Sistemas de Energia em Sociedade de Agentes Materiais

Energy Systems in Material Agent Societies

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Data de submissão: 18/07/2017, Data de aceite: 25/10/2017

Resumo: Este artigo concerne *sociedades de agentes materiais*, quer dizer, sociedades de agentes habitadas por *agentes materiais*. O artigo introduz o conceito de *sistema de energia* de uma sociedade de agentes materiais, caracterizando-o como o sub-sistema organizacional da sociedade que é responsável pela coordenação da produção, distribuição e consumo de energia naquela sociedade. Dois modelos (um *baseado em labor*, outro *baseado em trabalho*) de sistemas de energia são formulados, juntamente com as condições necessárias para seu funcionamento *equilibrado*. Os conceitos de sociedade de agentes materiais *energeticamente autossuficiente* e *energeticamente autônoma* são formalmente definidos. Uma possível relação entre os sistemas *econômico* e *político* e os sistemas de energia de sociedades de agentes materiais é indicada.

Abstract: This paper concerns *material agent societies*, that is, agent societies inhabited by *material agents*. The paper introduces the concept of *energy system* of a material agent society, characterizing it as the organizational sub-system of the society that is responsible for the coordination of the production, distribution and consumption of energy in that society. Two models (*labor-based* and *work-based*) for energy systems are formulated, together with the necessary conditions for their *equilibrated* functioning. The concepts of *energy self-sufficient* and *energy autonomous* material agent society are defined. The possible relation between the *economic* and *political* systems, and the energy systems of material agent societies, is indicated.

Palavras-chave: Sociedades de agentes, agentes materiais, sistemas de energia, labor, trabalho.

Keywords: Agent societies, material agents, energy systems, labor, work.

1 Introduction

1.1 Overview of the Paper

We base this paper on the idea that *agents* are, essentially, *abstractions of robots* (see, e.g., the way the *basic* concept of agent is presented in [1]). We expect, in consequence, that at some point in the future the two areas of *Robotics* and *Multiagent Systems* will come closer to each other than they are at the moment.

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Whenever such approximation happens, the concept of *society of autonomous robots* is surely one that should play a central part in the articulation of the two areas, and issues of *energy* should become, then, a serious concern in the definition of *organization models* for those societies, and in the definition of the *social mechanisms* expected to support those organization models.

It is well known that energetic issues, in particular that of *energetic self-sufficiency*, are already being tackled in the cases of *robots* and other types of *mobile* systems (see, e.g., [2]) .

Regarding specifically Multiagent Systems, however, it seems that the issue has not aroused yet, probably because this area has concentrated its efforts on systems of *software* agents, which happen to gather the energy necessary for their operation from the underlying computing system.

This latter issue - the issue of *energy* from the point of view of Multiagent Systems - is the main concern of the present paper. To deal with it, we introduce the concept of a *material agent*, that is, an agent endowed with a *material body* (which implies, of course, that material agents need *energy* for their operation).

We call *material agent societies* the societies of such material agents. We focus on material agent societies that can be said to be *energetically self-sufficient*, and we take that the *energetic self-sufficiency* of a material agent society implies that its material agents *obtain by themselves* the energy they need for their operation.

For definiteness, we assume that any material agent society is situated in a *material environment* and that the material agents of that society are to obtain the energy they need for their operation from that material environment. Energetic self-sufficiency requires, then, that the material agent society be endowed with an *energy system*, allowing the energy obtained from the material environment to be *produced* and *distributed* among the energy *consumers* (the material agents) of the society.

To advance such ideas, this paper formally introduces some concepts that seem indispensable for the design and analysis of *energetically self-sufficient* material agent societies. Besides, we define the concept of *energetically autonomous* material agent societies, and we advance some of the concepts that are necessary for allowing energetically self-sufficient material agent societies to become energetically autonomous.

1.2 Structure of Paper

Section 2 discusses the basic terms (*energy*, *labor*, *work*) with which the concept of *energy system* of a material agent society can be defined. Section 3 informally reviews the concept of *agent society*, focusing on the particular case of *material agent societies* and the characterization of their *energy aspects*.

