Determining Airport Sustainability

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Abstract

In a world with ever increasing attention to global warming and greenhouse gases, aviation has been put under pressure to operate more sustainable. Airports form an unmissable link in the air transport value chain and hence feel the pressure to operate more sustainable too. This drives the need for airport consultants to come forth with design options and solutions to create more sustainable airports.

This research sets out to investigate the following question: How can airport sustainability be determined using emergy theory?

The result is an application of the emergy theory to an airport system that provides a viable and reliable outcome of sustainability measured by performance indicators derived from emergy theory. The airport under study is shown to have a low sustainability that is comparable to other consumer processes. It sheds a light on why airports and cities can form a close connection. Finally, the model shows that a design option that airport consultants have at their disposal can improve airport sustainability.

Keywords: Performance indicators, sustainability, sustainable development, emergy, airport

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1 Introduction

Society nowadays seems to enter a new stage in thinking about how it has been using its natural resources. Although concerns about what the results of our apparently unbridled use of natural resources are, apart from inspired thinkers and scientists[1] from earlier days, such as Malthus and his "Essays on the principles of population" in 1798, the western world did not seem to look seriously into these matters until 1972 when Meadows published his report *"The limits to growth: a global challenge"* as issued by the Club of Rome. Ever since, continuous efforts have been made in many fields of science to address the problems that have been identified in the report. Nowadays, the advent of Al Gore's movie '*'An inconvenient truth"* [2] can be argued to have pervaded the common man's thinking about the issues first raised in the report of the Club of Rome too.

Also in aviation, there has been a renewed environmental interest, green movement, or desire for sustainable development. The air transport industry

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[1] See for example [de Haan 2007, 76].

[2] See http://www.climatecrisis.net/
The importance of Mr. Gore's work was also recently recognized by the Nobel Comittee.

is one of the driving factors that enabled the economic development of many regions. It drives globalization as it facilitates Just in Time, JIT, supply chains and the operations of multinational companies [Williams 2006, 4-17]. Air transport growth is directly positively correlated to GDP growth, locally, nationally and globally [Zhang 1997]. But on the other hand, air transport contributes to 2.4% of total global CO_2 emissions from fossil fuel alone [IPCC 1999, section 6.1.4]. It is seen as a mayor emissions culprit.

Therefore, aviation in general is under growing pressure to operate more sustainable. Recent examples are: the new proposals by the EU to create unilateral trade schemes for CO_2; the reaction of the International Civil Aviation Organisation, ICAO, to set up its own working group, GIACC, to create ICAO's own framework to identify means to minimize aviations's impact on the environment[3]; various airlines that offer carbon offset options to their passengers; and in Holland, Schiphol Airport's plans to grow without compromising the environment by using hybrid powered ground material and pyramid shaped noise blockers, and the Dutch government's proposal for a Green Tax on every flight.

Obviously, this pressure to operate more sustainable will move throughout the aviation value chain[4] from passengers and airlines, to arrive at airports. There are two ways to look at this pressure, one of which is as a threat to business as usual, and the other is as a new challenge to look for business opportunities, and gain a competitive advantage over the rest of the playing field, [Burke and Logsdon 1996]. If airports want to substantiate their gain however, they will first have to measure it in some way.

The objective of this paper therefore is to investigate how airport sustainability can be measured. The research leads to a model derived from emergy theory which is applied to Amsterdam Airport Schiphol as a test case. It is shown that this airport is representative of consumer processes and not sustainable in the long run. A modification in airport design is evaluated and shows that airport sustainability can be improved, albeit marginally.

2 Theoretical Framework

This section will provide the theoretical framework upon which the research is based. It will first define what an airport is, then it will investigate what sustainable development, or sustainability is, and then explain emergy theory.

2.1 Airports

In their international standards for airport design, annex 14 to the convention, the IACO defines an aerodrome[5] as: "a defined area on land or water (including any buildings, installations, and equipment) intended to be used either wholly or in part for the arrival, departure and surface movement of aircraft" [Aerodromes 1999]. This general, more infrastructural oriented definition does little credit to the modern airport of nowadays. Doganis writes: "airports are

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[3] The GIACC is thinking in particular about the following four broad fields: Technologically driven improvements in both aircraft and airport infrastructure, operational efficiency gains, ATM improvement, and economic incentives and market-based and measures.

[4] See [Jarach 2005, 15].

[5] For more on the term airport and aerodromes, see [Horonjeff 1962, 193-199].

complex industrial enterprises. They act as a forum in which disparate elements and activities are brought together to facilitate, for both passengers and freight, the interchange between air and surface transport" [Doganis 1992, 7]. However, airports are not only complex industrial inter changers between modes of transport anymore. Think for example of the airport city: "a business strategy on part of the airport operator.. . . In terms of territorial definition, [it] is a more or less dense cluster of operational, airport-related activities, plus other commercial and business concerns, on and around the airport platform. However, this cluster is called an airport city only if it shows the qualitative features of a city" [Güller and Güller 2001, 70]. Therefore it can be said that globalization, liberalization and economic growth have broadened the scope of an airport from the more or less technical facilitation from one form of transport to another, to a whole within which technical, economical, environmental, and social systems interact with each other. This is referred to as the airport system [de Neufville and Odoni 2003, 9; 25].

To analyze such a interaction of elements and systems, this research follows the approach advocated by de Neufville. In analysis of airport systems he calls for the "need to develop the capability to identify the salient forces acting upon the system, and to trace out their implications for its performance" [de Neufville 1976, 10]. Therefore, the research sets out to identify salient forces acting upon the airport system and traces out their implications for the performance in terms of sustainability. Before this analysis can take place, it should be clear what sustainability is first.

2.2 Sustainability

Perhaps it is of use first to semantically differentiate sustainability and sustainable development. Sustainability will be seen as the state of a system, and sustainable development[6] as (the rate of) progress of a systems toward more sustainability.

