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Efficiency and sustainability indicators for passenger and commodities transportation systems The case of Siena, Italy

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Abstract

Three different energy analysis approaches (energy and embodied energy, exergy and emergy analysis) have been applied to the road and railway systems of a medium size district of central Italy, in order to shed light on the dynamics of the local transport sector and develop a tool for analysis capable of taking the system complexity into account. Road and railway systems, respectively, support passenger flows of 3.57E9 p-km (passengers per km) per year and 0.17E9 p-km per year and commodity flows of 2.5E9 t-km (tonnes per km) per year and 0.35E9 t-km per year, generating a total energy consumption equal to 1.84E5 tonnes of oil equivalent per year. The passenger mass transport on road (buses) shows globally the best performance among the patterns investigated, while railway ranks higher for commodity transport, according to most of the calculated intensity indicators. Several improvement options are also evaluated on the basis of the first- and second-order exergy efficiency. Some of the suggested improvements, even showing high theoretical possibility, do not match the transport needs of the investigated area, as indicated by their huge material and emergy intensities (measures of ecological footprints) even if it cannot be excluded that they may appear more appropriate to nationwide transportation patterns.

In conclusion, although data and indicators refer to a well identified region under specific geographic and socio-economic conditions, results suggest that a complex system such as transport is very unlikely to be described by a linear relation between input resource and output service delivered. Even when thermodynamically based approaches are properly used to describe the system behavior, findings very often do not converge, and require that different indicators are compared to yield a comprehensive picture of the system dynamics. An integrated approach is therefore suggested to support decision making in the presence of diverging results.

Keywords: Transports; Energy; Exergy; Emergy; Environmental indicators

1. Introduction

Several techniques for energy analysis have been developed in the last 30 years, mainly focusing on a used-side approach. According to this value paradigm, a resource is valuable in proportion of the amount of

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work that the user can get from it (exergy; Szargut, 1998). This paradigm also reflects the dominant neoclassical economic approach, where the economic output of a process is the main product of interest. A different approach (emergy and the maximum power principle; Odum, 1996; Lotka, 1922a,b), derived from previous studies on embodied energy analysis, is more donor-side oriented, so that value is assigned to those resources that receive a larger environmental support, under competitive conditions. These two points of view also characterize other evaluation methodologies that have been suggested up to recent times (Sciubba's extended exergy, 2000; Hinterberger and Stiller's material flow accounting, 1998; Szargut's cumulative exergy consumption, 1998; among others). Several analysts have considered, and still consider, them as alternative and inconsistent approaches. This is due to the fact that their spatial and time scales as well as the goal of their use are very often different. Results that are in apparent contrast, may offer the opportunity for an integrated picture of the same process, when it is investigated under different perspectives and within different scales of development. Instead of trying to assess the superiority of one evaluation approach on another, possible integration patterns should be explored, in order to get more appropriate answers to questions that pertain to different spatial and time domains.

This paper explores the consistency of the results from several evaluation approaches, trying to get complementary information about the thermodynamic efficiency of the investigated transportation system and the environmental sustainability of different passenger and commodity transport options. In so doing, an integrated assessment of several mono-dimensional indicators is obtained, thus yielding a more comprehensive picture of the system dynamics. The multiple-indicator and multiple-scale assessment generates an "added value" in so that it highlights aspects that are not detectable when only one-dimension is explored. The complexity of modern technological and economic systems requires a significant improvement of the analysis tools, towards comprehensive and aggregated sets of indicators. The case study presented in this paper is used as a benchmark to present and validate a set of indicators that is believed capable of accounting for the increasing complexity of the transportation systems and of assisting in the search for environmentally sound designs and solutions.

2. The case study

The district of Siena has a surface of 3820 km^2, dominated by a hilly landscape (92%). The economy structure of the district is centered on a well developed agricultural activity as well as on a service sector displaying banking, university and health care activities. A non-negligible tourist flow also supports commercial activities. Due to a low population density (66 persons/km^2 versus 190 persons/km^2 in Italy, ISTAT, 1998a) and a small industrial activity, the level of pollution (traffic, noise, production of waste, release of chemicals, etc.) is perceived by the population as quite acceptable. This is confirmed by published data on the state of the environment in Tuscany (ARPAT, 1997).

The human presence and activities in the area are therefore very far from being critical. However, within the global frame of energy consumption at Siena (Basosi and Verdesca, 1998, 1999), the transport sector contributes to about the 39% of the energy consumption and related airborne emissions. The physical nature of the district heavily affects the transportation system, requiring the development of a web-shaped system of roads all over the territory (1630 km). The road system is integrated by a minor railway system centered in Siena and splitting into three different directions, for a total length of 227 km. Passengers (3.75E9 p-km (passengers per km) per year) and commodities (2.85E9 t-km (tonnes per km) per year) travel mainly by means of road transportation systems. Only 4.59% of total p-km and 12.19% of total t-km travel by train. A minor fraction of passenger traffic (4.16%) uses the system of buses that link Siena with the surrounding villages. This is the main reason we have chosen the transport system as the case study to test the validity of our hypothesis about the complementarity of different energy approaches. In fact, it represents a problem that is perceived as the main environmental problem of the area, and due to its high share of energy-related emissions, small improvements may translate into large benefits.

The technological level of individual road transportation is relatively good, also due to the incentives offered by the Italian government to favor the decommissioning of old cars. The railway system is based on an old fleet of diesel powered trains, mainly used for the transport of daily commuters to their villages outside of Siena. The bus fleet was recently improved, even if some very old buses are still in use on short distance trips.

