Heidelberg, (for more details see Faber and Winkler 2006). After dynamics and irreversibility of the natural environment were integrated by Niemes (1981) in the Neo-Austrian capital theory, Faber et al. (1983) extended this interdisciplinary approach further to create a comprehensive dynamic environmental-resource model. The English versions by

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Faber et al. (1987, 1995), especially motivated an impressive number of scientists to deal with specific environmental and resource problems, and to develop the dynamic model in different directions.

Although the economic kernel, the Neo-Austrian capital theory approach for characterizing the dynamics of these environmental resource models, has been modified and there is an impressive variety of applications, a more strict application of the thermodynamic laws for the description of ecologic and economic transformation processes has been shown by Baumgärtner (2000) and Baumgärtner et al. (2001, 2002, 2006). Special attention is given to prove (see e.g. Baumgärtner et al. 2006:63–65) that joint production, which is often assumed to be a special case in economics, must be considered the normal case for ecologic and economic processes to preserve consistency with the essential laws of the natural sciences. It was in this context that the famous physicist R.P. Feynman stated (Feynman 1999) "economics is no science at all in case of inconsistency of the economic models with natural scientific laws".

The general objective of our contribution is to develop this approach further by considering not only the energy and material but also the information characteristics of natural and economic transformation processes consistent with the laws of modern physics. Compared with classic physics, the modern disciplines in natural science, (quantum physics and information theory) introduce "subjective" aspects in the observations of transformation processes and systems. This modern view, focusing principally on the equivalence of the material, energy and information components, helps to close the gap between natural and social sciences, and to strengthen interdisciplinary approaches. Our specific objective in this book will be to develop a dynamic model consistent with natural sciences, which can be applied to natural resources, environmental and specific water problems, e.g. for the dynamic analysis of the water infrastructure of urban centers. We will illustrate, at least graphically, that this modern view requires essential revisions to the concept of the capital theory used by Faber and his colleagues at the University of Heidelberg for the construction of the dynamic resource and ecologic models. Addressing the problems of finding convincing measurement units for the information component and its subjective interpretation, however, would be too ambitious for this book (for more details about modern view of natural sciences and the problems of how to measure abstract information and its subjectivism see Görnitz and Görnitz 2006 and Baeyer 2005).

Our book is divided into two parts: in Part I, only water uses are integrated into a basic dynamic model; capital stocks for the water supply and wastewater sectors will be introduced in Part II. Since thermodynamics and information theory are used as a common language for describing natural and economic transformation processes, an introduction to these fields is given in Chap. 2 of Part I, where the interrelation between thermodynamics and the concept of the capital theory is emphasized.

Within the framework of this theoretical background, the general design of an economic model that is consistent with natural science and is intended for natural resources, especially for water uses and water protection measures, is the subject of Chap. 3. For the construction of our basic model for water uses, some additional assumptions and restrictions will be introduced in Chap. 4, which lead us to formulate the model constraints in Chap. 5. In Chap. 6, we derive the optimality conditions expressed in terms of non-profit conditions or marginal costs for both the production and water sectors.

Being guided by two case studies in Chap. 7 of Part II, our basic dynamic model will be extended in Chap. 8 to include essential water infrastructure components. To come to an applicable dynamic model, some additional assumptions, restrictions, and aggregations of processes to sectors are required. Based on the model constraints in Chap. 9, the optimal conditions being formulated in the form of non-profit conditions and marginal costs are derived in Chap. 10. Apart from possible modifications, extensions and a generalization of the dynamic water use and infrastructure models, our conclusions and perspectives will be summarized.

Part I
The Water Use Model

Chapter 2
Conceptual Foundations: Thermodynamics and Capital Theory

Abstract Economic transformation processes, specifically the extraction of non-renewable natural resources for production and reproduction activities, are irreversible. The entropy notion of classic thermodynamics and its equivalent in information theory can be applied to derive the relations between free energy, useful work (exergy), unusable work (anergy) and changes in the concentrations of desired raw materials and undesired residuals that are being discharged into the natural environment. Capital theory is a corner stone in economic theory and ecological economics for analysing the dynamics of environmental and resource problems. It will be shown that information theory can be used to extend thermodynamics and allow an interpretation of capital theory that is consistent with the natural sciences.

