White paper on synergies between sustainable development and cognitive systems

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1. Introduction: a framework for environmental sustainability and cognitive agency

The demands imposed by the industrialised societies result in a generalised degradation of the natural environment. This effect can be appreciated for instance in the collapse of natural resources, the pollution of the atmosphere, contamination and scarcity of hydrological resources and the global warming effect. The overall decay in the natural environment poses great risk to ecosystems, which is seen as direct consequence of the activities of our society.

The natural environment is the context in which human society has flourished. Historically the strong damage to natural resources has resulted in the disappearing or radical transformation of societies. The biological consequence of the transformation of the natural environment is, when possible, the adaptation of living species to new niches. Humans too, inasmuch biological systems, have adapted to the new circumstances, which include both the natural environment and the social environment.

Agriculture being historically been the most important human activity, and it was at the centre of human integration in its environment. Nowadays, nevertheless, activity has shifted towards modern industrial and technological activities. It is a widespread view are modern activities are generally dissociated from the environment. Human activities, concentrated in the urban context, are drawn towards specialisation and instrumental routines, creating a new form of agency that lies further from the natural environment than in the past.

The new condition of human activities and their unprecedented scale have introduced the possibility of chain reactions that may alter the natural environment in dramatic ways. Sustainable development is the attempt to conduct the changes associated to industrialised societies in a way that would avoid the collapse of the natural environment.

The challenge is twofold. On one hand, it concerns the stability of ecosystems and the difficulty of managing environmental resources. But, more fundamentally, it is also about whether current forms of human agency, dissociated to a great extent from the natural environment, can be sustained in the long term. Or, in other words, whether modern human agency can be said to be properly adaptive. For this reason environmental studies more often than not reach out to our constitution as cognitive agents, to find a direct responsibility in our everyday way of life. In a similar way, many have proposed a return to an environmentally conscious way of life.

Current research in environmental technologies looks for solutions that minimise the consequences of human activities, by either reducing the original impact, or by offsetting the impact with complementary actions. This approach deals with more or less local or specific effects, lacking a global perspective that can ensure the viability in the long term of such solutions. For this reason, it is essential to develop a science of ecological sustainability, which would also provide a practical framework for action.

This science should include not only the actual systems we want protect, but also the relationship between human activity and the environment. It is necessary, therefore, an interdisciplinary effort that would take into account physic and chemical aspects as well as biological and socio-economic. The centre of such theory, nevertheless, would be the interaction of an agent based society and its environment. In this sense, it would have much in common to cognitive science. This is more the case if, as argued earlier, not only the outcomes of behaviour, but also the cognitive stance of the agents is responsible for ensuring sustainability.

This paper introduces some of the shared characteristic between cognitive science and the science of environmental sustainability, and suggests the basis of a theoretical framework. In such framework, ecological sustainability and cognitive autonomy are seen as parallel phenomena that share underlying processes.

Cognitive systems are artificial systems that can interpret data arising from real-world events and processes; acquire situated knowledge of their environment; act, make or suggest decisions and communicate with people on human terms, This shared framework aims to set out some of the basis of the application of artificial cognitive systems to environmental management. The synergy between artificial cognitive systems and studies of sustainability thus needs may be expressed in concrete forms of control.

In section 1 we introduce the basic terms that are going to be applied throughout this paper. We then find some elements in common between environmental science and autonomous systems research.

In short, the relationship between cognitive science and a science of sustainability is twofold. On the one hand, there must be sustainability for an agent to be autonomous; on the other hand, the social and natural systems involved in our ecosystems may be considered autonomous. In section 3 we provide the sketch of a model to understand this synergy.

In the second part we focus on the problem of control in the sustainable development program. We first introduce the notion of self-organisation as a tool for control, as well as an environmentally central concept. We apply these insights to the study of environmental dynamics. Finally, as a case study, we present some guidelines for the control of waste management plants.

2. Core concepts

Sustainability

Sustainability refers to the capacity to maintain a process or state indefinitely. In recent years it has been used mainly in relation to side effects that the activity of human societies may impinge on the ability for these societies to continue as they did before. Sustainability can be endangered by the consumption of finite resources (e.g. fossil fuels, fresh water), the disruption of the natural regeneration of ecosystems, or the deterioration and pollution of natural resources. Although sustainability is mainly referred to human activities (such a manufacturing method or a government program), it is also a major characteristic of living organisms and ecosystems, which are naturally sustainable. If in individual terms evolution favours the fittest, in species terms it favours sustainable adaptation to current resources.