The state of roads is very good, as frequent maintenance operations are performed on the whole road web. The state of the railway is also well maintained, but the efficiency of this transportation system is negatively affected by the existence of only one track, so that trains stop frequently in intermediate stations, to give the way to the train going towards the opposite direction. This stop-and-go pattern increases the trip time, decreases the efficiency of fuel use, and makes the system less attractive.

3. The evaluation approach

The approach that is used in the evaluation of the case study compares and integrates several different methods that are deeply rooted in the principles of thermodynamics. As it clearly appears from the diagram of Fig. 1, a first-law inventory of mass and energy flows is preliminarily performed, to become the basis for a following second-law evaluation based on both user-side (exergy) and donor-side (emergy) evaluations. Conversions from first- to second-law patterns as well as from local to global scales are performed by means of intensity coefficients from

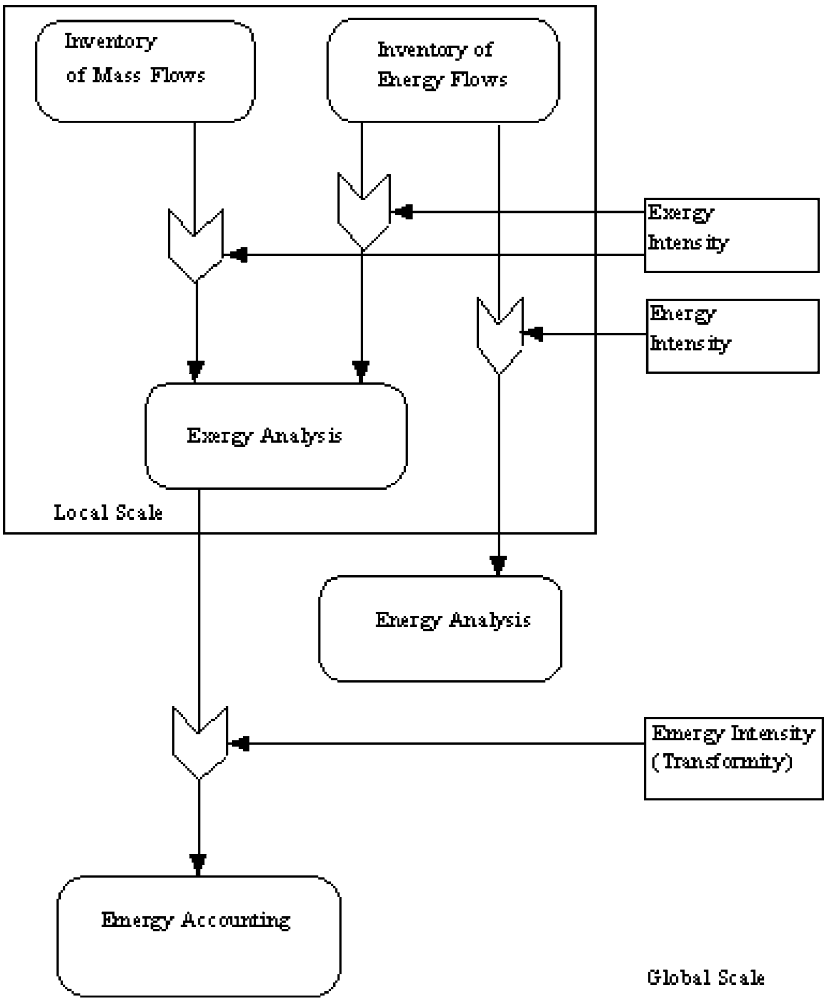

Fig. 1. Diagram showing the suggested integration of mass, energy, exergy and emergy approaches (system symbols from Odum, 1996).

scientific literature. The functional units of this investigation are the so-called "passenger per kilometer" and "tonnes per kilometer". Such aggregated units are needed because a separate account of the mass transported or the kilometers run only yields an incomplete picture of the process. The evaluation stems from an inventory of mass and energy input flows invested in roads, railways and vehicles construction (discounted over appropriate lifetime) as well as in their operation on an yearly basis. Each input flow is then multiplied by suitable intensity factors, to calculate the indirect energy cost, the exergy, the environmental support required, and the polluting emissions associated to it. Summing these values, over all the input flows driving the process and dividing by the process output (p-km, t-km) yields indicators of efficiency and environmental performance, as described below.

3.1. Concepts and definitions

3.1.1. Mass flow accounting at process scale

No process description can be provided, at any level, without a preliminary assessment of matter flows. Mass cannot be created or destroyed. The mass of each individual atomic species is conserved in any process and the total mass of reactants must equal the mass of reaction products.[1] If these changes are carefully accounted for, the process can be described quite well while we make sure that we are not neglecting any output chemical species that could be profitably used or that should be safely disposed of (Ayres, 1995). Output/input mass ratios (equal to one in the case of a careful accounting) and the mass of (polluting) byproducts released per unit of main product ($g_{\text{byprod}}/g_{\text{out}}$) are both useful indicators. After mass flows have been carefully accounted for, economic, energy and environmental evaluations become much easier, as in all of them a good process description is clearly the starting point. In the investigated case study, the masses of materials used in the creation and maintenance of transport infrastructure as well as the masses of fuels and goods used up are accounted for, with appropriate discounting over the whole lifetime of inputs. Annual output flows are calculated accordingly.

3.1.2. Energy accounting at process (local) scale

In general, fossil fuels and electricity are the only energy sources that are used locally in a process, unless a photovoltaic device is used, which is not considered in this study. In the case of the transportation sector in Siena, only fossil fuels are accounted for, due to the fact that the railway system is based on diesel powered engines. Input energy flows are therefore measured in terms of the 'lower heating value' of each fuel, in doing so, disregarding the small amount of heat that is released through the water vapor and flue gases without contributing to the transportation work. This energy accounting procedure allows for the calculation of the energy expenditure per unit of transport service (MJ/p-km or MJ/t-km), in order to compare different transportation patterns and suggest alternatives.