This now leaves the question on how to define that state which can be called sustainable, or the concept of sustainability. The search for such a definition presents some problems. The starting point of many publications on sustainable development is the definition of the WCED committee in 1987:

> Sustainable development is the development that meets the needs of the present generation, without compromising the ability of future generations to meet their needs [WCED 1987].

What the needs of present and future are however, is indetermined. Also, from an resource point of view, there is consensus that the earth contains a limited amount of resources. Taking one resource diminishes the stock of resources for the future. How can one therefore meet present needs by taking resources by *not* compromising the need for resources of those in the future? Therefore, this definition has been criticized as self contradicting and anthropocentric, [Norton 2003], and as an empirically empty categorical imperative, [Sikdar, Glavič and Jain 2004, 13]. Resuming, as Carley and Christie note, this definition leaves complex debates in progress.

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[6] For a discussion on whether development can be unsustainable as well, and a discussion on the decoupling of the terms sustainability and development, see [Carley and Christie 1992, 25-28].

Other definitions, proposed by [Barbier 1987], [de Haan 2007], [Daly 1990], [Sikdar 2003], [Weitzman 1997], or [Krautkraemer and Batina 1999] all fail to meet the strict demands set by various academic fields. The problem is that "…there are so many definitions"[de Haan 2007, 77], and "…'sustainability' clearly means different things to different people at the level of both principle and detail, and it is at the level of detail that consensus on its meaning is hardest to maintain" [Upham et al. 2003, 7]. As Pezzey puts it: "…to try to distill, from the myriad debates, a single definition which commands the widest possible academic consent…is an alchemist's dream, no more likely to be found than the elixir to prolong life indefinitely" [Pezzey 1997, 448].

Does that mean that the concept of sustainability is utterly illusive? Although indeed no concise definition is available, and Norton warns us that "…the search for an all encompassing definition of sustainable development that is self-consistent can be seen as a search for *the* axiom for action on sustainability, this search for a "Holy Grail" is a misguided notion"[Norton 2003], it is possible to see sustainability as an ideal, that provides an abstract concern to those working with it, even though they might differ profoundly on the precise definitions and processes to arrive at it [Sikdar, Glavič and Jain 2004]. Rather, using a meta definition, sustainable development may be defined as: that linguistic tool with which we denote the best of an effort, at any given scale, at any given hierarchical level of whatever theory or topic, taking into account as much as it can the various aspects, concepts, dimensions, and notions of what others mean by it, to co-evolve by among others trade-offs, to a more sustainable state.

To validate any operationalization or indicator of a system that has been derived from a distinct definition or perspective of sustainability, the emphasis lies on the use and the function of the indicator, [Azapagic and Perdan 2000, Hardi and Pintér 1995, Bossel 1999], and the criteria behind it, [Esty et al. 2005, Pintér et al. 2005, Sikdar 2003, Esty et al. 2006, Pintér et al. 2004]. The question is not whether it is indeed that unique representation of sustainable development. The broader the consensus on this indicator set, the more valid it is.

With this in mind, the search is now for a theory that takes as various aspects, concepts and notions of sustainability into account and operationalizes it with specific function and relevant criteria.

2.3 Emergy theory

Reality can be abstracted into systems. There are various forms of systems around. Nonetheless, all systems are governed by the same laws of thermodynamics [Bakshi 2000, 1768] and [Giannantoni et al. 2002, 28]. Therefore, a framework that is based on thermodynamic principles can be used in analysis of systems.

Nature consists of animals, plants, microorganisms, earth processes, and human societies. These individual parts of nature are linked by pathways over which material passes and cycles, thus carrying energy from one part to another, from one individual to another. Systems of the biosphere are actually maintained by these cycling flows of energy and material. Without continual flow of energy that creates order, systems degrade away. Energy however is not always the same. Although the same amount of joules of sunlight and joules of electricity are both theoretically capable of heating 1 cm^3 of distilled water at standard atmospheric pressure from 14.5 °C to 15.5 °C, it is clear that valuation of both types of energy on the basis of being able to heat water is not a fair one, even if thermodynamically they have the same value. To compensate this loss of qualitative information, Odum reasoned the energy used in previous transformations to arrive at the current state should be accounted for [Odum 1971, Odum and Odum 1981, Odum 1996, Odum and Odum 2000a, Odum 2002, Odum 2007].

To reflect the accounting of previously used energy, and to substantiate the qualitative aspect of energy, Odum defined emergy, a measure to evaluate the work of nature and humans, as follows:

> Emergy is the available energy of one kind previously used up directly and indirectly to make a service or product. Its unit is the emjoule [Odum 1996, 7].

Several authors point out that the available energy depends on the process and the environment and can therefore, where appropriate, be substituted by the concept of exergy[7].

To relate energy and emergy, transformity, τ, is defined as: "...the emergy input per unit of available (exergy) output. It is measured in emjoule per joule" [Brown and Ulgiati 2004a, 206].This is mathematically equivalent of stating:

$$Em = \tau \cdot Ex \tag{1}$$

Emergy thus relates the quality of the energy, expressed by the transformity, to the quantity of the energy, expressed by exergy [Lourenci and Zuffo 2004, 411], [Giannantoni 2004, 141], [Brown and Ulgiati 1997, 54], [Giannantoni et al. 2005, 1997], and [Hau and Bakshi 2004a, 3].This is illustrated by figure 1.

Emergy and money can also be related. Suppose money is something that can be exchanged for real wealth, that is: goods, services, material etc. Money comes in two forms: material and information [Odum 2007, 252], where either can be seen as energy. When real wealth comes into a system, it is accompanied by a counterflow of money, see figure 2 [Odum and Odum 1981, 41] and [Odum 1971, 174]. The emergy per unit money can be calculated for any economy by dividing the emergy use by its gross economic product under the assumption that the economy and the ecology are an integrated system. In other words, the ratio of emergy to money is in essence the fraction of total emergy required to circulate 1 dollar of gross economic product [Brown and Ulgiati 1999, 4]. If the total emergy of a product is divided by the ratio of total emergy over gross economic product, the economic equivalent of emergy is found. This can be expressed in emdollar or emeuro or any other currency. This unit denotes the part of the total buying power it contributes to the economy.