Sustainable development is a term applied to the social and economic development that allows a society to meet the present demands whilst not endangering its capacity to meet its demands in the future[1]. There are two fundamental insights that relate to the use and management of natural resources. First, the basic needs of the society must be met; second, development is not absolute, but it is limited by the current technology and social organisation, its effects on the environment and the ecosystem's capacity to accommodate to the effects of human activity.

In practice humans' behaviour is about accommodating the environment to their own needs. When acting in a **sustainable** way this modification takes into account the continuity of the environment. Unsustainable behaviour, on the other hand, has the consequence of altering the environment in ways that the conditions and resources required for that activity cease to exist. The irreversible damage to environmental condition demands from societies drastic solutions: the adoption of new activities, the transition to other environments, or simply extinction.

Life Cycle refers to the set of consecutive and interrelated stages of a system or activity, from the acquisition of prime materials or generation of resources to

[1] Definition derived from the one given by the Brundtland Commission (*Our Common Future*).

their consumption or disposal. The life cycle of an activity therefore belongs to a different time scale than the action itself.

Life Cycle Analysis is used as "a technique or tool to determine the potential impact associated to an activity or the production of goods, compiling an inventory of relevant inputs and outputs of the system; evaluating the potential impact associated to inputs and outputs of matter and energy, and interpreting the results of the different stages in relation to the objectives of sustainability.

Agency

Cognitive science deals with agents. An agent is a complex adaptive system that can reflect and act upon its environment (Moriello, 2005, p. 137). For Russell and Norvig, agent is anything that can be seen as perceiving its environment though sensors and acting upon it through its effectors (Russell and Norvig 1996, p.33). Thus one of the major characteristics of agents is that they are situated; they are embedded in a local environment with which it interacts and which influences directly on its behaviour (Florian 2003, Muñoz Moreno 2000, Innocenti Badano, 2000).

Autonomy

Autonomy (from the Greek *auto* = self and *nomos* = law) relates to self-governance. A system is autonomous if an only if the organization of internal system processes is the dominant factor in the system's self-preservation. In robotics and artificial systems, autonomy refers to the capacity to operating without external human control. A system is autonomous if it uses its own information to modify itself and its environment to enhance its survival, responding to both environmental and internal stimuli to modify its basic functions to increase its viability.

In situated cognitive science, pure autonomy is not possible – any agent has to rely on the regularities and affordances on its environment in order to be autonomous. Autonomy refers thus more to the capacity of surviving in an environment than to the extent that such survival is independent of external factors. In dynamic situated approaches to cognition autonomy may be defined as the "homeostatic maintenance of essential variables under viability constraints through self-modulating behavioral coupling with the environment." (Barandiaran 2004)

Dynamic Self-organisation

Self-organization is a process by which larger scale order is formed in a system through the promotion of fluctuations at a smaller scale via processes inherent in the system dynamics, modulated by interactions between the system and its surroundings (Collier 2004).

Autonomous systems are often characterized by being self-organised. "Autonomous systems are mechanistic (dynamic) systems defined as a unity by their organization … their organization is characterized by processes such that (1) the processes are related as a network, so that they recursively depend on each other in the generation and realization of the processes themselves, and (2) they constitute the system as a unity recognizable in the space (domain) in which the processes exist " (Varela, 1979, p.55).

3. Autonomy and sustainability, a shared framework.

The challenge of sustainable development depends on our capacity to perceive, predict and prevent the noxious effects of our activities upon the natural environment. The objective is to avoid those aspects of our development that endanger the natural resources we require, and in general the ecosystems upon which we rely. The outcome is the definition of courses of action that would allow us to meet the needs determined for the society, without compromising “the ability of future generations to meet their own needs."[2]

In cognitive science, an agent (or an autonomous system) is considered to perceive situations relevant to its concerns, lateral effects of its behaviour and affordances present in the environment. Only agents capable of satisfying these requirements to a certain level can ensure their survival and continuity over time. The purpose of cognitive science is to explain the behaviour of agents (whether biological agents or artificial and social systems) in terms of goals, perceptual and cognitive processes and dynamics of interaction.

