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New challenges for city logistics: a unified view of energy and transport systems for addressing sustainability

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Abstract

Urban freight transport has been studied from the point of view of economic efficiency, however, it is also important to consider energy efficiency with respect to the goals of the 2030 Agenda. The method used in this paper is to reconstruct the cycles from production to the end user for energy and transport/logistics by identifying the intersection areas, which turn out to be the vehicles and the exchange nodes. The measurement of impacts is introduced considering the "carbon footprint" indicator. The continuous advancement of automotive technologies is highlighted that requires a continuous updating of the impact results to make optimal economic and energy choices for city logistics within the framework identified by Agenda 2030.

Keywords: city logistics; energy; LCA; hybrid vehicle; urban logistic nodes; Agenda 2030

1. Introduction

Today's energy consumption together with the subsequent environmental impacts is particularly high. All estimates show that the most energy-consuming sectors are the industrial sector, the transport sector and the civil sector, accounting for about 30% each of total energy consumption.

Reducing the environmental footprint of transport at different scale is one of the priorities of the United Nations. The turning year for international politics was 2015. In that year, the Paris Climate Conference was held with the agreements signed by all participating countries in order to limit the growth of global warming. Also, in 2015, the United Nations approved the plan Transforming our World: The 2030 Global Agenda for Sustainable Development,

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articulated in 17 Sustainable Development Goals (SDGs). The main goals of interest for city logistics are "sustainable cities and communities" and "climate action" (Russo and Comi, 2023). Formal agreements were signed in 2015, but the complexity of pursuing them is considerable, also determined by the lack of a strong push to develop scientific and industrial research for new techniques aimed at pursuing the objectives, in particular in the most advanced countries. In fact, the UN report on sustainability a few years later (UN, 2019) pointed out the delays on many goals. At the same time, the EU has prepared an important plan for sustainable growth (COM, 2019) that includes, among its fundamental objectives, the need to make a modal shift towards sustainable and smart mobility.

International objectives aim to improve energy systems and thus their environmental impacts. At the same time, from the one side, the optimisation methods currently used by transport and logistics companies are aimed at optimising the economic efficiency of production cycles. From another side, the policies of public administrations are aimed at minimizing congestion and therefore introducing measures to limit flows.

To orient transport companies and public administrations towards new optimality objectives, this paper proposes a new approach in which the urban system has to be studied in an integrated way linking energy components and transport/logistics components. The challenges arise from the idea that production cycles of transport/logistics can be revised by improving their energy and then environmental impacts. Therefore, it is proposed to consider the two main cycles: the energy cycle and the logistics/transport cycle.

The relationship between the two cycles should be studied in the overall context defined by the smart city. The European Commission has been promoting the concept of a smart city since 2012, with three pillars of reference (EC, 2021): energy in terms of production and use, transport and mobility, information and communication technologies (ICT). Emerging ICTs are providing remarkable solutions to urban sustainability in the field of mobility and the Transport-ICT interaction has been strongly supported both scientifically and technically. Transport-Energy integration has not been sufficiently investigated, due to the industrial apparatus that conditions energy development: on the one hand the energy industry, i.e., mainly the oil and electricity industries, and, on the other hand, the manufacturing industry of means for transporting goods, i.e., the automotive industry. The combination/integration among ICT, transport and energy allows the development of transport planning on an urban scale, optimising infrastructure configurations and minimising energy consumption, in particular from non-renewable sources (EC, 2012). It is therefore necessary, recalling the most recent literature, to adequately outline the components of the energy cycle and the transport/logistics cycle. The objective is to identify the elements of direct intersection and therefore the integration between the two cycles. Therefore, it is necessary to analyse the methods currently available to study the main environmental impacts of the identified elements.

To answer the questions thus posed, this paper is organised into four sections, after the Introduction. Section 2 examines the Goals of Agenda 2030 on which city logistics can intervene. Section 3 outlines the main characteristics of the two cycles, thus recalling the main indicators to define the optimal conditions for environmental impacts. Section 4 examines impact estimation methods, recalling in more detail the method used internationally to study the carbon footprint. Section 5 draws conclusions summarising some elements derived from the possibilities offered by an integrated study, underlining the need to consider, for the development of the research, the three components: transport, ICTs (information and communication technologies), and energy. In fact, cities, industry and citizens are involved in the process to improve urban life through more sustainable integrated solutions. The areas of interest should thus start from smart growth, through innovations and therefore technological platforms (ICTs) and thematic forums (energy and transport) are intimately connected areas to improve services by reducing energy and resource consumption.