To understand the relationship between energy and the cycles of material and information, is key to gain insight in the relationship between society and the biosphere. Emergy theory uses the flows of energy and materials in systems to show the relationship between man and nature. These flows are not constant over time, but pulse. As a consequence of this, the best use of resources

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[7] See among others: [Yi et al. 2004, Bakshi 2000], [Bakshi and Ukidwe 2004, Brown and Ulgiati 2004a], [Bastianoni et al 2004, Brown and Ulgiati 2004b, Giannantoni et al. 2005], [Jørgensen et al. 2004, Hau and Bakshi 2004a, Hau and Bakshi 2004b], and [Heijungs 2007, Giannantoni 2004, Jørgensen et al. 2005, Odum 2002] and [Odum 2007].

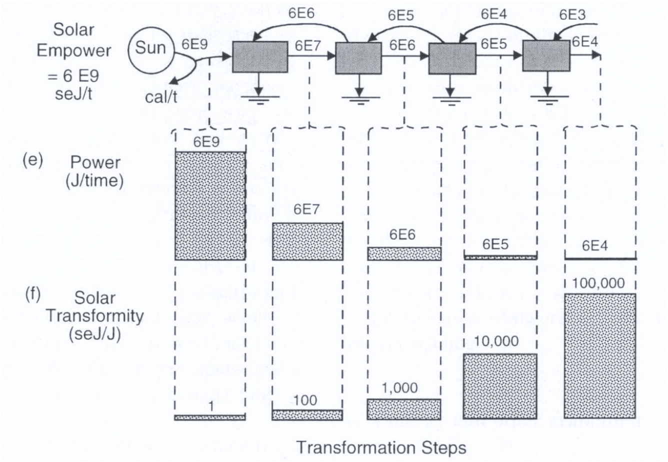

Figure 1: Energy hierarchy and transformation, from [Brown 2005, lecture 3].

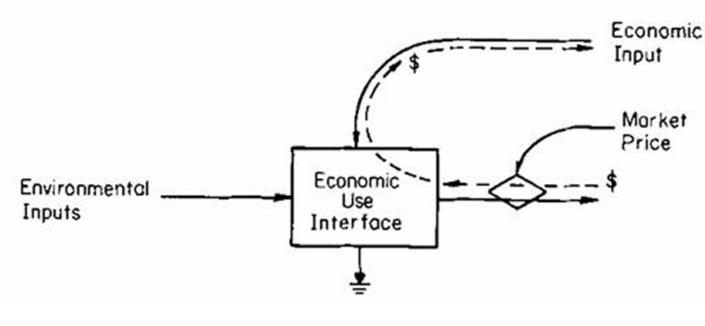

Figure 2: Ecological-economic interface, taken from [Brown 2005, lecture 3]

at different stages of systems differs. During growth, a system might have to process scarce non-renewable resources as fast as possible to survive in the long run, whereas during decline, survival of a system depends on the efficient use of renewable resources, and immediate use of scarce resources leads to imminent decline. Therefore, when describing criteria for judging sustainability of a system, with and without humans, during all phases of growth, the following factors need to be included: the net yield of the process, its environmental load, and the use of the (non-)renewable resources.

In emergy theory, all the flows that govern systems can be aggregated into the following flows: renewable resource flows, R; non-renewable resource flows, N; which can be subdivided into slowly renewable resources[8], SR, and true non-renewable resources[9], NR; the purchased or imported goods and services flow, F; and the yield flow, Y. This is schematically represented by figure 3. As these four aggregated flows represent all the flows in the system, using these flows, it is possible to analyze the system and its operation. To this end, several emergy performance indices have been compiled[10]. They are:

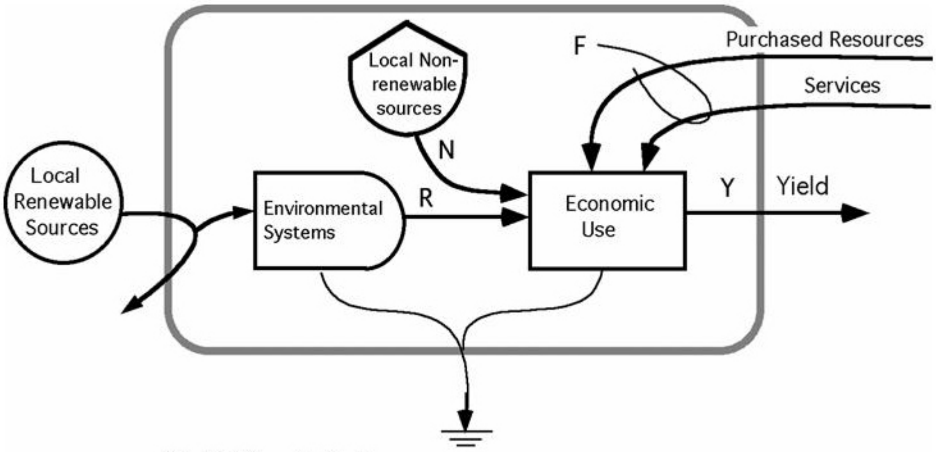

Figure 3: Aggregated flows, from [Brown 2005, lecture 3].

Y The process Yield. It is the total emergy delivered to the environment outside the system

$$Y = R + N + F$$

Φ_r The percentage renewable emergy. It is the renewable emergy used by the

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[8] For example wood if it is harvested at the rate of replanting. Hence, this adheres to the regeneration principle.

[9] These are resources that are used at rates much greater than their replacement time, such as oil and coal.

