On the Emergy accounting for the evaluation of road transport systems: an Italian case study

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Abstract

Road transportation is one of the most polluting as well as energy-intensive sectors, and requires planning policies capable to address at the same time several different environmental, social, and economic issues. Cost-benefit analyses are generally carried out with a major focus on fuelling and driving efficiency, whereas a systemic approach appears to be needed for a more comprehensive evaluation of the alternatives that may become available to address any issue, be it intended for either short-term or long-term spans. For instance, building up a new infrastructure might allow for savings in time or fuel per km, but this may require an equivalent or even higher socio-environmental investment. In this work, a short review is presented of some systemic studies on transportation that use the emergy synthesis methodology. A case study is also addressed, concerning recent important expansion works on the Apennine Mountains section of the Italian major highway A1. In particular, the analysis points out the role of time saving, since for a new or renewed transport infrastructure (and when comparing for example road to rail transport) saved time is likely to become crucial in justifying civil enterprises. Nevertheless, the present emergy synthesis and the teaching of H.T. Odum (Odum & Odum, 2001) warn us that such "luxury" highly depends on the abundance of available energy, which is less and less given for granted, whereas a systemic analysis approach may indicate different levels of criticality when oriented towards environmental and well-being issues.

1. Road transport: which approaches for a problematic sector?

The increasing energy demand and the polluting, climate change related emissions are widely considered among the main environmental issues for the XXI Century. In this framework, the transportation sector plays a primary role both in energy use and in pollutant emissions. In 2015, transports accounted for over 28% of the total energy use in the United States of America, and for the 70% of the country total petroleum consumption (equivalent to almost 15% of the world petroleum consumption in 2014), with more than 80% of the U.S. transportation energy use coming from highway vehicles (Davis *et al.*, 2016). In 2015, highway vehicles were responsible for the 39% of the total carbon monoxide (CO) emissions and for the 36% of the nitrogen oxides (NO_X) released in the U.S. (EPA, 2016). Although at a smaller scale, percentages in Italy appear even more dramatic: in 2014, over 39% of the national total energy use was related to the transportation sector (MISE, 2015), with on-road vehicles being responsible for the 23% of the total CO emissions and for the 50% of the total NO_X emissions (ISPRA, 2016). But whilst the problem is quite clearly addressed, the strategies for its overcoming are not. Facing transportation issues requires planning policies capable to address at the same time several different environmental, social, and economic aspects. Cost-benefit analyses[1] are generally carried out with a major focus on fuelling and driving efficiency, whereas a systemic approach and the

[1]https://www.fhwa.dot.gov/planning/processes/tools/toolbox/methodologies/costbenefit_overview.cfm

enlargement of the analytical boundaries appears to be needed[2] for a more comprehensive evaluation of the alternatives that may become available to address any issue, be it intended for either short-term or long-term spans. For instance, building up a new infrastructure might allow for savings in time or fuel per kilometre, but this may require an equivalent or even higher socio-environmental investment, which is hardly measurable by money – or at least quite indirectly. Emergy accounting (Odum, 1996) offers a great opportunity to account for environmental and labour/services costs and benefits at the same time, while addressing systemic interconnections and hierarchies. The limited available literature on emergy accounting applied to transportation has been reviewed, as described in Section 3. Emergy accounting is applied to an Italian case study, as illustrated in a forthcoming extended study (Cristiano, Gonella, & Ulgiati). Besides a short presentation of the state-of-the-art of the topic, this work discusses on how to frame the societal "value" and the socio-environmental "cost" of saved time in Odum and Odum's reasoning on a prosperous way down (2001) perspective.

2. Emergy accounting in a nutshell

In recent years, starting from the three pillars of sustainability (environmental, social and economic), the search for comprehensive integrated indicators of sustainability has been developing following various different approaches. What is needed to fully understand a system performance is an integrated approach capable to evaluate a process from two complementary points of view at the same time, namely, a "user-side" assessment that looks at final efficiency indicators (energy delivered per unit of energy input, emissions per unit of energy, and so on) along with a "donor-side" framework, that considers the work done by the supporting ecosystemic and social/productive environment in providing resources.