3.1.3. Exergy accounting at process (local) scale

Not all forms of energy are equivalent with respect to their ability to produce useful work. While heat is conserved, its ability to support a transformation process must decrease according to the second law of thermodynamics (increasing entropy). This is very often neglected when calculating efficiency based only on input and output heat flows (first-law efficiency) and leads to an avoidable waste of still usable energy and to erroneous efficiency estimates. According to Szargut (1998) "*exergy is the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with the above mentioned components of nature*." Chemical exergy is the only significant free energy source in processes based on fuel use.

Quantifying the exergy losses due to the irreversibility of a process (which depends on deviations from an ideal, reversible case) offers a way to figure out possible process improvements and optimization procedures aimed at decreasing exergy losses in the form of waste materials and heat. This is performed by multiplying each input flow by a suitable specific exergy factor (Szargut, 1998) and calculating the total exergy supplied to the process. The exergy cost per

[1] When chemical reactions are involved, all reactants and products must be accounted for. Atmospheric oxygen and nitrogen, for instance, are involved in the combustion reaction of fossil fuels via a large number of elementary reaction steps, with known or estimated reaction rates. Their masses must also be taken into account.

unit of transportation service is calculated accordingly. One of the most common exergy indicators accounting for the exergy efficiency of a process (i.e. the exergy invested per unit of product, MJ_{ex}/p-km and MJ_{ex}/t-km) is used in the present investigation. In addition, we try to assess the performance of each transportation device by comparing its exergy expenditure per unit of service with the exergy expenditure of the best performing vehicle of the same category presently available and marketed in the area. Diesel trains are instead compared with the calculated performance of an electric train in the best-use conditions. The exergy expenditures per unit of transportation service of these best available vehicles are used as a reference level to calculate the so-called "second-order" exergy efficiency (Moran, 1982; Cerri and Sciubba, 1988). This ratio allows for the comparison of both individual and mass transportation systems.

3.1.4. Energy accounting at larger (global) scale

The local-scale energy accounting described above is an incomplete measure of the energy cost of transportation, as it only provides an information about the different amount of fuel that is directly used up to operate the system. When the focus is expanded to encompass the larger area where minerals are extracted, goods produced, and fuels refined, additional energy expenditures are to be accounted for (embodied energy; Herendeen, 1998), according to

$$E = \Sigma_j E_j = \Sigma_j m_j \times c_j \tag{1}$$

where E is the total energy cost (J) of a given item, E_j the energy associated to and c_j the global unit energy cost of production (J/kg) of the jth mass flow m_j (kg).

The global scale energy cost can be considered the actual energy cost per unit of product and is, in general, much larger than the local, process-scale energy cost. In our investigation, the scale dependence of energy cost is different for the different carriers, as some costs are not directly proportional to the number of passengers or amount of commodities transported.

3.1.5. Emergy accounting

As a further development of the embodied energy approach, Odum and Odum (1987) and Odum (1996) introduced the concept of *emergy*, i.e. "the amount of available energy *of one kind*, usually solar, that is directly or indirectly required to make a given product or to support a given flow." S*olar emergy* is a measure of the total environmental support to all kinds of processes in the biosphere by means of a new unit, the *solar emergy joule*. Sources that are not of solar origin (like deep heat and gravitational potential) are expressed as solar equivalent energy by means of suitable transformation coefficients (Odum, 1996). The amount of input emergy dissipated per unit output energy is called *solar transformity*. The solar transformity (emergy per unit product) may therefore be considered a "quality" factor which functions as a measure of the intensity of biosphere support for the product under study. The total solar emergy of a product is calculated as:

$$\text{solar emergy (seJ)} = \text{available energy of the product (J)} \times \text{solar transformity} \left(\frac{\text{seJ}}{J}\right).$$

Sometimes coefficients of emergy per unit mass or emergy per unit of currency are also used (*specific emergies*, measured as seJ/g, seJ per US$, etc.). In so doing, all kinds of flows to a system are expressed in the same unit (seJ of solar emergy) and have a built-in quality factor to account for the conversion of input flows through the biosphere hierarchy, over larger time and spatial scales. It is useful to recall that emergy is not energy and therefore it is not conserved in the way energy is.

The emergy accounting procedure converts mass, energy and exergy flows into emergy units that are summed up, to yield the total emergy driving a production process. The transformity of the new product is then calculated by dividing the total emergy by the amount of the product itself, measured in an appropriate unit.

The transformity clearly appears to be a central concept in emergy accounting, due to its two-fold aspect of large scale efficiency and quality indicator.

In the investigation presented in this paper, the calculated specific emergies are measured as seJ/p-km and seJ/t-km.

3.2. The investigated system

The investigated transportation system in the Siena district is divided in two main sub-systems, i.e. road and railway. For each of them several sub-units are considered: (a) constructions of infrastructures and machinery (roads, tracks, cars, trains, etc.), (b) maintenance, and (c) use for transport of commodities and passengers. The diagrams in Figs. 2 and 3 show the main components of each system as well as the flows of energy and materials among them.

3.2.1. Construction of infrastructures and vehicles

The analysis of road construction is based on average inputs and design used in Italian road-making engineering. Input material for the construction of road layers is accounted for. A lower layer is mainly made with compacted gravel and other inert materials, for which an average lifetime of 50 years is assumed. The lower layer is then covered by upper layers made with bituminous materials, to which a 5 years turnover time is assigned. Concrete reinforcement banks are also built when this is required by the slope or the nature of the soil. This occurs in about 10% of total road length in the area. The machinery used for road construction has been also accounted for, and a lifetime of 30 years has been assumed. Data for road construction have been supplied by private companies operating in the field.