[10] For their origen, see [Bakshi 2000, 1771], [Brown and Ulgiati 2004b, 333], [Brown and Ulgiati 1999, 7], [Brown and Ulgiati 1997, 56], [Almeida et al. 2007, 65], [Valyi 2005, 16], [U.S. Environmental Protection Agency 2005, 2-13], [Campbell et al. 2007, 418], [Brown and Ulgiati 2001, 479], [Ulgiati et al. 1995, 524], [Marchettini et al. 2001, 268],[Higgins 2003, 87], [Brown and Vivas 2005, 293], [Ulgiati and Brown 1998, 26], [Odum 2002, 140] and [Odum 1996, 84]

process as a fraction of the total emergy.

$$\Phi_r = \frac{R}{R+N+F}$$

EYR The Emergy Yield Ratio. It is the ratio of the emergy output of the process divided by the emergy of those inputs that are fed back or imported from the outside of the system. The EYR is a measure of a process to exploit and make available local resources by investing outside resources. The lowest possible value is 1. If a process has a EYR slightly higher than one, it means that there is no significant net emergy contribution to the outside[11]. In this sense, the process is a consumer process and does not contribute to more real wealth[12].

$$EYR = \frac{Y}{F}$$

ELR The Environmental Loading Ratio. It is the ratio of the imported and non-renewable resources to the renewable resources. The ELR measures the pressure of the process on the local ecosystem and can be considered a measure of ecosystem stress due to production activity. If an ecosystem consists only of nature, it will only use renewable resources, and hence its ELR would be 0. The higher the ELR, the further away from natural conditions[13]. The lower the fraction of renewable emergy, the higher the pressure on the environment.

$$ELR = \frac{F+N}{R} = \frac{1}{\Phi_r} - 1$$

EIR The Emergy Investment Ratio. It is the ratio of the emergy purchased to the local renewable and non-renewable emergy. If compared with other processes, it shows the effectiveness of the use of imported emergy.

$$EIR = \frac{F}{R+N}$$

ρ_{emp} The empower density. This is total emergy of the process divided by the area, A, of the system. Higher empower densities are correlated with higher transformities on the individual process scales.

$$\rho_{emp} = \frac{Y}{A}$$

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[11] This can be the next higher system, the economy, or society.

[12] [Brown and Ulgiati 2004b] shows that primary energy sources, such as coal and oil, usually have EYR of higher than 5, whereas secondary energy sources and primary materials such as steel show an EYR of around 2 to 5.

[13] In [Brown and Ulgiati 2004b], the distinction is made as follows:

ELR	Value
$0 < ELR < 2$	Low stress
$2 < ELR < 10$	Moderate stress
$10 < ELR < \infty$	High stress

In [Brown and Ulgiati 2001, 479] an ELR of intense economic activity and highly urbanized areas was found to have values over 1000.

SA_r The renewable Support Area. This is the area using just renewable emergy needed to support the total process emergy. It denotes the necessary area of the surrounding environment that would be required if the economic activity only uses renewable energy.

$$SA_r = \frac{F+N}{\rho_{emp_r}}$$

Where ρ_{emp_r} is the renewable emergy R of the process, divided by area A.

EER The Emergy Exchange Ratio. This is the ratio of the emergy received to the emergy given in any economic transaction. It indicates whether the system loses or gains real wealth through a transaction.

$$EER = \frac{Y_m}{Y_g}$$

Where Y_m is the monetary value of the transaction times the emergy per money value of the system and Y_g is the emergy given in the transaction.

ESI The Emergy Sustainability Index[14]. It is the ratio of EYR to ELR and measures the potential contribution of a process to the system per unit of environmental loading. As all systems strive to maximize empower, the ESI measures how efficient a particular process uses it's emergy to maximize empower. The more yield per unit emergy, while loading the environment less per same unit, is the most sustainable way a system can use its emergy. This index, suggest [Brown and Ulgiati 1997], might be used in two ways:

- To compare different processes yielding the same product; the higher the ESI, the better the process uses its resources.
- To evaluate technical and technological innovations. Innovations can be investigated to see if they deliver higher yield per unit input of the system, thereby making it more sustainable.

Values can range between 0 and ∞, where values between 0 and 1 are indicative of consumer processes and values between 1 and 10 have been found for developing economies.

$$ESI = \frac{EYR}{ELR}$$

These emergy indicators provide quantitative insight into sustainability because they make the relations between environmental load and yield to society explicit.

3 Measurement

3.1 The systems diagram

To produce a systems diagram, Odum describes five steps that should be taken [Odum 1996, 76-77].

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[14] The ESI can be modified for the loss of real wealth of a system by multiplying with the EER.

The first step is defining where the boundary of the system lies. As was described in section 2.1 the airport system is a collection of various interacting systems and can therefore have many distinct boundaries depending on the perspective used. From the emergy point of view, it is important that the macroscopic view is taken so as to include all relevant aspects from a highly aggregated point of view. This has as a consequence that the model cannot be too detailed, as this will cloud the emergent aspects of the system. On the other hand, the scale of the system cannot be taken too large, as the number of inputs and processes will become harder to define and filter for relevance. For this reason, for example the catchment area of an airport is not taken as the system diagram. Although this is the theoretical area where one of its most important inputs, the passengers and cargo, comes from, it is clear that the analysis of a 200 km diameter circle, with it's cities, nature, and inhabitants is too complicated and time consuming. The system boundary that this research uses is the total land that is owned by the airport, or attributed to the airport by relevant authorities. Within this boundary exists another boundary, namely the boundary of the fence around the airport. As the fence demarcates the physical entity of the airport, the land owned by the airport is relevant because this is where for example airport cities, or airport green spaces, or other non-aviation related value is generated.

The second step lists the sources that contribute to the system. This step identifies in- and outputs. The sources can be divided into the aggregated system inputs R, N, and F, and the system output Y. The local renewable resources R that are fed into the system are: the sun, the wind, the rain, the use of geopotential and the use of geothermal heat. According to emergy theory conventions, they are placed at the left side of the systems diagram. Examples of each of the sources are given. The sun provides heating to buildings, allows airport green to grow, provides energy to agriculture, and produces energy through the use of solar panels if applicable. The wind provides for water evaporation, the dispersion of pollutants and sometimes the effective shortening of runway length. The rain provides for water 'for free' for all agriculture and greenery at the airport. Geopotential provides for the transportation of resources and allows for the retrieval of potential energy in water flows. Geothermal heat provides for the warming of buildings in the winter, and the cooling of them in summer. The local non-renewable resources N that are fed into the system are: the use of ground water more than it is refilled and the use of fertile top soils in agriculture. The purchased resources F that are fed into the system are: potable water, jet fuel, foods and drinks, goods and materials, electricity, labor, passengers and cargo, and money. Finally, the outputs of the system Y are: transported passengers and cargo; and emissions such as: CO_x, NO_x, SO_x, solid waste, contaminated surface water, noise, fine dust and VOC.