The description of transformation processes within the ecological system and its embedded sub-systems (e.g. economic) can be based upon a generalized entropy concept. Section 2.1 discusses entropy in the contexts of classic thermodynamics as well as information theory. Section 2.2 contains a short description of the capital theory and its thermodynamic implications.

2.1 Thermodynamics and Its Equivalency to Information Theory

In this section, special attention is given to show that only a portion of the external available free energy for shifting a system from its thermodynamic equilibrium to a new status can do useful work, while the other portion of free energy can not be used because of irreversible processes within the system. Furthermore, it will be derived that the entropy-free portion (the exergy) is comprised of a materialistic term and an informational term. For a biological system, with its internal information storage capabilities, it is not surprising that it is necessary to distinguish between the materialistic and informational characteristics of the system. We will show, however, that this extended interpretation of thermodynamics makes it necessary to distinguish between the materialistic and informational components for chemical systems, which are less, evolved than biological systems.

H. Niemes, M. Schirmer, *Entropy, Water and Resources*,
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2.1.1 Entropy, Temperature and Heat

As explained in more detail by Niemes (1981:3–12), Clausius' (1850) introduction of entropy led to the clarification that heat is not a special matter but an energy form similar to the others. Marginal changes in heat dQ are defined in Eq. (2.1) as the product of the intensive variable (temperature T) and the extensive variable (marginal change of entropy dS).

$$dQ := TdS. \tag{2.1}$$

Entropy, S, is introduced as the integral of marginal changes in heat between status 1 and 2 for reversible processes

$$\int_{rev.1}^{2} \frac{dQ}{T} := S(2) - S(1). \tag{2.2}$$

For a circular process in a closed system, where the change from status 1 to status 2 is irreversible and the change back from status 2 to status 1 is reversible, we receive

$$\oint_{rev.} \frac{dQ}{T} = 0 \quad \wedge \quad \oint_{irrev.} \frac{dQ}{T} < 0 \Rightarrow \int_{irrev.1}^{2} \frac{dQ}{T} + \int_{rev.2}^{1} \frac{dQ}{T} < 0. \tag{2.3}$$

With the definition of entropy from Eq. (2.2) for the case of a completely closed system, we obtain the so-called Second Law of classic thermodynamics

$$S(2) - S(1) > \int_{irrev.1}^{2} \frac{dQ}{T} \quad \Rightarrow \quad S(2) > S(1). \tag{2.4}$$

These equations show that the entropy of a closed system with irreversible processes never decreases. This can be extended to any system by extending it sufficiently. It also has the implication that an irreversible process can only be returned in the opposite direction when free energy is available for the sub-system where irreversible processes are occurring.

2.1.2 Entropy, Probability, and Information

Whereas entropy in classic thermodynamics formulates the macro state of a system, Boltzmann's formula connects the entropy, S, and the thermodynamic probability of microstates, W, of the system with the so-called Boltzmann constant k

$$S = k \ln W. \tag{2.5}$$

This relationship means that the Second Law of Thermodynamics, which is stated in terms of an increase in microstates, can also be expressed in terms of information changes in the microstates of the system. In the case where the system contains N particles (with $h = 1...$n properties), which do not depend on each other and can be combined in different ways, we get

$$S = -kN \sum_{h=1}^{n} p_h \ln p_h, \tag{2.6}$$

Where the frequencies $p_h = N_h/N$ is the probabilities of given particles having h sets of properties (see e.g. Jörgensen and Svirezhev 2004: Chap. 4 for more details).

Shannon's formula (2.7) for measuring information (or the information entropy) can be interpreted as a loss of information during a transfer of coded information, which has the characteristics of an irreversible process.

$$I = -N \sum_{h=1}^{n} p_h \log_2 p_h. \tag{2.7}$$

Consequently, free energy is needed to avoid potential irreversible loss of information.