There are major differences between natural and artificial agents, namely the capacity for autonomy. Natural agents are capable of adaptation through close coupling between its purposes and affordance the environment. Artificial systems are not properly autonomous, because they require continuous supervision for the continuation of their activity.

In principle, well-designed artificial agents may be capable of maintaining their activity by linking their predefined goals to supported actions. Another thing is the capacity of becoming aware of changes in the environment for which the system has not been designed for. Brittleness is a notion that denotes the problems that artificial systems that are designed for specific tasks fail utterly when faced with unanticipated perturbations, and constitutes one of the major problems of AI and robotics (Anderson & Perlis 2005). The autonomy of an agent is thus directly ‘s capacity of sustain its activities in its environment.

The fundamental characteristic of artificial systems, in contrast to natural organisms, is that they lack a tight coupling with the environment, thus lack sustainability. Goal-oriented autonomy is not sufficient to ensure that actions upon the environment may not endanger the resources and affordances of the environment, and render the repertoire of actions inefficient. The challenge for artificial systems is therefore not only goal-orientation, but sustainability.

[2] United Nations. 1987."Report of the World Commission on Environment and Development." General Assembly Resolution 42/187, 11 December 1987. Retrieved: 2007-04-12

4. Sketch of an autonomy/sustainability model at different time-scales

While autonomy and sustainability can be studied in the same framework, they occur at different time-scales. Action can be analysed in terms of goals, generally linking time t to t', while the life cycle of the same action refers to a larger temporal framework, which is not unidirectional in time. A model that encompasses both phenomena need to take into account this larger temporal framework.

Ensuring the sustainability of the behaviour of biological systems is not, generally, in the cognitive repertoire of singular agents. Sustainability is guaranteed by an evolutionary process that underlies the actual behaviour of natural systems, and which is analysed at a different time-scale. It is for this reason that the sustainability of human technological and social systems is not guaranteed by a close coupling with the environment. The analysis of life cycle becomes therefore an essential component to determine the adaptive value of human activity.

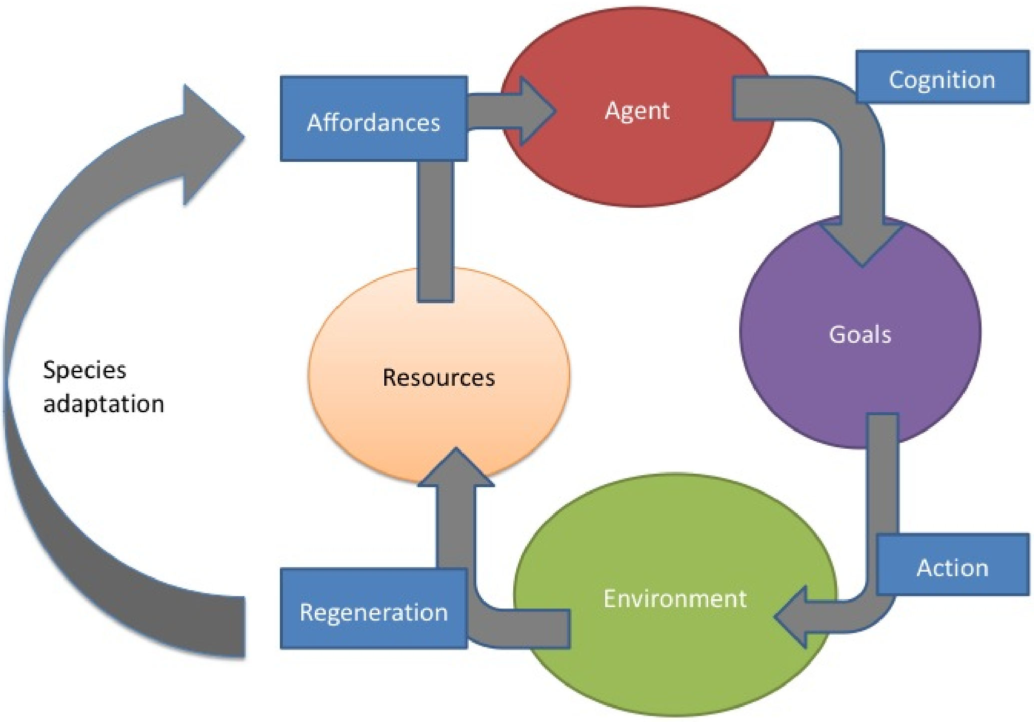

Figure 1. Life cycle of situated agency. The resources in the environment provide affordances for the agent. From its needs and concerns, perceptions as well as other cognitive processes, emerges goal-orientation or purpose (either relational or instrumental) in the agent / environment system. Actions will modify the agent's situation, and possibly involve the consumption of resources and other changes in the environment. If the resources are no longer available, the cycle is broken and there emerges an adaptive pressure to: find new affordances, new cognitive processes and goals,

different repertoire of actions. In short, changes in the cycle pose adaptive pressure to of the species.