2. Goals to pursue

The implementation of an urban logistics management system in its different components aims to promote sustainable development in the city. Therefore, it is necessary to recall the cornerstones of sustainable development agreed at the international level and achievable with targeted city logistics actions.

The first definition of sustainable development was given in 1987 in the report prepared by the World Commission for the Environment and Development (Brundtland, 1987), which highlights the three main themes of sustainable development: society, economy and environment.

Almost 30 years later, in September 2015, 193 member states of the UN approved the document, "Transforming our world: the 2030 Global Agenda for Sustainable Development" (UN, 2015; 2018). Agenda 2030 identifies 17 goals for sustainable development (SDGs – sustainable development goals). It is possible to structure groups of objectives, or goals, according to common denominators (Russo and Rindone 2023; Comi et al., 2023). In the following, the two basic groups of SDGs, pursued in all contexts, are recalled, then the two SDGs, which are the main reference for the theme examined in this paper, are pointed out.

The first group to consider is the definable group of "Vital Needs". The group can be defined by recalling the debate between Maslow's pyramid of needs (Maslow, 1943) and the development on a human scale. The group considers the three objectives that should be guaranteed to everyone to lead a qualitatively dignified life: (1) *No poverty*, i.e., to end poverty in all its forms everywhere; (2) *Zero hunger,* i.e., to end hunger, achieve food security and improved nutrition and promote sustainable agriculture; (3) *Good health and well-being*, i.e., to ensure healthy lives and promote well-being for all at all ages.

The second group includes goals that identify "optimal needs" for equilibrated development: (4) *Quality education*, i.e., to ensure inclusive and equitable quality education and promote lifelong learning opportunities for all; (5) *Gender equality*, i.e., to achieve gender equality and empower all women and girls; (6) *Clean water and sanitation*, i.e., to ensure availability and sustainable management of water and sanitation for all.

It can be assumed that these two groups are achievable with the general policies of the country. The two SDGs that must be explicitly considered for the integration of energy and transport systems in city logistics are SDG 11 and SDG 13:

- SDG 11 - *Sustainable cities and communities*, to make cities and human settlements inclusive, safe, resilient and sustainable. In this goal, are explicitly recalled the targets and indicators relating both to the need for transport systems to be accessible to all (therefore an urban logistics that is able to meet the demands of the whole territory) and to the need for a strong reduction in environmental impacts due to fine particles (the suggested indicators refer to directly to PM2.5 and PM10);
- SDG 13 - *Climate action*, to take urgent action to combat climate change and its impacts. This is one of the most important goals that comes from the Brundtland Report in 1987 and the Rio Conference in 1992. At the target level, reference is made to the need to explicitly include clear actions to contrast climate change in the policies of each country. It is defined as an unequivocal indicator given by the reduction of greenhouse gases.

The two SDGs must be seen in an overall framework, in which, on the one hand, the efficiency of industry defined in SDG 9, and on the other hand, SDG 7 with sustainable energy. Therefore, it is necessary to deepen the relationship between energy and transport/logistics in the field delimited by city logistics, precisely because it is necessary to identify the optimal balance between the various needs.

3. Energy and transport systems in city logistics

To analyse the developments that are expected to be given to city logistics in order to pursue the objectives of Agenda 2030, it is necessary to consider the different components and therefore to have an integrated vision of the two systems. The theme strongly deepened in the theoretical analyses reported in the literature (Ghiani et al., 2004; Thompson and Zhang, 2018) and in the technical components of the application is that related to the aspects of the economic efficiency of the system, i.e., the optimization of logistics and transport choices. In recent years, the theme has been particularly developed by introducing integration with emerging ICT technologies (Taniguchi et al., 2001; Campisi et al., 2023). Working in this direction, the aspects related to the economic objectives of Agenda 2030 are well pursued, and the ICT-Transport system has reached a higher level of integration, as evidenced in the introduction referring to the three main pillars of a smart city.