The formal similarity between entropy and information has a very deep meaning. Entropy is a deficiency of information for the full description of the system. The proof of the equivalency of information and entropy, however, has been seen in the context of the discovery by Bekenstein (1974) and its theoretical foundation by Hawkins (1975), which confirms that black holes of the universe also have entropy increase, or loss of information. Equation (2.8) means that the entropy increase (equal to the related loss of information) depends mainly on the mass of the black hole, M_{BW}, and on the mass of the object, m_{Obj}, disappearing into the black hole (for more details see Görnitz and Görnitz 2006:385).

$$\Delta S = \Delta I = konst. \cdot M_{BW} \cdot m_{Obj}. \tag{2.8}$$

2.1.3 Relations Between Work and Exergy

Assume a system is in thermodynamic equilibrium with its environment. A certain amount of work is required by the environment to change the system from its initial state, 0, to another state, 1. For the reverse transition, from state 1 to the initial state 0, the system must do work on the environment. For the direct forced transition, which requires the environment to supply the minimum work, $min\,(\delta_{01}) = \delta A_{min}$ there is a corresponding transition where the system does maximum work, $max\,|\,\delta A_{10}| = |\,\delta A_{max}|$. The latter transition is started when the forcing action stops and the system begins moving spontaneously towards its thermodynamic equilibrium. It is evident that the magnitudes of δA_{min} and $|\,\delta A_{max}|$ are identical. Equation (2.9) (cf. Jörgensen and Svirehev 2004: Chap. 15) shows that, for a reversible process, the external work equals the sum of the changes in internal energy, heat, compression, and chemical potentials

$$\delta A \geq \Delta U - T_0 \Delta S + p_0 \Delta V - \sum_{h=1}^{n} \mu_h^0 \Delta N_h. \tag{2.9}$$

The value of minimum work is given by the formula

$$\delta A_{min} = |\delta A_{max}| = \Delta U - T_0 \Delta S + p_0 \Delta V - \sum_{h=1}^{n} \mu_h^0 \Delta N_h. \tag{2.10}$$

When using Gibbs' equation, $dU = TdS - pdV + \sum_{h=1}^{n} \mu_h^0 \Delta N_h$,

Equation (2.10) can be written in the form

$$dA_{min} = |dA_{max}| = (T - T_0)\ dS - (p - p_0)\ dV - \sum_{h=1}^{n} \mu_h^0\ dN_h. \tag{2.11}$$

Another definition can be applied to the maximum work by using the following Eq. (2.12) (cf. Jörgensen and Svirehev 2004:98–99)

$$\delta A_{max} = T_0 \Delta S_{tot} = T_0 \left(S_{tot} - S_{tot}^{eq} \right) = \Delta U - T_0 \Delta S + p_0 \Delta V - \sum_{h=1}^{n} \mu_h^0 \Delta N_h. \tag{2.12}$$

In Eq. (2.12), ΔU, ΔS, ΔV and ΔN_h express the differences from thermodynamic equilibrium between the values of energy, entropy, volume, and number of particles in the system. This equation expresses how much the entropy of the closed super system (e.g. the whole universe) differs from its maximum possible value if the system is not in equilibrium with its environment. Since the concept of maximum work plays a very important role, a special term, exergy, has been introduced. Exergy, Ex, is defined as the amount of entropy-free energy that a system can perform when it is brought into thermodynamic equilibrium with its environment, i.e. $|A_{max}| = Ex$. As it is formulated by Jörgensen and Svirezhev (2004:100)

> It seems more useful to apply exergy than entropy to describe the irreversibility of real processes as it has the same unit as energy and is an energy form, while the definition of entropy is more difficult to relate to concepts associated with our usual description of reality. Furthermore, exergy facilitates the differentiation between low-entropy energy and high-entropy energy, as exergy is entropy-free energy.