The analysis of the railway system construction is performed in a similar way. A lower layer of gravel and small stones supports the track structure made with steel and cement, for which a lifetime of 30 years is assumed. Railway construction data have been provided by the Trenitalia Spa, a public company that manages the rail transport in Italy.

Resources used in the construction of road vehicles have been approximately estimated assuming that they are 80% refined steel and 20% plastic material including tires. Instead, a 100% steel content is assumed for trains, considering the mass of (plastic) seats negligible. Energy costs have been calculated accordingly.

Lifetimes of 10 years are assumed for cars, 15 years for buses, 20 years for trucks, and finally 30 years for trains.

3.2.2. Maintenance

Standard maintenance inputs based on interviews with car-repair dealers are assumed for cars, averaging over car makes and lifetimes. Instead, information about maintenance of buses and trains was supplied by the companies operating in the area (TRAIN Siena for buses; Trenitalia Spa for trains).

Road and tracks maintenance is implicit in the different lifetime assumed for these infrastructures. A shorter lifetime implies an additional effort for substitution and repair.

3.2.3. Use

A weighed average of fuel consumption was performed over the most commonly used cars in Italy. Calculation also took into account average distances yearly covered[2] according to the monitoring of the National Institute of Statistics (ISTAT, 1998b), assuming an average speed around 70 km/h. Diesel fuel consumption of buses and trains was directly supplied by operating companies.

Information about commodity transportation refers to the Energy Plan of the Tuscany Region for the year 1995. This is the most updated source of data available at regional level. According to this source, the annual commodity traffic is about 2.5 billion t-km. In the lack of detailed data about truck number and size, we assumed fully loaded, average-size trailer trucks and a yearly distance covered of 150,000 km per truck, as reported by specialized journals in the field (Tuttotrasporti, 2000). We are aware that this assumption may generate a non-negligible underestimate of fuel consumption.

Airborne emissions of the different kinds of vehicles have been calculated according to the estimates of the CORINAIR Working Group (1993).

3.2.4. Allocation of resources used

Since transportation systems are used both for passengers and commodities, the correct allocation of the resources and energy used in each sub-system is crucial and may affect the final results. We allocated all construction, maintenance and use costs in proportion to the intensity of use. An average passenger weigh of 65 kg was assumed, in order to calculate the total passenger mass transported versus commodity mass and allocate inputs accordingly. We are aware that this allocation procedure is questionable and will significantly affect the performance indicators calculated in this paper, by assigning a larger share of input to the

[2] 15,000 km per year for gasoline cars, 20,000 km per year for diesel cars.