Section 4 is the first central section of the paper, where the concepts of *material agent society* and *energy system of material agent society* are formally defined, as well as the concepts of *energy closure*, *energy self-sufficiency*, *energy autonomy* and *energetic equilibrium* of material agent societies. Section 5 is the second central section of the paper, where two base types of energy systems of material agent societies are defined, namely, the *labor-based* and the *work-based* energy systems.

Section 6 discusses complementary issues. In particular, the concepts of *economic* and *political systems* of material agent societies, and the role they may have in the equilibration of the energy systems of such societies.

Section 7 brings the Conclusion.

Figure 1. The Cartesian architecture of a material agent.

2 Labor, Work, Action, and Energy

The starting point of our approach to energy issues in material agent societies is Hanna Arendt's characterization of the three types of central activities of the *active life* of a human society, namely, *labor*, *work*, and *action* [3], which we summarize as follows:

- *labor* is the set of activities related to the *immediate physical maintenance* of the structure and operation of the bodies of the individuals of that society;
- *work* is the set of activities related to the *production of objects* that, being capable of persisting beyond the individual lives, constitute a *system of objects* that supports individual and collective activities in that society;
- *action* is the set of activities that individuals and groups of individuals *exercise directly on each other*, in order to direct the system of their individual and collective lives.

We claim that this conceptualization, properly adapted, determines a path toward a sound understanding of the notion of *material agent society*. For that, we take the *need of energy* as the main concern of both the individual material agents and their collectives, and the central issue around which proceed the three types of activities of their *active life* in that society.

For the specific purposes of this paper, however, we concentrate on the relations that may exist, in material agent societies, between the *need of energy* and the sets of *labor* and *work* activities. We leave for further investigation the relation between the need of energy and the set of *action* activities (but, see Sect. 6).

3 Material Agents

3.1 Material Agents and their Energy Oriented-Behaviors

We assume what we call a *Cartesian architecture* for material agents, that is, we assume that material agents are organized in terms of a *mind-body* articulation, with the *body* constituted by an energy-consuming material mechanism whose operation is regulated by the material agent's software based-*mind*. Mind and body are assumed to be interconnected through an *implementation* relation (see Fig. 1).

The having of a physical body implies that every material agent requires *energy* to operate (that is, to perform its *behaviors* and *interactions*, and to *function properly* in the society that it inhabits). We assume that, in *material agent societies*, material agents commonly extract the energy they need from the

material environment that exists in that society². We call *ground* the part of the material environment that material agents can operate on to extract energy.

We say that a material agent is *self-sufficient*, from the energy point of view, if it can get by itself, from the available ground, the energy it needs for its operation. Otherwise the material agent is said to be *energy dependent* on other material agents.

We assume that material agents are so constituted that a *drive for energy seeking* can arise in them, when the *need of energy* goes beyond some specified threshold, and that some *energy seeking behavior* can be activated in them, in response to that drive (see [4] for the notion of *drive* in artificial agents). In addition, we also assume that *rationally driven energy-oriented behaviors* (of seeking, storing and exchanging energy in advance of surgings of energy needs) can occur in material agents.

3.2 The Energy Aspects of Material Agents

To formally characterize material agents from the energy point of view, we state the following:

- time is discrete, denoted by $T = t_0, t_1, \dots$, and ranged over by the variable t ;
- there is a definite *time unit* separating any two time instants, which we denote by: $\blacktriangle_T$;
- there is a *discretely quantified leveled notion of energy*, which we denote by $E = e_0, e_1, \dots$, ranged over by the variable e ;
- there is a definite *energy unit*, or *quantum of energy*, separating any two energy levels, which we denote by: $\blacktriangle_E$;
- there is a set of material agents, which we denote by MAg , ranged over by the variable mag ;
- the operation of each material agent mag determines, at each time t , a definite *operation cycle*, denoted *opcy*, during which the agent *consumes* a definite amount of energy quanta, called *energy consumption per cycle*, which we denote by: $ecpc_{mag}^t$;
- the dimensionality of the *energy consumption per cycle* is given in terms of *energy quanta per operation cycle*, which we denote by: $\blacktriangle_E/opcy$;
- at each time t , each material agent mag operates under a definite *instantaneous operation speed* (a certain number of operation cycles per time unit), which we denote by: ios_{mag}^t ;
- the dimensionality of the *instantaneous operation speed* is given in terms of *operation cycles per time unit*, which we denote by: $opcy/\blacktriangle_T$;
- in consequence, for each material agent mag , at each time t , there is a definite *instantaneous energy consumption*, which is denoted by: iec_{mag}^t ;
- the dimensionality of the *instantaneous energy consumption* is given in terms of *energy quanta per time unit*, which we denote by: $\blacktriangle_E/\blacktriangle_T$;
- the *instantaneous rate of energy consumption* of a material agent mag , at any time t , can be determined by:

$$iec_{mag}^t = ecpc_{mag}^t \times ios_{mag}^t \quad (1)$$

²Unless the society is *energetically open*, in which case the material agents can get energy from energy sources that are external to the society, but we don't consider this possibility here (see Sect. 4).

We require that every material agent mag be endowed with an *internal stock of energy* (ise_{mag}^t) that, at each time t , determines the amount of energy the agent has internally available, to support its operation.

In addition, we require that each material agent be endowed with *two threshold levels*. One of the thresholds, called *critical energy threshold*, denoted by cet_{mag} , determines the level of *stocked internal energy* below which energy seeking behaviors are to be activated in the agent. That is, energy seeking behaviors are to be activated in mag at any time t at which $ise_{mag}^t < cet_{mag}$.

The other threshold, called *minimal energy threshold*, denoted by met_{mag} , determines the level of *stocked internal energy* below which the agent mag is incapable of any type of operation, having to rest quiet until some external agent feeds it with the minimum required energy. That is, the material agent mag stops all its operations at any time t at which $ise_{mag}^t < met_{mag}$.

Also, we assume that:

- every material agent is capable of performing *energy dig* operations, denoted by $edig$, in the available ground of the material agent society;
- for every material agent mag , and at each time t , we call *instantaneous efficiency of energy dig operations* the number of energy units that mag can gather from each energy dig operation, and we denote it by $iedo_{mag}^t$;
- the dimensionality of the *efficiency of energy dig operations* is given in terms of *energy quanta per energy dig operation*, denoted by: $\blacktriangle_E / edig$;
- we denote by $irdo_{mag}^t$ the *instantaneous rate of energy dig operations* that the material agent mag is performing at time t ;
- the dimensionality of the *instantaneous rate of energy dig operations* is given in terms of *dig operations per time unit*, denoted by: $edig / \blacktriangle_T$;
- we call *instantaneous energy yield* the amount of energy that a given material agent mag digs, at a time t , from the ground on which it operates, and we denote such yield by iey_{mag}^t ;
- the *instantaneous energy yield* of the material agent mag , at the time t , can be determined by:

$$iey_{mag}^t = irdo_{mag}^t \times iedo_{mag}^t \quad (2)$$

In addition, we state the following:

- we call *instantaneous energy excess*, produced by a material agent mag at the time t , denoted by iee_{mag}^t , the *difference* that occurs, at the time t , between the instantaneous energy yield iey_{mag}^t and the instantaneous energy consumption iec_{mag}^t of the agent mag , at the time t . That is:

$$iee_{mag}^t = iey_{mag}^t - iec_{mag}^t \quad (3)$$

- we assume that, at each time t , the instantaneous energy excess iee_{mag}^t (which can be positive, negative, or null) is *transferred to/from* the internal stock of energy ise_{mag}^t , so that:

$$ise_{mag}^{t+1} = ise_{mag}^t + iee_{mag}^t \quad (4)$$

Table 1. Quantitative concepts that characterize the functioning of the material agent mag at time t (where $\Delta t = t' - t$, for some $t' > t$).

Quantitative Concept	Notation	Dimensionality	Calculation
Internal Stock of Energy	ise_{mag}^t	$\blacktriangle_E$	Basic value
Critical Energy Threshold	cet_{mag}	$\blacktriangle_E$	Basic value
Minimal Energy Threshold	met_{mag}	$\blacktriangle_E$	Basic value
Energy Consumption per Cycle	$ecpc_{mag}^t$	$\blacktriangle_E / cycle$	Basic value
Instantaneous Operation Speed	ios_{mag}^t	$opcy / \blacktriangle_T$	Basic Value
Instantaneous Energy Consumption	iec_{mag}^t	$\blacktriangle_E / \blacktriangle_T$	Calculated
Instantaneous Efficiency of Energy Dig Operations	$iedo_{mag}^t$	$\blacktriangle_E / edig$	Basic Value
Instantaneous Rate of Dig Energy Dig Operations	$irdo_{mag}^t$	$edig / \blacktriangle_T$	Basic value
Instantaneous Energy Yield	iey_{mag}^t	$\blacktriangle_E / \blacktriangle_T$	Calculated
Instantaneous Energy Excess	iee_{mag}^t	$\blacktriangle_E$	Calculated
Updated Internal Stock of Energy	ise_{mag}^{t+1}	$\blacktriangle_E$	Calculated
Net Energy Excess	$nee_{mag}^{\Delta t}$	$\blacktriangle_E$	Calculated