Therefore, it is helpful (cf. Cerbe and Hoffmann 1996:470) to represent free energy E as the sum of the entropy-free exergy, Ex, and the anergy, An, caused by the entropy of the irreversible processes of the system:

$$E = Ex + An. \tag{2.13}$$

2.1.4 Exergy Far from the Thermodynamic Equilibrium

Now that various thermodynamic equations have been introduced, let us approach the transition of a chemical system from its initial state, 0, thermodynamic equilibrium, to another state, 1, that is far from the thermodynamic equilibrium. When assuming that the infinitesimal change of exergy $d(Ex)$ takes place in an infinitesimally short time, dt, so that the environment is not able to change, we obtain from (2.12) the simplified Eq. (2.14) (Jörgensen and Svirezhev 2004:106)

$$\frac{d(Ex)}{dt} = \sum_{h=1}^{n} (\mu_h - \mu_h^0) \frac{dN_h}{dt}. \tag{2.14}$$

When using the definition of the chemical potential

$$\mu_h = \mu_h(0) + RT \ln N_h, \; h = 1, \ldots, n,$$

Where N_h can be considered as the molar concentrations of corresponding chemical substances h, and R is the gas constant, we can rewrite Eq. (2.14) for the case where $T = T_0$ as

$$\frac{d(Ex)}{dt} = RT_0 \sum_{h=1}^{n} \ln \frac{N_h}{N_h^0} \frac{dN_h}{dt}. \tag{2.15}$$

By integrating both sides of Eq. (2.15) with respect to time and taking into account that $Ex(t_0) = 0$, we get

$$\begin{aligned} Ex(t) = RT_0 \int_{t_0}^{t} \sum_{h=1}^{n} \ln \frac{N_h(t)}{N_h^0} \frac{dN_h}{dt} dt = RT_0 \sum_{h=1}^{n} \int_{t_0}^{t} \ln \frac{N_h(t)}{N_h^0} \frac{dN_h}{dt} dt = \\ RT_0 \sum_{h=1}^{n} \int_{N_i^0}^{N_i} (\ln N_h - \ln N_h^0)\, dN_h = T_0 \sum_{h=1}^{n} \left[N_h \ln \frac{N_h}{N_h^0} - \left(N_h - N_h^0\right) \right]. \end{aligned} \tag{2.16}$$

We can see that $Ex\,(t) > 0$ for any $N_h > 0$, except $N_h = N_h^0$, $h = 1, \ldots, n$, if $Ex \equiv 0$.

When using N to represent the total number of particles in the system, Eqs. (2.14) and (2.15) can also be written in concentration form

$$\frac{d(Ex)}{dt} = NRT_0 \sum_{h=1}^{n} \ln \frac{c_h}{c_h^0} \frac{dc_h}{dt}, \text{ with } N := \sum_{h=1}^{n} N_h \tag{2.17}$$

$$\begin{aligned} Ex(t) = NRT_0 \int_{t_0}^{t} \sum_{h=1}^{n} \ln \frac{c_h(t)}{c_h^0} \frac{dc_h}{dt} dt = NRT_0 \sum_{h=1}^{n} \int_{t_0}^{t} \ln \frac{c_h(t)}{c_h^0} \frac{dc_h}{dt} dt = \\ NRT_0 \sum_{h=1}^{n} \int_{c_h^0}^{c_h} (\ln c_h - \ln c_h^0)\, dc_h = NRT_0 \sum_{h=1}^{n} \left[c_h \ln \frac{c_h}{c_h^0} - \left(c_h - c_h^0\right) \right]. \end{aligned} \tag{2.18}$$

We obtain the relation that entropy-free work done on the system by its external environment for transitions from one state to another, called dissipative work, must be the negative value of exergy

$$Diss(c^0 \to c^1) = Diss(c^1 \to c^0) = -Ex\,(c^1,c^0). \tag{2.19}$$

Equation (2.19) implies that (cf. Jörgensen and Svirezhev 2004:109)

1. Work done on the system by its external environment in the forced transition $c^0 \to c^1$ is equal to $|A_{01}| = -\mathrm{Diss}(c^0 \to c^1)$.
2. In the course of the transition, the system accumulates exergy, in an amount equal to the absolute value of the work done on the system $Ex(c^1, c^0) = |A_{01}| = -\mathrm{Diss}(c^0 \to c^1)$.
3. When the system is closed, it returns spontaneously to the stable state, c^0, and dissipating exergy in the process. The transmission is complete when the system reaches c^0: specifically, at this moment the work $|A_{10}| = -Diss(c^1 \to c^0) = Ex(c^1,c^0)$ and all of the exergy has been exhausted.