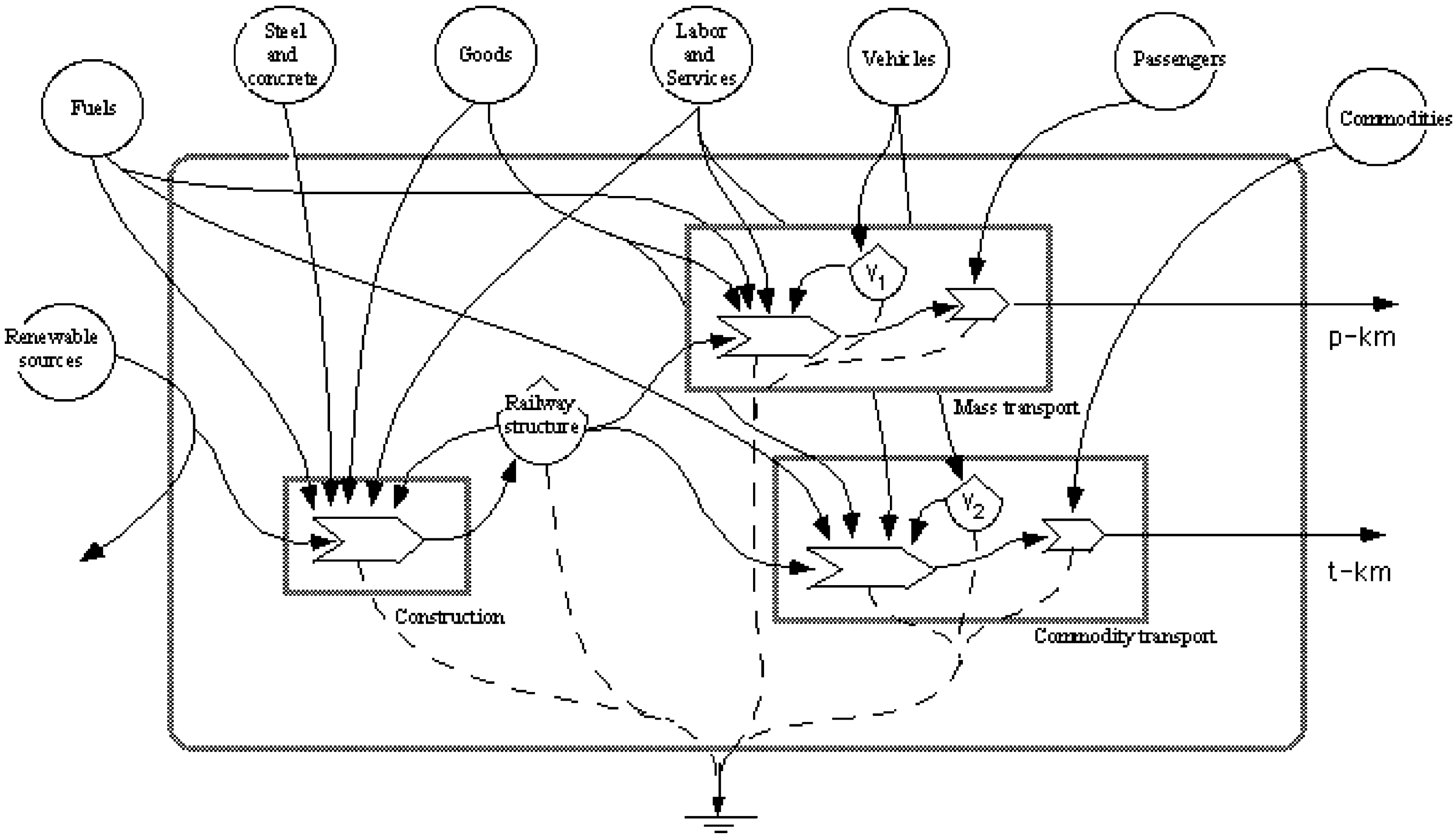

Fig. 2. Diagram of material and energy flows into the Siena railway system (system symbols from Odum, 1996). The product flows are units of passengers (p-km) and commodities (t-km) transported. V_1 and V_2 are the annual fractions of vehicles allocated to each sub-system. Dashed lines are waste flows.

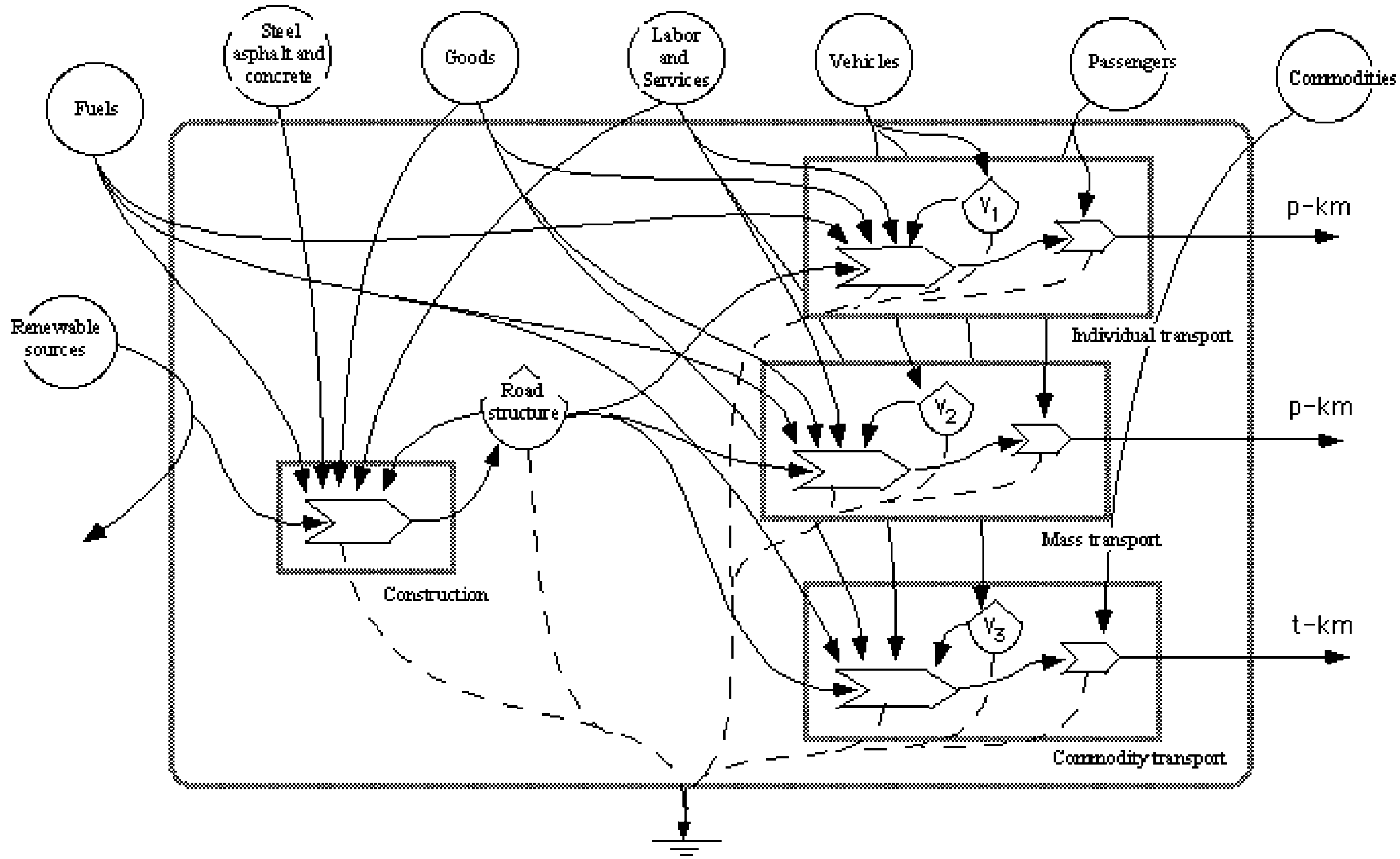

Fig. 3. Diagram of material and energy flows into the Siena road system (system symbols from Odum, 1996). The product flows are units of passengers (p-km) and commodities (t-km) transported. V_1, V_2 and V_3 are the annual fractions of vehicles allocated to each sub-system. Dashed lines are waste flows.

transport of commodities. In fact, the amount of t-km calculated for railway passenger transport are much less (1.12E7 equivalent t-km) than those calculated for commodity transport (3.47E8 actual t-km). A different allocation procedure might be based on the total time required by each transportation pattern in the investigated year. This procedure would assign more of the input to the passenger system, but would not properly account for the impact of heavier commodity loads on the whole infrastructure and vehicle lifetime.