The third step lists the system components. This step identifies the components within the boundary though to be important for the scale of the system. As the spatial scale of the system is the land area owned by the airport, only components that influence on this scale are listed. The temporal scale of the system is in a one year analysis period. This implies that all influences either or larger scale are discarded. On a high aggregation scale, the components identified in the system are the following: agriculture outside the fence; airport green inside the fence; the terminal, piers, aprons, taxiways, and connected buildings such as ATC tower; a waste (water) treatment plant; fuel storage; commercial stock, such as the goods sold in airport retail shops and canteens; fixed solid assets, such as real estate; and image, that is the airport branding and awards, and customer satisfaction. As a final components, passengers, money, and cargo are present at the airport.

The fourth step lists the processes within the system. Processes are the information flows, relationships, transactions, interactions, and production processes. To given one example of such processes, the 'terminal' is taken. The terminal receives warmth, and potentially solar power, from the sun. The terminal also gets input from the agriculture. This is because first the agriculture might deliver products to the terminal that will be sold to passengers, and second because it collects money each year of leasehold property. Local non-renewable resources can also form input to the terminal, such as a local quarry on the airport terrain such as in Taiwan. Some terminals use geothermic couples to generate energy, or use geothermal heat exchangers to regulate their climate. The landscaping or airport green gives input to the terminal because it heightens the attractiveness of the terminal, and if incorporated properly, can influence terminal climate. Further inputs to the 'terminal' are potable water; jet fuel, through the fuel storage and dispense facilities; foods and drinks, together with other goods and materials, manifested in stored commercial stock, and of course the solid facilities that make up the buildings, runways etc; and of course labour and electricity. Then the terminal itself also generates processes. It produces solid waste and waste water, and through aircraft movements various emissions. Because of its characteristics and operations, the airport generates a certain image that has its influence on passenger and cargo behavior. Most important, it provides the added value of the airport system to the passengers and cargo. In similar fashion other elements are linked.

The fifth and final step consists of the graphical translation of the previous four steps in the system diagram. The outer boundary represents the total land area under control of the airport. The inner boundary can be seen as the fence. Sources are arranged from left to right according to their expected transformity. Money is only paid to human services. For the sake of clarity, the pathways of degraded energy to the sink are left out. The resulting system diagram is presented in figure 4.

3.2 The emergy evaluation table

Once the systems diagram is made, the next step is the construction of an emergy evaluation table. For all flows, separate tables are constructed to evaluate the emergy contents. As described in [Brown and Ulgiati 2004b], these tables consist of 7 columns. These columns are described below:

- Column 1 is the number of the item under investigation. The number serves to identify footnotes that explain calculations.
- Column 2 is the name of the item under investigation.
- Column 3 is the raw input data of the item under investigation.
- Column 4 is the units in which column 3 is expressed.
- Column 5 is the emergy per unit of the item under investigation.

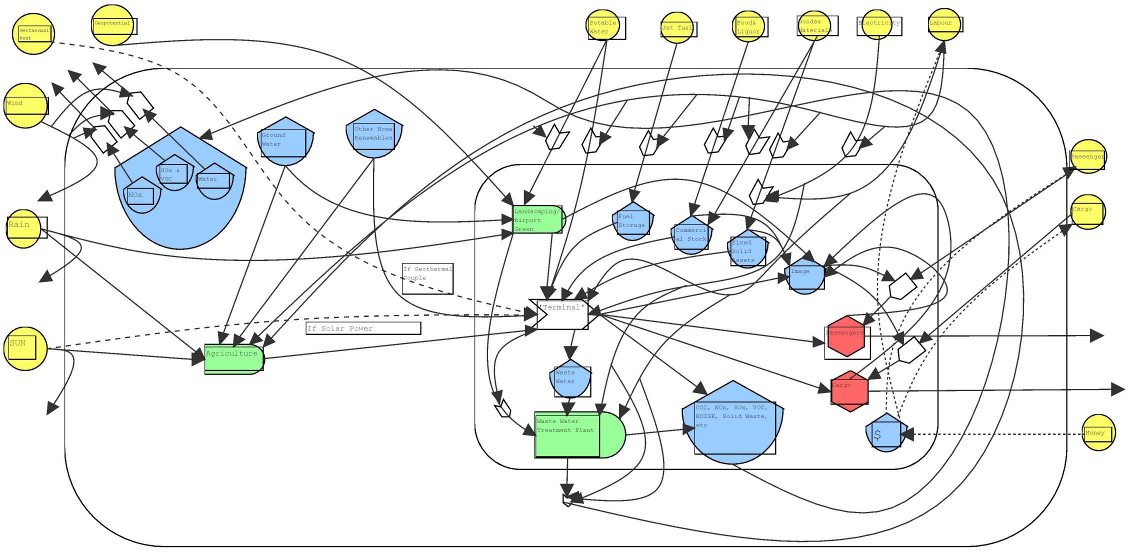

Figure 4: The system diagram

- Column 6 is the solar emergy of the item under investigation.
- Column 7 is the emeuro value of the item under investigation.

The input for column 2 comes from an evaluation of the sources as identified by figure 4. Each of the individual sources is evaluated according to existing evaluation methods in emergy literature. All transformities have been taken to the base global emergy budget of $15.83E24seJ$. As an example, the kinetic energy of the wind, parameter $R3$ is evaluated as follows:

The wind is taken as acting on a certain surface. On that surface, the energy of the wind can be calculated by it's speed, drag and density. The formula can be found in [U.S. Environmental Protection Agency 2005]. Now that the wind energy in Joule per year is known, it can be expressed in emergy by multiplying it with the average transformity of wind [Kangas 2002]. Finally, the emergy value of the wind can be related to money by multiplying it with the emergy to money ratio, see 2.3, to produce its emvalue. In similar fashion, all identified inputs have been evaluated.