2.1.5 Relations Between Exergy and Information

By introducing the variable $p_h = N_h/N = c_h$, we can rewrite Eq. (2.16) for the exergy as

$$Ex \;=\; N\sum_{h=1}^{n} p_h \ln\frac{p_h}{p_h^0} + \left[N\ln\frac{N}{N_0} - (N - N_0)\right]. \tag{2.20}$$

The vector of the intensive variables $\vec{p} = \{p_1, \ldots, p_n\}$ describes the composition of the system, while N is the extensive variable for the status of the system.

The value $K = \sum_{h=1}^{n} p_h \ln\left[p_h/p_h^0\right]$ with the constant factor $1/\ln 2$ is the Kullback measure of the increment of information, which was introduced in Eq. (2.6). That is, we can present the expression for exergy as the sum of an informational and a materialistic component

$$Ex = Ex_{inf} + Ex_{mat}. \tag{2.21}$$

The two terms:

$$Ex_{\mathrm{inf}} = NK\left(p, p^0\right) \;\geq 0 \text{ and } \quad Ex_{mat} = N\,\ln\left(N/N_0\right) \;-\; (N - N_0) \;\geq 0$$

Represent the structural changes in the system and the change of the total mass of the system. Consequently, the application of thermodynamic laws extended to include information aspects results in useful work, or the entropy-free energy (exergy), being the sum of materialistic and informational components for chemical systems.

Since biological systems have internal information storage capabilities, whereas chemical systems do not, chemical systems are considered to be on a lower evolutionary level than biological systems. These concepts must be considered when describing economic transformation processes from the extended thermodynamic point of view.

Equation (2.21) also shows that the evolution of chemical systems on earth, which started more than four billion years ago, has both materialistic and informational components. Three billion years was required for biological systems to evolve with internal information processes for survival and sexual reproduction. Approximately 10 millions ago, the evolution process began which resulted in human intelligence, which has developed to the cultural level that supports permanent reproduction through modern education and information systems (for more details see e.g. Ulmenschneider 2006:Chap. 6 and Jörgensen and Svirezhev 2004:109). Equation (2.21) can be extended to Eq. (2.22) by adding terms for the evolution from the chemical to the biological system and then on to intelligent life and its social systems.

$$Ex = Ex_{inf}^{soc} + Ex_{inf}^{bio} + Ex_{inf}^{chem} + Ex_{mat}^{soc} + Ex_{mat}^{bio} + Ex_{mat}^{chem}. \tag{2.22}$$

Ex_{inf}^{soc} Stands for the cumulative information of the individual and social education process i.e. (human intelligence). The other terms represent the information and material exergy components needed for the survival of the biological and chemical processes of this specific system. Such an extended interpretation of economic transformation processes and its interrelation with the natural environment are the contributions of Binswanger (1992), Beard and Luzada (2000) and Lozada (2004).

2.1.6 Thermodynamics of Economic Transformation Processes

The entropy and exergy concept developed previously will now be used to describe the thermodynamic structure of modern industrial production in terms of mass, entropy, and exergy. Modern industrial production is described as the joint production of desired goods with high exergy (entropy-free energy) and by-products with low exergy (high anergy) caused by the entropy of irreversible processes. As illustrated in Figs. 2.1 and 2.2, economic activities must always be seen as joint production in accordance with the laws of thermodynamics. Consequently, joint production is the normal case and not a special case, as is often assumed in economic theory. According to Eq. (2.13), in the case of fixed inputs of free energy and materials, an increase in exergy of the desired outputs requires a decrease in anergy of the system.