Table 2. Formulas for the calculation of the non-basic quantitative concepts.

Quantitative Concept	Formula
Instantaneous Energy Consumption	$iec_{mag}^t = ecpc_{mag}^t \times ios_{mag}^t$
Instantaneous Energy Yield	$iey_{mag}^t = irdo_{mag}^t \times iedo_{mag}^t$
Instantaneous Energy Excess	$iee_{mag}^t = iey_{mag}^t - iec_{mag}^t$
Updated Internal Stock of Energy	$ise_{mag}^{t+1} = ise_{mag}^t + iee_{mag}^t$
Net Energy Excess ($\Delta t = t' - t$)	$nee_{mag}^{\Delta t} = \sum_{\tau=t}^{\tau=t'} iee_{mag}^{\tau}$

In many situations, we will be mainly interested in the *net energy excess* that a material agent mag produces along a given *time interval*. For the time interval $\Delta t = t' - t$, where $t' > t$, this is given by the summation:

$$nee_{mag}^{\Delta t} = \sum_{\tau=t}^{\tau=t'} iee_{mag}^{\tau} \quad (5)$$

In particular, we will be interested in situations where the net energy excess $nee_{mag}^{\Delta t}$ obtained by the energetically self-sufficient material agent mag during a time interval $\Delta t = t' - t$ is positive enough not only to take its internal stock of energy $ise_{mag}^{t'}$ above the critical energy threshold cet_{mag} , but also to allow for energy to be *supplied* to other material agents, through the intervention of the *energy production and distribution system* of the material agent society (see Sect. 5).

Table 1 gives an overview of the quantitative concepts introduced above, regarding the way we assume that material agents function. Table 2 shows the formulas for the calculation of the non-basic quantitative concepts.

4 Material Agent Societies

4.1 The Architecture of Material Agent Societies

Figure 2 sketches the architecture of material agent societies (see [5] and [6] for further details of this architectural style of agent society).

At the lowest architectural level is the material environment ($MEnv$) of the society, containing the

material objects that participate in the behaviors and interactions of the components of the society.

Next, in the hierarchy of architectural levels, is the populational structure (*Pop*), constituted by the material agents of the society. Notice the split situation: the minds of the material agents are taken to belong to the populational structure, while their bodies, considered to be material objects, belong to the material environment.

The micro-organizational level (*Org_ω*) is constituted by the *organizational roles* that the agents perform in the *organizations* of the society. Such organizations belong to the meso-organizational structure (*Org_μ*) and are constituted by *networks of interacting organizational roles* (possibly organized in terms of sub-organizations, which also belong to *Org_μ*).

Sets of organizations of the society may network with each other, in *inter-organizational networks* that constitute the *organizational sub-systems* of the society, which belong the macro-organizational structure (*Org_Ω*).

In the figure, dotted trapezoids indicate some organizational sub-systems. For one of them, the figure shows the organizations and organization units that implement it, together with the organizational roles that respectively implement them. The implementation relation also shows which material agents implement each organizational role: one organizational role is implemented by two agents, one agent implements (i.e., participates in the implementation of) two organizational roles. Notice that *Org_ω*, *Org_μ* and *Org_Ω* constitute the overall organizational structure (*Org*) of the material agent society.

At the right side of the model is the symbolic environment (*SEnv*) of the society, containing the symbolic objects that participate in the behaviors and interactions of the components of the society (symbolic objects that have a material substrate combine a symbolic component with a material component, with the latter implementing the former, much as a material agent combines a mind with a material body that implements it).

Notice that both *MEnv* and *SEnv* are considered to be *internal environments* of the material agent society. Not shown in Fig. 2 is the *external environment* of the society (for instance, the other agent societies with which that society interacts [7]).