4. Results and discussion

An annual flow of about 3.74 billion p-km (passengers) and 2.85 billion t-km (commodities) characterized the Siena transport system in the year 2000. Road traffic was, respectively, 96.1 and 87.7% of total passenger and commodity flows transported (Table 1), thus indicating a dominant role of road transportation compared with railway. Table 1 also shows that the material size of the whole transportation system at Siena was 66.4 million tonnes (all vehicles and infrastructures, including roads and tracks). When this material amount is used to calculate the local material intensity (Table 2), the average lifetime of each component was considered. The total amount of fuel used was 184 ktonnes oil equivalent, that is the 0.46% of total fuel used for transports in Italy (Ministero dell'Ambiente, 1999) and 12% of Tuscany.

It is worth noting that the road system mass is only 3.26 times the railway system mass, due to the high material intensity of the latter. Instead, the road system used 25.28 times more fuel than the railway, mainly due to the above mentioned larger flows of traffic in the road system.

Several evaluation approaches have been described in Section 3, based on thermodynamic principles. Of course, as already pointed out, each of them may have a different ability to account for specific characteristics of the investigated system, so that their integrated use is strongly recommended (Ulgiati, 2002). Table 2

Table 1
Mass flow accounting of transportation systems at Siena, Italy

	Passenger flow (10^9 p-km per year)	Commodity flow (10^9 t-km per year)	System mass (10^{10} kg)[a]	Total fuel used (10^5 toe per year)
Road traffic	3.57	2.5	5.08	1.77
Railway traffic	0.17	0.35	1.56	0.07

[a] Vehicles and infrastructures.

Table 2
Performance of the whole transportation system at Siena, Italy

	Unit	Mass flow accounting: local scale (kg/unit)	Energy accounting: local scale (MJ/unit)	Exergy analysis: local scale (MJ/unit)	Emergy analysis: global scale (10^{11} seJ/unit)
Passenger transport[a]					
Road individual transport	p-km	0.19	1.75	1.63	1.66
Road mass transport	p-km	0.07	0.49	0.47	0.51
Railway (diesel)	p-km	0.12	0.61	0.58	0.74
Railway (electric)[b]	p-km	0.09	1.78	1.60	5.03
Commodity transport[a]					
Road	t-km	0.50	1.59	1.29	2.37
Railway (diesel)	t-km	0.95	0.30	0.28	4.17
Railway (electric)[b]	t-km	1.44	0.07	0.06	6.17

Comparison of results based on different accounting procedures.
[a] Figures include fuel consumption and infrastructures allocated.
[b] Calculated for comparison purpose. Figures refer to the conversion of the present infrastructure and vehicles from diesel to electricity. A 4 MW locomotive E444R is assumed, as in most of electric Italian trains, working at 50% of maximum power.

shows a comparative view of the results of the investigation in order to evaluate the performance of individual and mass transportation systems on a multi-criteria multi-scale basis.

As far as passenger transportation is concerned, it clearly appears that the individual way (cars, motorcycles) is the one generally showing the highest material, energy, and exergy intensities at the local scale. The local-scale energy intensity of individual passenger transport matches very well the Italian average figure of 1.7 MJ/p-km (Malosti and Romanazzo, 1997). The individual transportation also shows the highest energy as well as emergy intensity (i.e. the highest demand for environmental support is equal to the highest ecological footprint) at the global scale of the biosphere. The best performance (all indicators) is shown by the road mass transportation system. These results are somehow surprising, as it is a common belief that the railway transport is characterized by higher efficiency and can be partially explained by the oversize design of the railway system, compared to actual intensity of use.

Commodity transportation instead requires a more careful interpretation of data. First of all, it must be recalled that a larger amount of inputs are always allocated to the commodity railway sub-system than to the passenger railway sub-system, as indicated in the above Section 3.2.4. In addition, a larger demand of material and emergy input per t-km is generally shown by the railway sub-system, compared with the road one, due to the significantly higher amount of matter (steel and construction material) invested in railway vehicles and infrastructures. Notwithstanding this, the railway energy and exergy indicators still are much better than those shown by the road sub-system. The reason of this result relies on the very efficient way commodity traffic is organized in Siena, with an exact matching of offer and demand, so that trains always travel fully loaded.

An interesting result comes out from the assumption (also shown in Table 2) of a complete substitution of diesel trains with the average-power electric trains used in the Italian railways. It is assumed that modern 4 MW electric locomotives E444R are used and that the infrastructures are modified accordingly (construction of electric lines and better trackway). Under these assumptions, the passenger transport shows a small local-scale decrease of the unit material demand, compared with diesel railway, due to the fact that there is no mass associated to electricity on this scale. The transport of commodities does not show the same behavior only because the allocation of a larger fraction of infrastructure and vehicle mass to this form of transport hides the drop of fuel mass. The local-scale energy figures would further increase to 1.78 MJ/p-km for passengers and decrease to 0.07 MJ/t-km for commodities. Similar behavior is shown by exergy indicators. This might indicate that an electric railway would still be an appropriate tool for the transport of commodities in the Siena system, while it would not be appropriate at all for passengers transport, due to the small number of people and the inefficient way this transport is performed. On the other hand, the emergy intensities show a huge increase both for passengers and commodities, mainly due to the large emergy associated to the input of electricity for passengers (94% of total electricity used) and to the larger allocation of material input for commodities. Therefore, the energy and exergy advantage of shifting to an electric railway system is partially offset by the burden that may come out from the increased demand for environmental support.