In the practise of economics, contradictions between natural laws and common economic assumptions are often not known, ignored, or "corrected" by using strange assumptions. One such assumption is free disposal costs for unavoidable by-products. Another common, yet contradictory, assumption is that the marginal production of an additional output of the desired good is a decreasing function

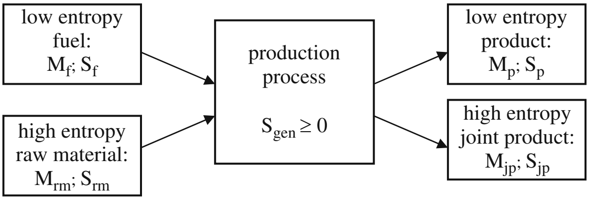

Fig. 2.1 Thermodynamic structure of industrial production in terms of mass and entropy (adapted from Baumgärtner et al. 2006:51)

of the required production inputs. This assumption requires that the anergy of the by-product must increase because the total amount of all energy forms must remain constant.

So far, however, the parameters for the external relations of the system with the surrounding environment have not been considered. Consequently, the description of economic transformation in Figs. 2.1 and 2.2 is incomplete. The transitions from state 0 to state 1 of a chemical or economic system must be formulated by an extended set of differential equations $dc_h/dt = f(c_1, \ldots, c_n; \alpha_1, \ldots, \alpha_n)$. The parameters α_h; $h = 1, \ldots, n$ of the vector $\vec{\alpha} = (\alpha_1, \ldots, \alpha_n)$ represent the external intervention for changing the composition of the system. The concentration vector $\vec{c} = (c_1, \ldots, c_n)$ includes the flow variables. The vector $\vec{\alpha} = (\alpha_1, \ldots, \alpha_n)$ can be interpreted as stock variables that keep the system far from thermodynamic equilibrium within a time period, T. To be complete, Fig. 2.2 should include the relationship between the economic sub-system and its environment. This is done in Fig. 2.3.

In Fig. 2.3, the role and characteristics of capital and public goods for production and consumption activities are shown for two follow-up time periods, where we strictly distinguish between flow and stock variables for the transformation processes. The active role of capital and public goods in physical terms is limited to delivering physical inputs for the transformation processes. This is measured as deterioration, or exergy losses, of the stock variables and must be permanently compensated by equivalent flow inputs for the maintenance of the capital stock. The embedded information of the capital stock and public goods and its interaction with the embedded information of the human labour is the main driving force of the

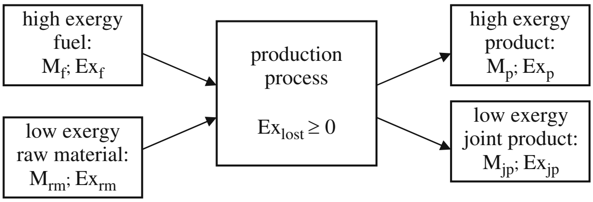

Fig. 2.2 Thermodynamic structure of industrial production in terms of mass and exergy (adapted from Baumgärtner et al. 2006:51)