The figure above attempts to show the different time-scales that relate to the goal-oriented and autonomous agency of a system, and the life cycle of its adaptation to the environment. The agent responds to needs and concerns of situations to attain general goals. This action is nevertheless dependant on the availability of whatever resources are required. The actions also modify the ecosystem in a way that, if the resources are not anymore available, the autonomy of the system is under question.

Although referring to different time-scales, both autonomy and sustainability resort on each other, and are both framed in the context of a systemic agency. Artificial systems (which may be of a social or technological nature) have been designed to solve the goal-orientation problem, resorting on human intervention for ensuring the system's sustainability.

This shared background between artificial cognitive systems and environmental science provides two insights. First, in order to achieve true artificial autonomy we must design not only for goal-orientation, but also for sustainable agency. Second, environmental management can gain benefits by considering the use of artificial cognitive systems in the control of social and technological systems to exploit autonomy and ensure sustainability.

The gap between both concepts is that, whereas cognition refers mainly to the individual action, as a process that mediates needs and concerns towards action-defined goals, sustainability and adaptation refers mainly to the action within a social or species context.

Despite this gap, cognitive agency and sustainability emerge from the same context, and are closely interdependent. The diagram above shows that an adaptive form of behaviour involves an inherent life cycle. The possibility of sustainability of the system emerges not only from cognitive operations at a small time-scale, but from the life cycle of the system.

There are therefore several ways to spell the interdependence between sustainability of a system and its cognitive capacities. On the one hand, intelligent and adaptive agency can only be possible in the context of sustainable operation. On the other hand, the study of behaviour can enlarge its natural individual time-scale to incorporate the life cycle of such activity. Thus, the study of autonomous agency cannot be reduced to the realisation of short term goal-oriented activity, but also understand how the behaviour is sustainable.

In the case of natural systems, such as living species, life cycle analysis will show the evolutionary adaptation of the species to a determined environment. In the case of artificial systems, evolution has to be substituted by a form of design that, taking into account and analysis of the life cycle, would ensure the sustainability of the system.

5. Self-organisation and autonomous cognitive systems

The scientific study of natural systems faces the challenge of explaining behaviour in terms of mechanical causes, or take into consideration that the system itself is such that drives on its continuation in space/time. The notion of circular causality, first applied in the field of biology, has gained relevance in cognitive science, allowing to understand the holistic organisation and reciprocal dependence of the processes involved.

The idea is that natural systems are defined by the unity of their organisation. Control is not effected from an external perspective that compares goals and concerns to current situations, determining adaptive courses of action. In natural systems, intrinsic forces that relate to the systems unity, can account for much of the control that ensures the continuity of the system. Such form of self-organised control is not only autonomous, but also sustainable.

Different studies have been carried out to determine if ecosystems are capable of stabilizing in time, allowing for a natural regeneration. A central question is whether this capacity may be attributed to its own intrinsic dynamics, demonstrating their condition as self-regulated systems capable of homeostatic functions.

Simberlogg and Wilson (198) develop such a study. They removed the entire anthropod faunas of six small mangrove islands in the Florida Keys, and later observed that the islands had been recolonized by terrestrial arthropods. They demonstrated that, even though the islands had been inhabited by different species, the total number of species was very similar to the previous one. Later they showed that the trophic structure of the communities in the different islands showed stability, even when the species that existed in each island had dramatically changed.

It is nevertheless important to be aware of the difference between the recovery of an altered ecosystem, as in the case just mentioned, and the generation of a new ecosystem, such as when landfills are created and later adapted to the natural surroundings. But the fact that different species were able to take up different trophic functions is relevant insofar as it demonstrated the capacity for adaptation of the mechanisms that ensure the homeostatic stability of the ecosystem.