Table 3 helps quantify the increase of energy intensities when the attention shifts from local to global scale. This expected increase of energy costs is due to the inclusion of the indirect energy required to actually make and supply goods and fuels to each process. The sub-systems, which show smaller increases, are those transport typologies where fuel is the dominant input, since the indirect energy cost of fuel is generally low. Instead, higher increase is shown by those sub-systems involving larger structures or infrastructures, with a non-negligible embodied energy content, as well as by those running on electricity (due to the low efficiency of the fuel-to-electricity conversion).

All the above figures are in good agreement with Boustead and Hancock (1979), from which a range of 1.2–1.8 MJ/t-km for road commodity transport and 0.28–0.37 MJ/t-km for the railway commodity transport on the local scale can be estimated. Jarach (1985) reviewed several authors worldwide, estimating a global-scale range of 1.2–7.9 MJ/t-km for road commodity transport and 0.5–1.4 MJ/t-km for railway commodity transport.

An additional insight into the system performance comes from the comparison of first- and second-order

Table 3
Energy intensity of transportation systems at Siena, Italy

	Passenger: individual transport (MJ/p-km)	Passenger: mass transport (MJ/p-km)	Commodity: transport (MJ/t-km)
Local scale			
Road	1.75	0.49	1.59
Railway	n.a.	0.61	0.30
Road to railway ratio (local scale)	n.a.	0.80	5.34
Global scale			
Road	2.10	0.61	1.66
Railway	n.a.	0.73	0.42
Road to railway ratio (global scale)	n.a.	0.85	3.92
Global to local ratio of energy intensities			
Global to local ratio, road	1.20	1.24	1.04
Global to local ratio, railway	n.a.	1.20	1.42

n.a.: not applicable.

exergy efficiencies (Table 4). The first-order exergy efficiency (=work actually delivered/work potentially deliverable from fuel use) indicates the average distance of the investigated process (real case) from a reversible one (ideal case). This distance could be decreased by means of technological improvement and use optimization, but cannot be completely cancelled due to thermodynamic reasons. However, this task belongs to engine and car designers more than to transport planners. Instead, the second-order exergy efficiency (=minimum exergy expenditure by the best available technology/exergy actually used up) indicates the distance of the present system (all used vehicles + infrastructures) from a possible system where less efficient vehicles are replaced by the best ones already available, used according to the an optimal use pattern (full load). This distance can potentially be cancelled in a short time by redirecting the customer preferences toward cars that are more exergy efficient instead of more powerful and fast. The reference system is not an ideal system, but can be as real as the investigated one. The lower the second-order exergy efficiency, the higher the potential improvement (and saving) that can be obtained. The chosen reference vehicles are: the car, Volkswagen Lupo 1.2 Tdi; the bus, Fiat Iveco 8460.31X; and the diesel locomotive, ALN 663. These vehicles are already in use in the area, but their number is small. Table 4 shows that the road systems still offers huge improvement potentialities, while the diesel railway is closer to the best case.

Table 4
First- and second-order exergy efficiencies of the passenger transportation systems at Siena, Italy

	Road: individual transport (%)	Road: mass transport (%)	Railway: mass transport (%)
ε[a]	26.00	40.00	30.00
η[b]	16.00	40.00	60

[a] Average values (Tuttotrasporti, 2000; Quattroruote, 1999; Trenitalia Spa, 2000).
[b] Calculated in this work. The reference vehicles and use pattern are described in the text.

The second-order exergy efficiency of the passenger railway system in the above assumption of a shift to electric powered trains would be 41.5%, thus indicating a theoretical possibility of improvement higher than in the previous case (not shown in Table 4). As already pointed out, transferring this improvement to the Siena system would require the electrification and modernization of the whole line. In order for this to be possible, a huge material and emergy investment in the form of high quality steel, copper and cement would be needed, much larger than the theoretical energy savings. As a consequence, the material and emergy costs of an electric option would be, at Siena, much larger than the present diesel-based emergy costs, as indicated in Table 2. In addition, the new system would only improve the energy and exergy performances of commodity transport, while remaining unable to compete with the diesel option for passengers. Therefore,

Table 5
Main local and global scale emissions of the transportation system at Siena, Italy

	Unit	CO_2 (g/unit)	CO (g/unit)	NO_x (g/unit)	PM[a] (g/unit)	VOC (g/unit)	SO_x (g/unit)
Passenger transport							
Road individual transport							
Local scale	p-km	109.46	3.72	1.21	0.020	0.85	0.330
Global scale	p-km	121.70	3.75	1.26	0.024	0.86	0.331
Increase (%)		11.19	0.72	4.44	20.31	0.13	0.30
Road mass transport							
Local scale	p-km	33.75	0.210	0.610	0.040	0.07	0.09
Global scale	p-km	35.10	0.212	0.614	0.041	0.07	0.10
Increase (%)		4.10	1.34	0.96	1.33	0.15	4.44
Railway mass transport							
Local scale	p-km	41.21	0.140	0.530	0.060	0.060	0.120
Global scale	p-km	45.60	0.148	0.546	0.063	0.062	0.123
Increase (%)		9.72	5.73	3.32	2.68	0.56	3.28
Commodity transport							
Road							
Local scale	t-km	0.09	0.56	1.65	0.11	0.20	0.30
Global scale	t-km	0.107	0.57	1.69	0.20	0.201	0.3
Increase (%)		14.59	2.36	2.27	87.66	0.78	0.09
Railway							
Local scale	t-km	0.01	0.03	0.10	0.01	0.01	0.06
Global scale	t-km	0.02	0.05	0.16	0.02	0.012	0.061
Increase (%)		88.14	65.96	60.44	99.09	18.56	3.33

[a] Includes all kind of particulate matter.

even if the second-order exergy efficiency suggests that a significant improvement is in principle possible based on average performance data for Italy, all the other indicators do not confirm it as a viable alternative for the investigated case, due to factors of scale and intensity of use.