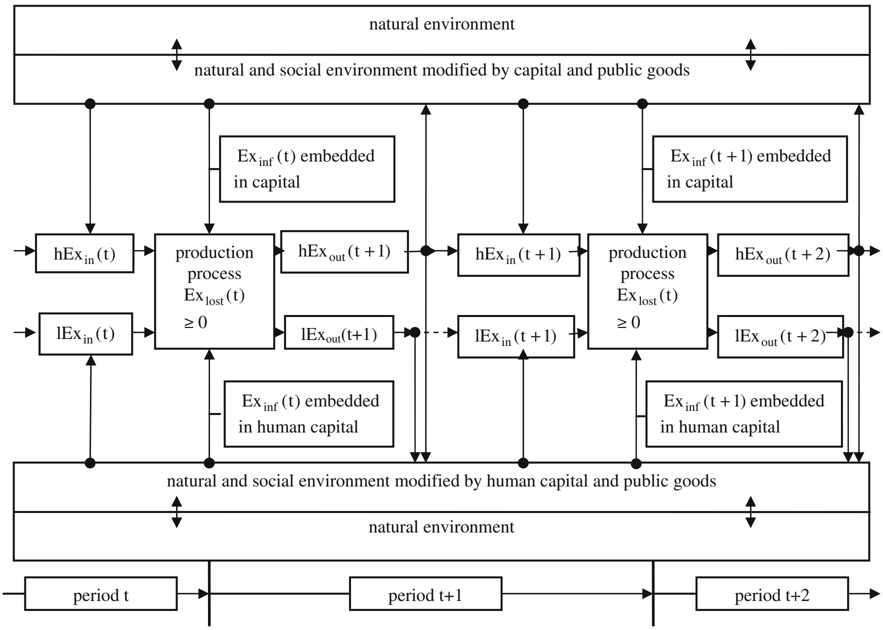

Fig. 2.3 Extended thermodynamic structure and time characteristics of industrial production in terms of (specific) exergy

transformation processes. Recalling that exergy and information are equivalent, the exergy contribution for economic activities has a physical and informational component. The industrial revolution of the last two centuries can be generalized as having reduced the hard physical work of labour by embedding this less comfortable coordinative work into the capital and public goods. This then allows more time to be spent on reproduction activities and the improvement of the levels of education and qualifications of the human labourers.

The preceding has explained the physical and informational components of the human labour. Although the total labour input for production may have remained constant or even reduced during the industrial evolution process, the physical portion of the human labour force is, on average, a declining function when it is compared with the increase in the coordinative and creative portion that is required for operating and managing capital stocks. Essential indicators for this evolution process are the efforts, time and resources spent on education and professional qualification, which are needed to be an efficient participant in both the production and reproduction processes. Therefore, we have to distinguish the human labour force into its physical (or flow related) and informational (or stock related) components. The rapid change in production and reproduction technologies requires a permanent change in the education and qualification stock, which has to be seen as a complementary "twin set" of the capital stock.

2.2 The Concept of Capital Theory

Although we cannot cover economic theory in detail, a short description of capital theory will be the subject of this section. Aside from other advantages, when compared with the neoclassical capital theory (for more details see Faber 1979), the Neo-Austrian capital theory, with some modifications, might be a more flexible approach for constructing disaggregated models. To the extent that they provide sufficient understanding of the rationale behind inter-temporal optimization problems, only graphical illustrations will be provided.

2.2.1 Neo-Austrian Capital Theory as Example

When deriving optimal conditions under model constraints, it is common in economics to use individual utility or social welfare functions. This practise reflects the usual properties of a preference order system for the comparison of consumption bundles (for more details see e.g. Breyer 2004:117–123). When we start (for more details see e.g. Stephan 1995:69) with a fictitious central planning economy and assume that a central planning authority maximizes an aggregate, strictly quasi-concave, strictly monotonic and differentiable welfare function, the conventional dynamic characteristics of the inter-temporal welfare are given by Eq. (2.23).

Assumption 2.1 (for the inter-temporal welfare function)

$$W(\vec{Q}(1),\ldots,\vec{Q}(T)) = \sum_{\tau=1}^{T} (1+\delta)^{1-\tau} W_\tau(\vec{Q}(\tau)), \tag{2.23}$$

Where the discount rate $\delta > -1$ measures the society's time preference and

$$\mathrm{W}_\tau(\vec{\mathrm{Q}}(\tau)) \;\; \tau \in \{1,\ldots,\mathrm{T}\} \wedge \vec{\mathrm{Q}}(\tau) := (\mathrm{Q}_1\tau),\ldots,(\mathrm{Q}_\mathrm{q}(\tau))$$

Are welfare functions in interval τ for consumption vectors of q-types of goods used for consumption and reproduction purposes. These functions are assumed to be identical for a different interval, $\tau' \neq \tau$, and to be quasi-concave, strictly monotonic, and differentiable functions for the N-dimensional consumption vector $\vec{\mathrm{Q}}(\tau)$ for each of the periods $\tau \in \{1,\ldots T\}$. W, therefore, also has these properties.

When using Assumption 2.2, which is also common in economics,

Assumption 2.2 (for producing feasible consumption bundles) There are technology sets that are used to produce feasible consumption bundles for each of the τ-intervals, as well as between the intervals τ and $\tau + 1$. These sets form a convex and closed *NT*-dimensional vector space.