Interactions of components situated at higher levels are implemented by interactions between components situated at lower levels, much as higher level components are implemented by lower level ones (but, in the figure, we omit the representation of the implementation relation for interactions).

Finally, we should mention that we take that the minds of the agents also regulate the behaviors and interactions of the organizational roles that they perform, as well as the behaviors and interactions of organizations and organizational sub-systems that those organizational roles implement³.

4.2 The Functional Characterization of the Energy Systems of Material Agent Societies

Of the various types of *organizational sub-systems* that can be formed in material agent societies, we are interested in this paper in a particular type, namely, the organizational sub-systems that may be called the *energy systems* of those societies.

We give, here, a *functional* characterization of such energy systems. We let for the next section the *architectural characterization* of the energy systems of material agent societies.

We assume that every material agent society has to be endowed with an organizational sub-system that functions as its *energy system*, whenever that society is: (a) *heterogeneous* regarding the energetic

³As has already become usual in the multiagent systems area, we may construe the implementation relations between such behaviors and interactions in terms of the *counts-as* relations that were introduced by John Searle [8].

Figure 2. Sketch of an architectural style for material agent societies.

self-sufficiency of their material agents (mixing self-sufficient and non self-sufficient agents); (b) *energetically closed* regarding its interaction with the external environment (so that it cannot be supplied externally with the needed energy).

4.2.1 Functional Characterization of General Components of General Agent Societies We call *interactional function* of a component, performed in behalf of another component, in an (not necessarily material) agent society, any *activity* that the former component performs in the society, so that such activity contributes to support the proper functioning of the latter component. We formally define such concept of interactional function as follows (see [9]).

Let C_1 and C_2 be components of an agent society. Let B_2 be a behavior that C_2 is required to perform in that society. If it happens that, in the context of that agent society, C_2 can perform B_2 only if an exchange process ep happens between C_1 and C_2 , and ep can happen between C_1 and C_2 only if C_1 and C_2 respectively perform the behaviors B_1 and B_2 , then we say that C_1 *performs an interactional function for* C_2 , and we denote such interactional function by the expression $\langle C_1 : B_1 \rangle \xrightarrow{ep} \langle C_2 : B_2 \rangle$.

In such situation (see the *functional scheme* in Fig. 3), we say that C_2 is the component *served* by the interactional function performed by the *server component* C_1 . The *inflow* and the *outflow* between the server and the served components constitute the *exchange process* between those components⁴.

Finally, we state that by the *functional requirement* of a general component of an agent society we understand the *set of interactional functions* which that component is required to perform in that material agent society, possibly serving several other components.

4.2.2 Functional Characterization of Energy Systems of Material Agent Societies We assume that, in any material agent society, the functional requirement of the *energy system* of that society requires that such system performs three interactional functions for the various material agents of the society: *production*, *distribution* and *consumption* of energy.

⁴But notice that functional schemes are *symmetrical*, in that a function $\langle C_2 : B_2 \rangle \xrightarrow{ep} \langle C_1 : B_1 \rangle$ is also being performed, whenever a function $\langle C_1 : B_1 \rangle \xrightarrow{ep} \langle C_2 : B_2 \rangle$ is, so that C_2 operates as a *server* for C_1 , with the directions of the inflow and outflow processes reversed [9].

Figure 3. The *server* and *served* components of a generic interactional function in an agent society.

Production is the core activity of any energy system. *Distribution* is an intermediary activity, which the *energy system* and its *consumers* (in principle, all the components of the society) jointly perform, to allow the energy produced by the energy system to be distributed to such consumers. *Consumption* of energy is, clearly, an activity performed by *any* material agent of a material agent society (thus, by any of the material agents that implement the energy system itself).

Using the notation explained above, we formally express the basic *functional scheme* of the energy system of a material agent society as follows:

$$[\langle \text{EnergySystem} : \text{Production} \rangle \xrightarrow{\text{Distr}} \langle \text{Consumers} : \text{Consumption} \rangle] \quad (6)$$

There are two main types of situations in which such functional scheme may occur, depending on the energetic self-sufficiency of the *producers* (i.e., the material agents that implement the energy system):

- either all of the producers are always energetically self-sufficient;
- not all the producers are always energetically self-sufficient (and, so, should be sometimes supplied of energy by other producers).