With the results from the emergy evaluation table, the aggregated flows N, F, R, and Y are determined. These in turn serve as input to the performance indicators.

The emergy evaluation tables that are presented in this research are in a certain sense not complete. The emissions of the aircraft have not been taken into account. This is because of two reasons. First, there is no clarity in emergy theory how to model these parameters in the systems diagram exactly. Although they are clearly a product of the system, it is hard to see them as pure yield to society. Therefore, it becomes debatable how to incorporate them. Second, there is no procedure or data at hand to estimate to a first order the transformities of these data. Therefore, even if it was known how to model the emissions, it would not have been possible to evaluate them in terms of emergy. As a result, they have been left out.

Nonetheless, although even without the more detailed data and emissions the reliability might be lower, the model still validly reflects sustainability.

4 Results of the airport measurement

4.1 Results evaluation

The first thing to notice when evaluating table 1, is that of all the local renewable resources, wind by far plays the largest role. Of course, given the geographical location and the absence of geothermal couples, not much input can be expected there. As stated in section 3.1, wind contributes to the airport in the sense that it shortens take offs and landings, it distributes emissions to concentrations that are less harmful and transports nutrients for local agricultural systems. Given the fact that so much wind emergy is present, and wind has such a positive effect on the overall airport sustainability, more use of this energy source should be taken.

Of all the purchased resources, the biggest contributions are made by fuel, labor, and cargo. An increase in these resources lowers the ESI. Therefore, in a sense, it is not so much the construction of an airport that is detrimental to the environment, but more its use. Although more fuel probably means more flight movements and hence more passengers and turnover for the airport, the overall cost of increasing emissions and using up more of the available oil weighs heavier for sustainability. One option for airports to think about is pro-actively making the airport one such where no kerosene can be tanked. With low cost carriers tanking at their home hubs, and increasing attention to fuel prices and hence bunker behavior, this option could be viable and would result in a more sustainable airport within this frame of analysis. Decrease in labor will reduce airport cost, and would free up labor for the bigger system around the airport. Besides these aspects, if current airport operations can be maintained, it would be an increase in efficiency. Cargo and passengers are both inputs to the system that use up a lot of resources. However, without passengers or cargo, and airport has no right of existence. There seems to be a certain trade off or dilemma here that seems worthwhile to investigate. Is it more efficient to cap the pax and cargo number for an airport and spread them to smaller reliever airports, or does the hub operation of scale prove to be most sustainable? There are certain some questions worth following up.

The emergy performance indicators show that the percentage of truly renewable energy of this airport lays around the 14%. This is still relatively good if it is compared to for example the same ratio for the state of West Virginia of around 3%, [U.S. Environmental Protection Agency 2005, 3-16]. The EYR of around 1.17 is representative for a process that does not contribute much net emergy to the outside. In other words, the process takes 5 resources from the bigger system it is embedded in, and only gives 6 back. The ELR of around 6 is indicative for systems with moderate environmental stress. However, it seems still far off from the values of over 1000 that were found for intense economic activities and highly urbanised areas found by [Brown and Ulgiati 2001, 479] and the value of around 20 for West Virginia [U.S. Environmental Protection Agency 2005, 3-16]. The

<table>
<tr><th colspan="7">Locally Renewable Flows R</th></tr>
<tr><th>Item #</th><th>Name Item</th><th>Data</th><th>Unit</th><th>Transformity[a]</th><th>Emergy[b]</th><th>Emmoney[c]</th></tr>
<tr><td>1</td><td>Sun</td><td>9,13E+15</td><td>J/y</td><td>1[d]</td><td>9,13E+15</td><td>120</td></tr>
<tr><td>2</td><td>Rain</td><td>2,39E+14</td><td>J/y</td><td>30408</td><td>7,29E+18</td><td>95.876</td></tr>
<tr><td>3</td><td>Wind</td><td>4,96E+18</td><td>J/y</td><td>2513</td><td>1,24E+22</td><td>1,63E+6</td></tr>
<tr><td>4</td><td>Geopotential</td><td>9,92E+8</td><td>J/y</td><td>37536</td><td>3,72E+15</td><td>49</td></tr>
<tr><td></td><td>Total R</td><td></td><td></td><td></td><td>1,24E+22</td><td>1,64E+6</td></tr>
<tr><th colspan="7">Locally Non Renewable Flows N</th></tr>
<tr><td>1</td><td>Top Soil loss</td><td>1,39E+13</td><td>J/y</td><td>123984</td><td>1,72E+18</td><td>22.722</td></tr>
<tr><td></td><td>Total N</td><td></td><td></td><td></td><td>1,72E+18</td><td>22.722</td></tr>
<tr><th colspan="7">Purchased Flows F</th></tr>
<tr><td>1</td><td>Potable water</td><td>6,70E+12</td><td>J/y</td><td>423360</td><td>2,83E+18</td><td>37.303</td></tr>
<tr><td>2</td><td>Fuel</td><td>1,01E+17</td><td>J/y</td><td>186312</td><td>1,89E+22</td><td>2,49E+6</td></tr>
<tr><td>3</td><td>Food</td><td>7,12E+14</td><td>J/y</td><td>5,72E+4</td><td>4,08E+21</td><td>5,36E+5</td></tr>
<tr><td>4</td><td>Liquor</td><td>2,39E+13</td><td>J/y</td><td>637476</td><td>1,52E+19</td><td>200.996</td></tr>
<tr><td>5</td><td>Electricity</td><td>1,13E+15</td><td>J/y</td><td>3,36E+6</td><td>3,81E+21</td><td>5,01E+5</td></tr>
<tr><td>6</td><td>Goods & Materials</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>De-icing</td><td>4,70E+4</td><td>l/y</td><td>3,8E+11</td><td>1,78E+18</td><td>23.471</td></tr>
<tr><td></td><td>Asphalt</td><td>3,43E+7</td><td>J/y</td><td>186312</td><td>6,40E+14</td><td>8</td></tr>
<tr><td></td><td>Concrete</td><td>7,55E+6</td><td>kg/year</td><td>9,26E+8</td><td>6,99E+18</td><td>91.931</td></tr>
<tr><td></td><td>Steel</td><td>1,00E+5</td><td>kg/year</td><td>1,8E+11</td><td>1,80E+18</td><td>23.739</td></tr>
<tr><td></td><td>total</td><td></td><td></td><td></td><td>1,05E+19</td><td>139.149</td></tr>
<tr><td>7</td><td>Total labor</td><td>3,86E+14</td><td>J/y</td><td>5,97E+5</td><td>2,31E+22</td><td>303E+6</td></tr>
<tr><td>8</td><td>Natural Gas</td><td>1,26E+16</td><td>J/y</td><td>739200</td><td>9,35E+21</td><td>122.E+6</td></tr>
<tr><td>9</td><td>Passengers</td><td>6,24E+13</td><td>J/year</td><td>5,97E+5</td><td>3,73E+21</td><td>4,90E+5</td></tr>
<tr><td>10</td><td>Cargo</td><td>1,61E+4</td><td>ton/year</td><td>7,23E+15</td><td>1,16E+22</td><td>153E+6</td></tr>
<tr><td></td><td>Total F</td><td></td><td></td><td></td><td>7,47E+22</td><td>982E+6</td></tr>
</table>