The term "EMERGY" is derived from the expression "EMbodied enERGY". The foundations of emergy analysis are the main scientific output of the work by Howard T. Odum (Odum, 1996; 2000; Odum & Brown, 2007). Starting in the 1970's, Odum structured and applied the emergy analysis over a surprisingly wide range of systems (see Brown & Ulgiati, 2004) within several disciplines, among which complexity science, ecology, economics, informatics, geo-bio-physics, sociology and so on. The emergy, defined as the available energy of one kind that is used up in transformations directly and indirectly to make a product or service (Odum 1996), may be regarded as a sort of "memory" of what has been invested, in terms of energy involved either directly or indirectly, to realise something. Emergy represents the common unit (defined along with a proper algebra) for accounting at the same time all the quantities, flows and processes that concur in defining the system at issue. The unit of emegy is the *solar emjoule*,in the case of solar energy reference. The emergy of a resource will include all the upstream and downstream contributions provided by both the environment and the anthropic activities necessary to maintain that resource. The emergy approach takes quantitatively into account within the same unit all the flows, namely, matter, energy, information and money, so putting into the same technical-scientific analysis also quantities not computable in terms of money or energy units, that are therefore typically neglected in economic or energetic analyses.

The general methodology for the emergy analysis of a system is typically organised in

[2] http://bca.transportationeconomics.org/published-guidance-and-references

the fundamental steps:

1. Build up of an emergetic diagram of the system;
2. Preparation of an inventory table for the flows;
3. Determination of the corresponding emergy values;
4. Calculation of suitable emergetic indicators for the analysis interpretation.

The elements of the emergy diagrams are mutuated from the formal and graphical language used by engineers for energy networks (Odum, 1996). Starting from the emergetic diagram, all data for the respective flows are converted in emergy units by means of their respective Unit Emergy Values (UEVs), which are given by the emergy required to generate an output unit, be it made of mass, energy, labour, money, and so on, independently of the renewability of inputs.

3. On the prosperous way down

The Prosperous Way Down outlined by the Odums frames a possible scenario for the future of the humanity, where the depletion of nonrenewable fossil energy sources may lead to a society living on fewer resources but at the same time that may be prosperous as well. To pursue this, human activities should follow an epistemological picture based on a donor-side perspective, like that substantiated by the emergy analysis, that may indicate in a scientific manner how to try modifying the economy and keeping the environment prosperous as resources become more and more limited. Odum pointed out several features of modern society that must undergo a profound change, among which the transport sector plays a role in as much it is related to several human activities of a global society that produces and consumes as much fossil fuels as possible, mostly for private interests strongly intertwined with global politics. Among the indications for a prosperous way down, some are of particular interest for the topic at issue (Odum & Odum, 2006), namely:

- Decrease in urban concentration, based on the fact that the concentration of economic enterprises and people in cities is ultimately based on the availability of inexpensive fuels.
- Re-shaping of the automobile culture, by reducing the number of cars as well as unnecessary horsepower.
- Communication replacing transportation, whenever an activity does not require physical displacement of matter.

All of these aspects require that the whole economy re-shapes its basic postulates concerning the use of fossil fuels, still allowed and promoted at the global level despite any environmental concern. In this sense, a bottom-up approach may regard the local level, and so the analysis presented in this contribution.

4. Emergy accounting and transportation

The literature reporting emergy accounting approaches for road transportation systems is quite limited. Roudebush (1996) focused on the comparison between the different costs and impacts of concrete versus asphalt road pavements; Brown & Vivas (2005) tangentially addressed transportation infrastructures while incorportating roads (specifically, their empower density) in the calculation of the Landscape Development Intensity index of a given territory; Reza *et al.* first used paved roads as a case study to investigate the uncertainties in emergy accounting (2013), and then adopted an emergy-based Life Cycle Assessment to compare two road scenarios (2014). Comparisons among road and other transportation systems (mainly railways) have been proposed by Federici *et al*. (2003; 2005; 2008; 2009) and by Threadcraft (2014).

5. An Italian case study

The case study at issue consists of a recent important deviation and expansion on the Apennine Mountains section of the Italian major highway A1, the so called "A1 var" section, opened to public in December 2015. The works lasted over ten years and costed 7 billion euros[3], with the expected benefits of saving travel time and fuel consumption due to the increased capacity and the higher quality of the service. Two independent studies were carried out (Cristiano, 2012, 2016) for an adjacent section, involved in the same broad deviation and expansion programme as the "A1 var" one, without finding significant savings in terms of pollution per unit of service (i.e., g/km per vehicle) nor hints of major improvements in terms of fuel consumption – although these studies only investigated indirect information such as the opening of the throttle valve. In the study at issue, expected benefits after the renovation works are verified and compared with the socio-environmental inputs required for construction in terms of emergy. Figure 1 reports the essential scheme which the analysis has been based on.