For simplicity, we consider here that all the *producers* are always energetically self-sufficient, so that, at each time, the amount of energy they make available for distribution to the *consumers* has already been deducted by the amount of energy that they needed for their operation, up to that time.

Also for simplicity, we consider that there is *no loss of energy* during the energy distribution process, and we consider that, at each time t , all the energy that is distributed to the *consumers* is completely consumed (and/or stocked) by them, without loss.

4.3 Energy Closure and the Functional Indispensability of Energy Systems in Material Agent Societies

The *functional indispensability* of the energy system of a material agent society arises when not all *material agents* are allowed to, or interested in, acting as *energy producers* in that society. Clearly, such agents become consumers that are *not* self-sufficient energetically.

In such situation, some agents (the *energy producers*) should be charged with producing energy not only for themselves, but also for those consumers that do not produce their own energy, and the *energy system* becomes necessary as a means for the production, distribution and consumption of energy among the members of the society.

The only situation in which an *energy system* is dispensable, in a material agent society where not all *consumers* act as *producers*, is that in which the society is *energetically open* and elements that are *external* to the society operate in order to provide the necessary complimentary energy.

The condition of *energy closure* of a material agent society is, thus, what imposes the *indispensability* of energy systems, in such societies.

4.4 Energetic Self-sufficiency and Energetic Autonomy of Material Agent Societies

We finish this section by defining the following:

- a material agent society is *energetically self-sufficient* if and only if the energetically self-sufficient material agents of the society *actually dig* all the energy they need for their own operation, plus the energy necessary for sustaining the operation of all the material agents that are not energetically self-sufficient;
- a material agent society is *energetically autonomous* if and only if the *surplus of energy* of the society is effectively *produced and distributed* among the agents of that society, in an *equilibrated* way, by the energy system (see next section, for the concept of an energetically equilibrated material agent society).

5 Two Architectural Types of Energy Systems for Material Agent Societies

We build on [3] to define two architectural types of energy systems for material agent societies: the *labor-based energy systems* and the *work-based energy systems*⁵.

5.1 Labor-Based Energy Systems

We call *labor* the set of activities, by one or more material agents, through which *energy is extracted* from the available ground, and immediately made available for consumption, in a material agent society. We call *labor-based energy system* any energy system whose activity is essentially based on *labor* activities.

Given that *labor* is the production and distribution of energy for immediate consumption in a material agent society, the fundamental operational requirement of labor-based energy systems is that of supporting the *fast distribution of energy*, for that immediate consumption.

The kernel of labor-based energy systems has to be, thus, a *network of distribution channels* capable of realizing such fast distribution of energy.

Formally, then, we characterize the architecture of labor-based energy systems as a structure $LBES = (Producers, Consumers, Channels)$ where:

- *Producers* is a non-empty set of *producers*;
- *Consumers* is a (possibly empty) set of *consumers*;

⁵Notice that, in this section, we assume that the *material environment* of any material agent society is an *infinite* source of energy (cf. Sect. 6).

- $Channels \subseteq Producers \times Consumers$ is a *distribution relation*, such that for each pair $(prod, cons) \in Channels$ we say that there is a *distribution channel* between the producer $prod$ and the consumer $cons$;
- and such that each consumer is supplied with energy by at least one producer, that is, for each consumer $cons \in Consumers$ there is at least one producer $prod \in Producers$ such that $(prod, cons) \in Channels$.

Given our assumption, mentioned above, of *no loss of energy* in the consumption processes, we may formulate the following equations, determining the condition of *energy equilibrium* under which a labor-based material agent society may operate.

Let $Producers_{cons} = \{prod \mid (prod, cons) \in Channels\}$ be the set of producers that supply energy for the consumer $cons$. Let $\sup[(prod, cons)]^t$ denote the amount of energy supplied by $prod$ to $cons$, at the time t . Then, the relation between the instantaneous energy consumed by $cons$ at the time t , denoted by iec_{cons}^t , and the total amount of energy supplied to $cons$ at that time is given by:

$$iec_{cons}^t = \sum \{\sup[(prod, cons)]^t \mid prod \in Producers_{cons}\} \quad (7)$$

We remark that, in any labor-based energy system, at each time, the total amount of energy distributed to the consumers is exactly the amount of energy that the producers have produced in excess of their own energy needs.