From a technological perspective, the aim is to facilitate the design of systems that can be considered autonomous. Human intervention is desired to a minimum, at least during the operation of the system, although it will always be required to continuously judge the suitability of the system for the overall goals it has been designed for, including the sustainability of its functioning. The gap human intervention needs to fill relates directly to the coupling of the artificial system with its natural environment.

Robotics is an area of artificial cognitive systems in which the coupling with the environment has been a key issue. Robots are designed not only to perform goal-oriented tasks, but to be able to maintain a stable relationship with the environment. Self-organising design techniques, such as artificial evolution or neural networks, offer the possibility to maximise the coupling with the environment, therefore not only providing goal-directed design, but also robustness, generalisation and a degree of sustainability.

Self-organisation is nevertheless a wider technological tool. Its use underlies from the steam engine, to modern financial systems. The principle is that when a system generates its own dynamics, rather than being imposed from external forces, the system is more robust.

Self-organisation approaches to control are of interest not only for robotics, but for the engineering of control for complex industrial, economic and social systems. They may also play an important part in the challenge of leading a form of sustainable development. The perspective of cognitive science can be applied to environmental control, by considering systems such as social structures, industrial plants or parts of the ecosystem as autonomous agency.

6. Case study: the landfill

6.1 Environmental dynamics

In this section we introduce the notion of environmental dynamics as the behaviour of autonomous system. In brief, the idea is to consider systems derived from human activities as autonomous agents, that is, systems whose behaviour is determined by perceptions of the environment and directed to more or less defined goals, always ensuring the autonomy and sustainability of the system.

This perspective on sustainable development may be useful for the investigation of the behaviour of relevant systems, for instance landfills, places where solid waste generated by our population are daily disposed. We thus attempt to show that intelligent systems technologies can be used for the monitoring and control of the environmental impact of social and technological systems.

The development of an activity in its natural environment emerges from the dynamics generated by its physical, chemical and biological substrate. The notion of governance can be used to denote the intrinsic dynamics of the system in its interaction with its environment. A waste disposal plant, and in particular its embodiment in a waste mass. The process is goal oriented as the ultimate objective of the plan is the decomposition and medium-long term stabilisation of the waste in its environment. Nevertheless, a process of self-organisation is also in place, which governs the overall dynamics of the system.

Even when human control is active on the waste mass (which is the case only in a minority of world waste disposal plants), there is, to a certain extent, self-organised homeostatic control of the system. Change in the concentration of solid, liquid and gaseous substances is balanced by the system as a whole, probably through the generation of interactions with its environment that may or may not be noxious. The decomposition of the waste mass is always the product of self-organisation, whether the system can be said to have affected environment or not. The degree of environmental affection, is related to the sustainability of the system, and marks the viability of such systems in terms of the homeostatic equilibrium and environmental affection. This sustainability can be analysed through as Life Cycle analysis of the process of decomposition and stabilisation of the waste mass.

A homeostatic instability in the waste mass is normally associated to the presence of external factors to the self-organisation of the system. If we are talking about an external agent, it may lead the system to the fulfilment of its own goals, which in turn may not be sufficient to satisfy the requirements on the sustainability of the system. The waste mass may compared to a biological system insofar as it may have the capacity to correct its behaviour when the whole is altered.

An interesting concept that can be related to the goals of sustainability is that of health. Hippocrates thought that illnesses were healed by the natural actions of the body. The situated system formed by the waste mass contains physical and chemical mechanisms that form and regulate the system as a whole. Odum (1983 "Basic Ecology" Saunders Collage Publishing, Philadelphia; pag.46) asserts "ecosystems can be considered cybernetic by nature, but the control of its functions is internal and diffuse, not as in the human cybernetic devices where it is external and specific". Can both types of effects be reconciled?

In summary, we can say that the landfill generated by a communities waste is an autonomous dynamic system that can be described as possessing mechanisms that lead to homeostatic equilibrium. The landfill will be unsustainable when its dynamics impact upon the environment in ways that interfere with the natural stabilisation of the landfill in time.

6.2. The Landfill as self-organized System

In this section we develop the principles for a methodology for the control of waste management plants. The main feature of the approach is the consideration of the plant as an autonomous system, or in other words, as a unity that continues in time and is subject to intrinsic dynamics. The objective of the control task is thus to ensure that the resulting dynamics of interaction with its natural environment is stable in terms of its sustainability, minimising the need for actions external to the system.