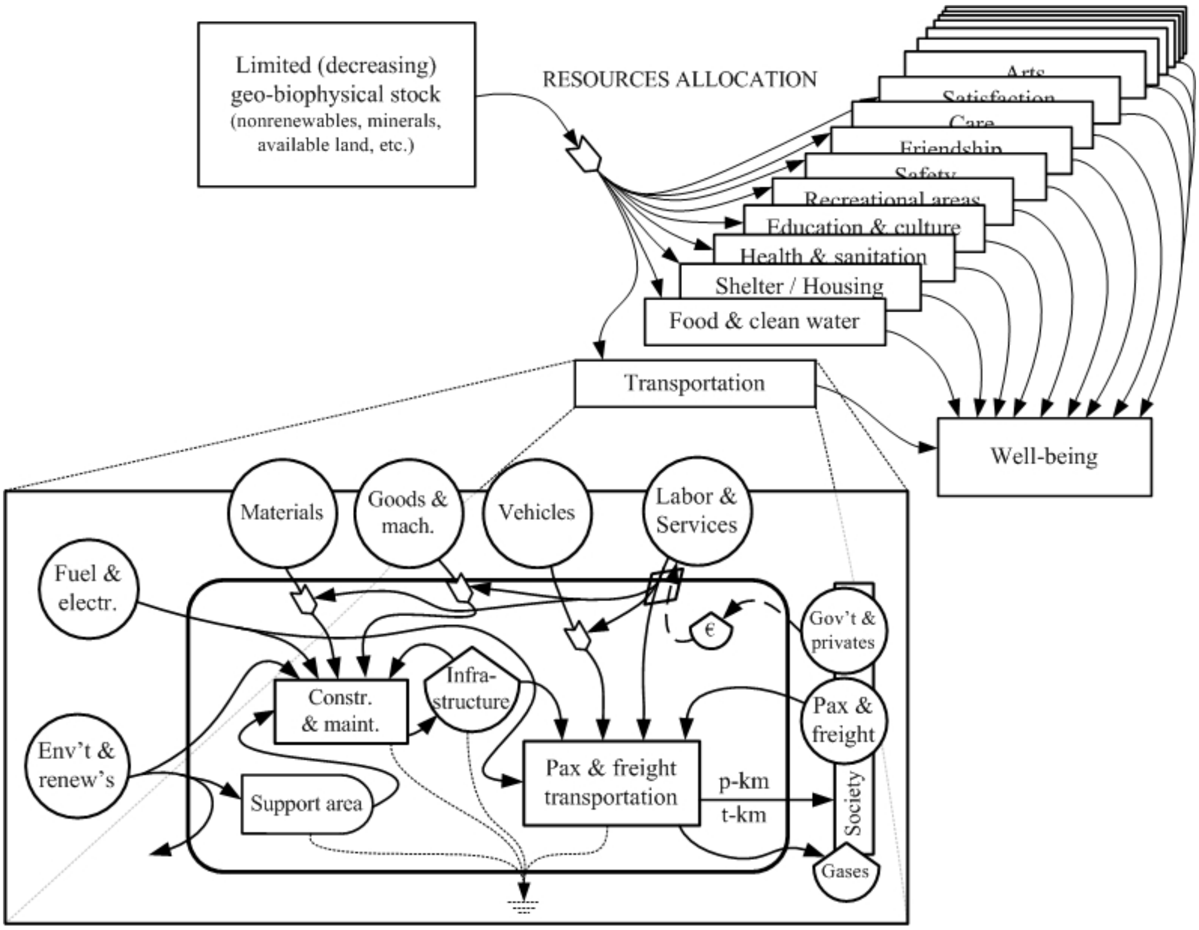

Fig. 1: Conceptual scheme for the analysis

3 http://www.rainews.it/dl/rainews/articoli/Apertura-della-Variante-di-valico-Renzi-Grande-emozione-non-ci-credeva-piu-nessuno-f60702bf-3008-455d-93d1-04db0b1df461.html