That is, let

$$Consumers_{prod} = \{cons \mid (prod, cons) \in Channels\} \quad (8)$$

be the set of consumers that are supplied with energy by the producer $prod$. Then, the relation between the total amount of energy supplied by $prod$ to its consumers and the instantaneous energy excess produced by $prod$, at each time t , denoted by iee_{prod}^t , is given by:

$$\sum \{\sup[(prod, cons)]^t \mid cons \in Consumers_{prod}\} = iee_{prod}^t \quad (9)$$

As material agents are supposed to be endowed with internal energy stores, the *energy equilibrium* of a labor-based material agent society is given by the following relation between the total amount of energy supplied by all the producers to all the consumers, during an interval $\Delta t = t' - t$, and the energy the consumers either consumed or internally stored, during that interval:

$$\sum_{\tau=t}^{\tau=t'} \{iee_{prod}^{\tau} \mid prod \in Producers\} = \quad (10)$$

$$\sum_{\tau=t}^{\tau=t'} \{iec_{cons}^{\tau} \mid cons \in Consumers\} \quad (11)$$

$$+ (\sum \{ise_{cons}^{t'} \mid cons \in Consumers\} - \sum \{ise_{cons}^t \mid cons \in Consumers\}) \quad (12)$$

In summary, instantaneity is the main *operational* requirement of the labor-based energy systems, and the availability of a network of energy distribution channels, to provide such instantaneous energy distribution, should be their main *architectural* feature.

5.2 Work-Based Energy Systems

We call *work* the set of activities, by one or more material agents, through which *energy is embedded in objects*, after being extracted from the available ground, in a material agent society. We call *work-based energy system* any energy system whose activity is essentially of the *work* type.

Having been injected into *energy objects*, energy may be *stored* in appropriate storages, and also *exchanged* between material agents, through *exchange processes* concerning such energy objects.

Given that the *production* process of a work-based energy system is the production of energy objects, the corresponding processes of *distribution* and *consumption* of energy in the society need not be performed, in general, immediately after the production of the energy objects, but may be differed in time, on the basis of the storage and exchange of such objects.

The fundamental *architectural feature* of work-based energy systems is, then, that it supports the distribution and consumption of energy on the basis of the storage and exchange of *energy objects*.

The kernel of the architecture of work-based energy systems has to be, thus, a *network of stores* for the distribution of energy objects, with such stores supporting operations of *delivery* and *retrieval* of energy objects.

Let *EnergObj* be the set of all energy objects that may be stored in the stores of the work-based energy system of a material agent society. Formally, we may characterize the architecture of the work-based energy system of that material agent society as a structure

$$WBES = (Producers, Consumers, Stores, OutLinks, InLinks, States, deliver, retrieve) \quad (13)$$

where:

- *Producers* is a non-empty set of *producers*;
- *Consumers* is a (possibly empty) set of *consumers*;
- *Stores* is a set of *stores* for energy objects;
- *States* = $Stores \times T \rightarrow \wp(EnergObj)$ is the set of *states* in which the energy system may be, each $state \in States$ giving, for each store $sto \in Stores$ and each time $t \in T$, the set $state(sto, t) \in \wp(EnergObj)$ of energy objects that are stored in that store, at that time⁶; we often denote $state(sto, t)$ by sto^t ;
- *OutLinks* $\subseteq Producers \times Stores$ is the *out link relation* which determines, for each *producer*, which *stores* it may use to store energy objects, after having produced them;
- *InLinks* $\subseteq Stores \times Consumers$ is the *in link relation* which determines, for each *consumer*, which *stores* it may use to retrieve energy objects, in order to consume the energy embedded in them;
- $deliver_{sto} : EnergObj \times States \rightarrow States$ is the operation of *delivery* of an energy object that a producer *prod* may perform on the store *sto* (if the producer can use that store, i.e., if $(prod, sto) \in OutLinks$); if the delivery operation is performed at the time $t \in T$, with an energy object $eobj \in EnergObj$, then it holds that:

$$deliver_{sto}(eobj, sto^t) = sto^{t+1} \quad (14)$$

where $sto^{t+1} = sto^t \cup \{eobj\}$;

⁶For every set X , we denote by $\wp(X)$ the power-set of X .