Table 1: Schiphol Airport emergy evaluation table

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[a] The transformity is given in seJ/unit.
[U.S. Environmental Protection Agency 2005] gives the transformity of items $R2$, $R4$, and $N1$.
The transformity of item $R3$ is taken from [Kangas 2002].
The transformities of items $F1$, $F2$ are taken from [Higgins 2003].
Transformitiy of $F3$ comes from the average of [U.S. Environmental Protection Agency 2005, Pulselli et al. 2007, Siracusa et al. 2007, Ulgiati et al. 1994].
Transformitiy of $F4$ comes from the average of [U.S. Environmental Protection Agency 2005, Brown and Ulgiati 2001].
The transformity of $F5$ comes from the average of values in [Wang et al. 2005], [U.S. Environmental Protection Agency 2005, Marchettini et al. 2001, Ulgiati et al. 1994, Brown and Ulgiati 2001].
The transformity of de-icing is approximated by the value of chemicals in [Ulgiati et al. 1994].
Asphalt has the assumption that it has oil as a basis and therefore takes the transformity of oil.
The transformity of $F7$ is the average of [Odum 1996], as updated by [Higgins 2003].
The transformity of $F8$ is the average of [U.S. Environmental Protection Agency 2005, Pulselli et al. 2007].
Finally, the transformity of passengers is approximated by the same transformity as for humans while performing labor, and the transformity of cargo is approximated by the average of mechanical equipment from [Ulgiati et al. 1994] and machinery [U.S. Environmental Protection Agency 2005].

[b] The emergy is given in seJ/year.

[c] Emmoney is expressed in euro/year.

[d] By definition.

Performance Indicator	**Value**	**Unit**
Y	8,72033E+22	seJ/year
Φ_r	0,143072196	-
EYR	1,166986453	-
ELR	5,989478218	-
EIR	5,988509737	-
ρ_{emp}	1,89511E+15	seJ/m2
SA_r	275605840	m2
ESI	0,194839418	-
Emergy to money ratio	7,60E+13	sej/euro

Table 2: Schiphol Airport performance indicators

airports EIR of around 6, which denotes how effective the use of purchased resources is against the local resources, also seems quite below that of the Taipei metropolitan service district, with a ratio of around 77, see [Huang et al. 2001]. Furhter investigation in these discrepancies is advised. The empower density is very high and closely resembles those found for the high density urban residential areas in Taipei. It seems logical that airports do take their place in the so called airport - city corridors as described by [Güller and Güller 2001] as a place where resources and inputs converge to create high transformities[15]. Because of its high load on the environment, this airport would need a support area of around 275 square kilometers to offset its effects. In other words, if the system had to yield as much to society just using nature, it would need this area. In a certain sense, this is an indicator that can be compared with the area needed for CO_2 offset. Finally, the sustainability index, ESI is around 0.2. Again, in train with section 2.3, this agrees with values found for consumer processes. This means that for every unit the process yields to society, it loads the environment with 5 resources. It indicates that the system does not use its resources scarce while delivering the greatest contribution. In that sense, it is far from having maximized its empower and there is much room for improvement. The process is a consumer process and does not contribute to more real wealth. In that sense, it is not a process that seems to have viability in the long term.

As was described in section 2.3, the transformity can be expressed by:

$$Em = \tau \cdot Ex$$

Where:

- Em is the emergy of the passenger, $1,85423E+15$ seJ/y; and
- Ex the exergy of the passenger is approximated by the energy that a person needs to stay alive and well fed, by the number of hours, 3, the energy need per hour, 104 kcal/hour, and the conversion to joules. This amounts to 1306032 J.

Hence the transformity of one passenger using this airport system is: $1,379E+9$ seJ/J. This is four orders of magnitude higher than the transformity of human labor, see table 1. This result shows that indeed for most people a lot of work

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[15] See also [Huang et al. 2001].