Some improvements are addressed for our case study, also in light of recent advances in emergy accounting research. Compared to the works by Federici *et al*. (2003, 2005, 2008, 2009), the services provided for free by nature to dilute pollutants are added, as in Reza *et al*. (2014) and – above all – following the procedure suggested by Ulgiati and Brown (2002), i.e. calculating the emergy associated with the wind energy to bring pollutants within acceptable concentrations as by legal limits. A further improvement is the calculation of the labour associated with the driving activity; this appears to be particularly suitable to describe major differences in what is expected from travellers in different transport modes (e.g., road driving or bicycle riding, or small-boat rowing versus driving-free road, motorised maritime, or air mobility), while requiring further discussion to understand its actual valence when making comparisons within the same transportation mode. It is worth noting that the output of the road transport infrastructure system may be addressed following different viewpoints, taking the form of sej/km, sej/passenger-km, or sej/tonne-km, in so emphasising either the investment referred to the structure build-up and maintenance or that related to the services provided to the public. This has some consequences in how the "vehicles" stock should be systemically framed within an emergy diagram. In the case of a systemic output defined as the sole physical highway, users vehicles do not play a role, whereas in the cases of systemic services expressed in terms of users' exploitation, vehicles are an input necessary for providing the output, and so has to be taken explicitly into account.

6. Discussion: time as "luxury"

A detailed presentation of the quantitative analysis is beyond the purpose of this contribution, and will be the object of the comprehensive study in preparation (Cristiano, Gonella, & Ulgiati, forthcoming). However, following the analysis of the addressed case study, one of the most interesting aspects is the quantitative role of time, that seems to be one of the keys for understanding the highway transport system from the point of view of its real sustainability. In fact, when opting for a new or renewed transport infrastructure (and when comparing for instance road mobility to rail mobility), saved time is likely to become a crucial reason in justifying civil enterprises (see for example the high-speed train projects proposed or realised all around the world). In the commented study, an overall advantage is not actually expected following the renovation works in none of the three functional units considered (functioning of the highway section per kilometre, emergy per passenger-kilometre, and emergy per tonne-kilometre). A situation close to a balance between benefits (input savings) and costs (input investments) is nearly achieved only if labour and services – including drivers labour – are accounted for. On the contrary, when drivers labour is not considered, the functional units are more emergy demanding, with the emergy per passenger-kilometre up to 25% higher and that per tonne-kilometre up to over 50% higher on the renewed section. It is worth underlining how emergy accounting output is generally given both with and without labour and services, since these might not describe properly any process and – at the same time – the question of standardisation in the way they are calculated is currently under debate in the emergists community. As per the emergy related to the drivers activity (labour), this is something definitely useful to account for and highlight the significant effort required in road transportation when compared to the minimisation of the driving responsibilities that characterise other transportation modes (rail, maritime, air), as after all done in conventional transport economics. When comparing two or more scenarios for a road transport system, instead, one might wonder whether or to what extent this information should be relevant, especially when considering that savings in time are not due to the instrinsic features of the same transportation mode, which cannot allow for alternatives presumably implying less resources consumption in operation owing – for instance – to the sharing of vehicles and fuel or electricity as for railways. In analyses of a same transport mode such as a road system, it seems that time saving might become the reason why a civil infrastructure is built or renewed, and such a goal is generally reached through the use of the resources and labour that we can financially afford from the privileged position *here and now*, often involving the exploitation of someone else's labour as well as the claiming of a right to use resources at the expense of people living in other areas (mainly in the Global South) or in the future (next generations). A real, winners/losers based "luxury". Yet, even for the most uncaring readers, the Odums (2001) ammonish that "[t]he auto age will come to an end when alternate needs for the fuels running the personal autos become more important than the time saved by having individual cars".

7. Conclusion

The results of the emergy synthesis here commented, if read while keeping in mind the wise words by Howard T. Odum and his wife Elizabeth (2001; 2006), warn us that such "luxury" highly depends on the abundance of energy (more generally, on the abundance of "cheap" resources and labour), i.e., of something which is less and less given for granted in a changing world undergoing a systemic crisis. Whether we want it or not – we will soon be led to reconsider our priorities due to the criticality and systemic unsustainability of a way of reasoning based on the aforementioned "luxury". Environmental sustainability and social equity might rather be reconsidered to turn this warning into an opportunity to pursue a lasting well being, which might include the recovery of *slowness* as a value, so that perhaps the labour-intensity of transportation could be judged on a case-by-case basis, with more (systemic) emphasis on the resource-intensity of a given transportation mode, including the evaluation of construction and maintenance environmental inputs. Framing an emergy accounting analysis in the more general picture of a prosperous way down is quite a complex task, but it is nevertheless one of the reasons why the donor-side perspective provided by the emergy conceptualisation was first established. Given the central role played by the transportation systems in defining the basic characters of any modern socio-economic system, it appears extremely important that an emergy analyis is carried out for the major transportation infrastructures, aiming at connecting a quantitative sustainability analysis with the mandatory transition towards a society where the fossil fuel will be no longer a focus of the overall productive activities.

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