Table 5 shows a comparison between local and global scale airborne emissions. Of course, local scale results reflect the same pattern presented by energy consumption data. Therefore, emissions generated by road individual traffic largely overcome emissions from the other systems of passenger transportation. Instead, the increase of emissions calculated for the global scale is not only due to an increased fuel consumption, but also to other non-combustion sources (example: cement production and material inputs to road manufacture generate a non-negligible increase of particulate matter). It must be pointed out that emissions from fuels used for fuel refining and manufacture of goods at global scale are not the same for the different fuels (EPA, 1996); therefore, different fuels generate unequal indirect increases that add up to local emissions. Finally, as already pointed out in Section 3.2.4, the input allocation procedure penalizes the pattern with higher use intensity (commodity transport), which therefore show higher percent increases of emissions. The railway system of commodity transportation is the one characterized by higher percent increase of emissions. In fact, due to its high local efficiency, as already underlined, it is more affected by the allocation of inputs from the large scale.

5. Further considerations for policy-making

A necessary premise is required before moving through a further discussion of results. Our investigation is based on thermodynamic and environmental parameters while other economic, technological and social factors are not taken into account here. The decision maker will have to integrate our findings with goals different than minimization of energy costs or environmental impact, to make any decision consistent with the social demand of transportation service, lower cost and comfort.

5.1. Options and scenarios based on results

Results confirm the already common belief that the mass transport is the best way to move people compared with individual transport. Instead, the better performance of road mass transport of passengers (buses) compared with railway is a somehow unexpected result, no matter the scale considered. The advantage of road compared with railway transport is less evident in the case of commodities, as pointed out above, due to a contradictory behavior of performance indicators. The way indirect inputs (infrastructure and vehicles) are allocated to commodity transport penalizes more the pattern (railway) where these inputs are bigger. The better energy and exergy performance suggest that increasing railway commodity traffic would be a good policy for energy saving. This in turn would make the material and emergy intensities to decrease, at the expenses of road traffic, and would result into a lower demand of all kinds of energy and environmental inputs to the transportation system.

The second-order exergy efficiency suggests an improvement potential linked to the system ability of replacing the low-performance vehicles with already existing higher-performance ones as well as the adoption of optimum use patterns (car pooling for full load of vehicles versus the present 1.2–1.4 people per car). This is not a trivial option, because it requires the customer preferences to be educated and oriented towards better exergy-performing vehicles instead of faster and larger ones, as it happens at present. At this regard, it is not unimportant that the second-order exergy efficiency is very low for road transport (Table 4), suggesting that much more can be done to improve the existing road fleet. This option, of course, should be integrated with strong policy actions for orienting people preferences towards mass transport.

It is, however, worth noting that not all kinds of technological improvement are appropriate to the scale of interest. In our study, this is the case of electric railway. The feasibility of this option, even if suggested by a better second-order exergy efficiency, is denied by the other material and thermodynamic parameters calculated in Table 2. Instead, the replacement of a fraction of existing buses, cars and diesel trains with more exergy-efficient vehicles would not lead to a significant worsening of material, thermodynamic and environmental parameters, due to a practically unchanged demand of energy and materials for their production. In fact, efficiency improvements are mainly due to a better vehicle body and engine design, whose additional inputs are quickly distributed to the large number of vehicles sold.

Finally, even if we do not explore the economic cost issue in this paper, it is interesting to recall some results obtained by other authors. Malosti and Romanazzo (1997) calculated the economic cost of saving the same amount of energy by means of fleet renewal favored by Government subsides or by simply orienting customers towards a better use pattern (appropriate mix of individual and mass transport, car sharing, car pooling, etc.). In the first option, saving 1 Mtoe would cost €23.2 billion (US$ 21.4 billion) while in the second option the same energy saving would cost up to ten times less.

5.2. The “added value” of integrated approaches

It clearly emerged from the investigated case study that it is impossible to get completely converging results from the different approaches applied to the system. Depending on the relative importance of direct and indirect inputs as well as the intensity and appropriateness of use, performance indicators do not always converge but instead may show diverging results. It is therefore warmly recommended that no policy decisions are made based on the optimization of only one indicator (energy demand, labor demand, economic cost, material intensity, emission, etc.). The approaches used in this paper are not necessarily the best ones for any system and situation, and may require integration and illumination from other points of view.

In addition, results showed to be heavily dependent on local use factors. This suggests that the same solution might not be applicable to other systems characterized by different use patterns and demand.

The decision maker should plan investments and system organization trying to account for (sometimes) irreducible indicators, weighed according to other social and economic factors.

In so doing, the reliance on a larger set of physical data, instead of only one "optimized" indicator, might contribute to a more complete picture of the system of interest as well as to the design of possible scenarios for further discussion among policy makers and stakeholders.

6. Conclusion

A careful consideration of several aspects of a transport system dynamics is required to get a reliable picture of any kind of transportation process. We have investigated a local transportation system, trying to take its complexity into account, both from the point of view of vehicle performance and system structure. It clearly emerged that the thermodynamic performance of an individual vehicle is not in itself a sufficient parameter for the understanding of possible governance options. The integration of several and sometimes diverging indicators, despite very useful to design a first performance assessment, requires a larger scale context to illuminate scenarios and suggest actually feasible policy actions. Patterns that were not expected to be appropriate instead showed better performances than other options supported by the common belief, thus suggesting that technological and thermodynamic feasibility must always match the specificity of use pattern and demand.

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