- $retrieve_{sto} : States \rightarrow EnergyObj \times States$ is the operation of *retrieval* of an energy object that a consumer $cons$ may perform on a non-empty store sto which it may use (i.e., $(sto, cons) \in InLinks$); if the retrieval operation is performed at the time t , then it holds that:

$$retrieve(sto^t) = (eobj, sto^{t+1}) \quad (15)$$

where $sto^{t+1} = sto^t - \{eobj\}$, where $eobj$ is the object retrieved by the operation.

The *energy equilibrium* of a work-based material agent society, operating under the condition of non-loss of energy, expresses the fact that the total amount of net energy excess (nee_{prod}) delivered by each producer $prod$, during a certain time interval, should equal the sum of the following amounts:

- the net amount of energy moved out/into the stores of the material agent society during that time interval (that is, the difference between the total amount of energy stored in those stores at the end and at the beginning of that time interval);
- the net sum of energy internally stocked by the consumers during that interval;
- the energy that was consumed by the consumers, during that interval.

That is, the *energy equilibrium* of a work-based material agent society, regarding a time interval $\Delta t = t' - t$, is given by:

$$\sum \{nee_{prod}^{\Delta t} \mid prod \in Producers\} = \quad (16)$$

$$(\sum \{sto^{t'} \mid sto \in Stores\} - \sum \{sto^t \mid sto \in Stores\}) \quad (17)$$

$$+ (\sum \{ise_{cons}^{t'} \mid cons \in Consumers\} - \sum \{ise_{cons}^t \mid cons \in Consumers\}) \quad (18)$$

$$+ \sum_{\tau=t}^{\tau=t'} \{iec_{cons}^{\tau} \mid cons \in Consumers\} \quad (19)$$

6 Complementary Issues

6.1 Disposal Processes

A realistic account of the *energy cycle* in a material agent society should include the *disposal* processes, through which the material agents dispose to the material environment the residues that they produce during the energy consumption process.

This is illustrated in Fig. 4 for the case of a labor-based energy cycle. The case of the work-based energy cycle should include an intermediate store in the energy deliver process between the producer and the consumer.

Notice that, as a consequence of the presence of disposal processes, the energy equilibrium condition has to take into account the *energy profile* of the material environment, which cannot be considered anymore an *infinite energy resource*, as was done in Sects. 5.1 and 5.2.

Figure 4. The labor cycle, with trashing.

Figure 5. The energy, economic and political systems of material agent societies.

6.2 Economic and Political Systems in Material Agent Societies

Given the *accountability* of the energy processes of material agent societies, made possible by the formulas and equations given in the sections above, it is only natural to ask about the ways such energy processes may be coordinated and optimized.

One possible answer to this question, based on the example of human societies, comes from forcing material agent societies to implement *economic* and *political* sub-systems, capable of imposing *economic* and *legal norms* to the energy systems, and to the relations that such systems maintain with the material agent societies where they are embedded. Figure 5 illustrates the *hierarchy of coordination and optimization levels* that economic and political sub-systems may constitute in material agent societies.

Clearly, the economic and political systems are two of the organizational sub-systems of a material agent society where *action* (the third type of activity of the *active life* of the material agents) occurs in that society.

7 Conclusion

This paper aimed to contribute to the proper theoretical treatment of the *energy aspects* of material agent societies. For that, the paper introduced the idea of *energy systems* of material agent societies, and formal concepts for the analysis of their structure and functioning.

The backbone of the paper is a *materialistic* approach to agent societies, where *energy* is taken to be the central concern. Such approach was built on Hanna Arendt's analysis of the *active life* in human society, given in terms of the activities of *labor*, *work* and *action* [3].

The concept of energy system of material agent society was defined in a way that supports the

definition of two additional (and, in fact, indispensable) organizational sub-systems of energetically autonomous material agent societies, namely, the *economical* and the *political* organizational sub-systems, through which the structure and functioning of the energy systems of those societies are to be managed.

To the best of our knowledge, no previous work has concerned itself with the concepts of material agents, material agent societies, and energy aspects of material agent societies.

8 Acknowledgements

The author thanks the participant of WESAAC 2017 that raised the issue of the *optimization* of the energy processes, during the discussion of the paper presentation. This work had partial financial support from CNPq (Proc. 310423/2014-7).

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