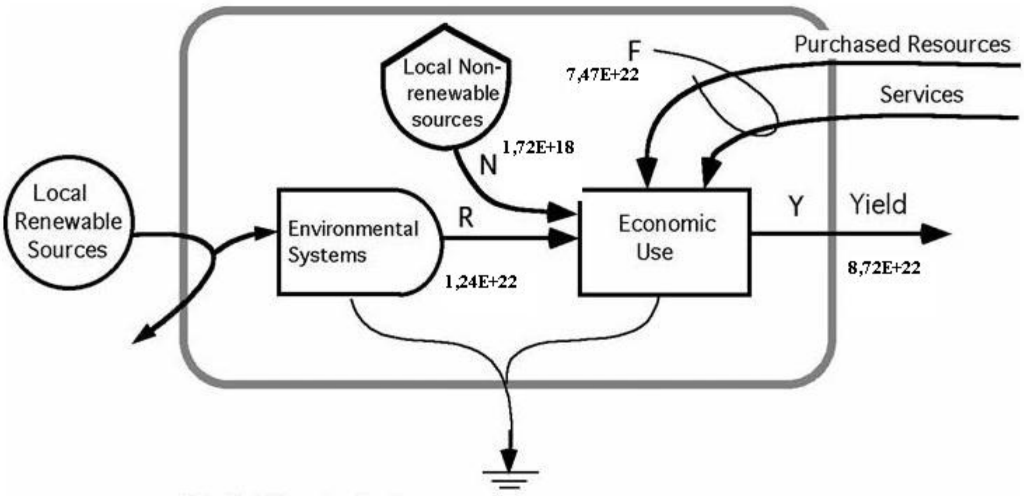

Figure 5: Aggregated flows and their values

and resources are spent to make use of air transport. If the result of their transport is used to increase the yield for the next bigger system, it is indeed a measure for the quality[16] of the people that fly and reflects a process high in the emergy value chain. With this measure, transformities of passengers across airports can be derived and used to compare which airports add more value than others. The same can be done for the other parameters.

A change in airport design Currently, there are many proposals done to further the sustainability of airports. This section describes how such a proposal for a more sustainable airport can be incorporated and evaluated in the model.

One of the many options under consideration is the change of apron, taxiway, and soon runway lighting from traditional Halogen Lamps to modern LED lights. The energy requirement of this apron, taxiway and runway lighting is approximately 3% of the total annual energy budget for an airport[17]. A preliminary study executed by NACO on behalf of a client in Asia revealed that the use of LED lightting will cut energy consumption for lighting roughly in half. The use of less energy is seen as a smaller burder on the environment and is therefore proposed as a means to make the airport more sustainability. It is therefore interesting to investigate the effect of these changes measured by the model.

The total airport electricity demand on an annual basis is 315227000 kWh. 3% of this energy budget amounts to 9456810 kwh. If half of this electricity is saved by using LED lighting, and the resulting total energy figure is entered in the model, the following values appear in tabels 3 and 4. It has to be noted that the trade off presented is not the most elaborate. LED lighting requires less power to run, and therefore decreases the energy budget of the lighting.

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[16] See section 2.3.

[17] This figure is established by means of personal communication.

Because of less demand, the generators, switches, batteries, and fuses can all be downscaled, which comes at lower cost. Also, the housing and cabling of the lighting system can be done with less material due to lower loads. Additionally, LED lights have a longer life span, they require less maintenance, but their cost is probably higher than traditional halogen lamps[18]. Therefore, an analysis purely on the basis of energy alone does not accurately reflect the real situation. Nonetheless, as longer life span, less maintenance, and a decrease in materials up the chain would even further decrease the emergy in these lamps, the higher cost are most probably easily compensated by this decrease. In that sense, the gains of LED lighting would be even higher.

Situation	**parameter**	**Energy**	**Unit**	**Transformity**	**Emergy**	**Emmoney**
Old:	Electricity	1,13482E+15	J/y	3360000	3,81299E+21	50.109.128
New:	Electricity	1,11779E+15	J/y	3360000	3,75579E+21	49.389.885
Difference		0,01703E+15	J/y		0,05720E+21	719.243

Table 3: Emergy evaluation input change due to LED lighting

Indicator	**old**	**new**	**difference (%)**
Y	8,72033E+22	8,71461E+22	-0,065593848
Φ_r	0,143072196	0,143166096	0,065631201
EYR	1,166986453	1,167114363	0,01096071
ELR	5,989478218	5,984893968	-0,076538387
EIR	5,988509737	5,983926123	-0,076540144
ρ_{emp}	1,89511E+15	1,89386E+15	-0,065959232
SA_r	275605840	275394896	-0,076538291
ESI	0,194839418	0,195010032	0,08756647
Emergy to money of system	7,60936E+13	7,60437E+13	-0,065577131

Table 4: Performance indicator change due to LED lighting

The case of the LED lighting illustrates that a change in design parameter with respect to the situation as is, is indeed reflected by the model in the direction that would be assumed at first. Even though the analysis is not complete, it is reliable in reflecting the trend in real life. Using LED lights indeed makes airports on the whole more sustainable. As can be seen from table 3, the proposed change would save quite some energy and emergy per year, resulting in a monetary gain of around 720 thousand euro per year. Given the lifespan of this type of lighting, this would suffice to offset the higher cost of lamps well within their life span and thus yield net economic wealth. To put things into perspective: the lighting energy consumption would decrease with around 50%, the total energy consumption would decrease with 1.5%, and finally the overall sustainability measured by the ESI would increase with 0.08% to a better state of sustainability.

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[18] Information based on NACO research and personal conversation.

5 Conclusion

This paper evaluates the performance of the airport system Amsterdam Airport Schiphol in terms of its sustainability, described and measured by emergy. It was found that airports do have a small net yield to society, but for the amount of resources yielded, the environment is loaded 5 times more. The values found in the performance indicators demonstrate that an airport is a consumer process and does not create net real wealth. It is therefore not a sustainable process. The empower density found at this airport is comparable to those of city centers. The linkage of airport and city is thus logical seen from this perspective.

The sustainability of an airport can be influenced by certain design and operational parameters. One of these parameters, the change from Halogen to LED lighting was evaluated. It was shown that the airport lighting energy budget could be cut by 50%, but on the field of improving the total airport sustainability, the increase was only 0.08%. Even though this figure remains small, the monetary worth of the improvement was calculated at 720 thousand euro per year. Given the long lifespan of the lamps, this is therefore economically and sustainably viable.

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