The accumulation of waste over a determined environmental location is called landfill. The fact that it contains organic matter generates a series of physical, chemical and biological processes. The interaction of such process and its environmental creates a complex dynamical system that depends on many variables. The complex interactions of the different processes are nevertheless reflected in global behaviour of the waste mass, as a self-regulated homeostatic system. In a certain sense, we could say that the waste mass is a quasi-organic entity, capable of interacting with the environment.

Whatever the conditions and nature of the waste disposed and the environmental surroundings of the landfill, a particular dynamics of interaction and a potential for decomposition and stabilisation can be observed in any landfill. This dynamic is associated to a life cycle, which can be said to start when waste is deposited in the natural location. A landfill is said to complete its cycle when it stops interacting with its surroudings, decomposition concludes and the system stabilises. In that moment we can say that the waste mass has become ground.

Given that the waste materials, as well as the place and its surroundings are always different, not two landfills present the same dynamics. Nevertheless, behaviour is to a certain extent predictable, at least in the same way that the behaviour of animals is predictable given knowledge of the species.

The regulation and control of landfills as autonomous systems relies on the understanding of the dynamics involved. As any other complex system, modelling its dynamics is facilitated by the identification of relevant parameters (Kelso 1995). These spring from the observation of the behaviour from a holistic way, measuring mechanisms and the identification of variables. When variables can be externally modified they are called control parameters, and they may be used for the monitoring and control of the system.

The use of differential equations or computer simulations can allow us to discern whether the significant aspects of behaviour of the system can be predicted knowing the value of such variables. The type of knowledge achieved in dynamical models is limited, as it is based on a low-dimensional set of variables. It is therefore always possible to find particularities in concrete cases that may not be predicted by the model.

The dynamics of complex systems can be regulated and controlled to make the impact on the environment sustainable. Low-dimensional modelling allow, in principle, to determine how the modification of control variables would lead the system through different dynamic patterns.

In order to develop such form of control we must take into account two factors at large. On the one hand the Chemicals, physical and biological processes that occur within the waste mass (that depend of the characteristics of waste and how it is processed), and on the other, the capacity of the environmental surroundings to absorb the interactions (for instance emissions) with the waste mass. That capacity depends, not only on the actual state of the environment, but the history of natural cycles the have occurred in such place.

The interconnection between reactions- emissions of the waste and the place's capacity for contention is what determines the landfill. The landfill is therefore an intentional process or action, that is contained by the capacities of the environmental surroundings. The sustainability of the landfill is directly dependant on the impact-contention trade off.

The control and regulation of landfills consists of four aspects:

- The reactions generated by the underlying processes are known and can be determined through the study of relevant parameters.

- The polluting potencial of such processes are always effected unless the contention capacity of the enviornment allows their dissolution
- Different landfills present different dynamics
- The monitoring and control of the dynamics of the landfill is possibilitated through
  - The study of parameters or characteristics selected for their relevance in determining the direct or indirect effect of biochemical and physical processes in terms of pollution
  - The study and modelling of wastemass / environment relationship. These studies will generate conditions in the natural environment that will enhance the capacity for contention of the polluting effects of processes in the waste mass

7. CONCLUSIONS

In this paper we have considered some of the common aspects in the cognitive sciences and the principles or self-organisation, on the one hand, and the environmental sciences and the need of sustainable development, on the other. We have shown that the adaptive pressure on an autonomous cognitive system and the need for sustainability are closely linked and are interdependent, although they are phenomena that can be analysed in different time-scales.

This has led us to offer a shared perspective that would allow the modelling of the dynamics of systems situated in the natural environment, as autonomous cognitive systems. In this framework, we propose that the design for autonomy and sustainability social/environmental systems can be achieved through the definition of methodologies for control with the assistance of the technology of autonomous intelligent systems. One major advantage of such approach would be the exploitation the principles of self-organisation the underlie natural systems.

We have provided an introduction to the field of waste management through the analysis of the landfill methodology for waste management. We have offered an analysis in which the wastemass can be considered an autonomous system situated in a natural environment. The identification of relevant parameters can help us understand that self-organising principles that determine the autonomy of the system, as well as develop a methodology for control based on the such model.

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