It is particularly important to identify the aspects related to the energy and, therefore, environmental efficiency of city logistics, and the relationships with the main components of the transport and the logistics cycle. A synthetic analysis of the two systems allows one to identify which are the elements of a close interaction for which it is necessary to deepen the analysis. The environmental components on which transport activity heavily impacts are many. This paper mainly refers to carbon as CO_2 because it is the element that, although produced in a single city, by its very nature spreads globally, creating serious problems for life in all its forms, as it is known today. Carbon is therefore indicated, at international level, as a reference element for all types of chemical compounds that contribute to the greenhouse effect.

3.1. Energy cycles

The main components of the energy cycle are: energy production, transmission, storage, distribution and consumption. The end use in city logistics is varied but can be summarized in the mechanical energy consumed by transport vehicles and the various forms of energy, mainly electrical and thermic, required for storage and transhipment facilities.

The mechanical energy consumed by vehicles is now produced by two types of engines: heat and electric. To the two basic types, it has to add the hybrid vehicles which, at the limit, can be supplied from the two sources, and hydrogen vehicles, which belong to vehicles with heat engines, but which need an energy source currently produced using electricity.

For electricity, the production phase takes place in power plants (including the end users' places – houses or offices, when electricity is generated by solar panels on roofs, for example) that can be powered by renewable sources or not. The plants from renewable sources are: hydroelectric, geothermal, wind, solar, and biomass. Those from non-renewable sources are: nuclear, and thermoelectric. Nuclear power is considered non-renewable considering the current uranium-fired power plants. The intermediate phase between production and distribution is transmission, which takes place through a dedicated ultra-high and high voltage network. Final distribution takes place through dedicated medium and low voltage networks. Although transmission is usually handled by states directly or through exclusive dealers, distribution is often handled on a market-based basis that can be accessed by multiple distribution companies. A particularly important issue for electricity is that of storage: both for the large quantities connected with constant production in the plants and periodic consumption, and for small quantities to make vehicles of all types autonomous. The issue is not easy to solve. One of the methods used for electricity in hydroelectric plants is to transform it back into mechanical energy and therefore into potential energy.

For heat energy, the transformation into mechanical energy takes place directly on board the vehicles. The energy cycle, referring to fossil hydrocarbons, can be reconstructed from the final consumption to the extraction. Following the literature approach (Alvarez et al., 2018), the overall chain can be disaggregated into its three main macro-arcs: upstream, midstream and downstream.

The *upstream* macro-arc is placed at the beginning of the process and includes the phases of "exploration and production". It includes all phases, from research to the construction of wells and extraction plants.

The *midstream* macro-arc includes all transport and storage phases. It should be noted that the problem of storage at all scales, in the case of fossil fuels, can be solved immediately with very simple technologies involving the construction of adequate tanks. These technologies may be more complex for gas storage and transport, but still widely known and applied worldwide.

The third macro-arc is the *downstream* one and concerns the refinement processes and the final distribution.

The segmented cycle is quite general. In real applications, there can be many variants, just think of the refineries that today can be found immediately after the wells and therefore before transport over long distances. Often, in fact, instead of crude oil, the refined product is transported.

The final problem is that of the environmental impacts to be considered: both those suffered by users, but which to date do not affect mobility choices, and those on non-users of the system. Functions that relate the physical and functional parameters of the transport system to flows are called impact functions and are often indicated by the specific impact they measure.

Impact functions are specified for each link of the network and for each type of event, and have the following specification:

$$\boldsymbol{e}^* = \boldsymbol{e}(\boldsymbol{f}, \boldsymbol{\lambda}) = \boldsymbol{e}(\Delta\, \boldsymbol{h}, \boldsymbol{\lambda}) \tag{1}$$

where $\boldsymbol{e}^*$ is the vector of the impact value; $\boldsymbol{e}$ is the vector of the impact function which is function of $\boldsymbol{f}$ (i.e., the vector of the link flows) and λ is the vector of the physical and functional parameters. Link flows can be expressed by the product of the link-path incidence matrix (Δ) and the vector of route flows ($\boldsymbol{h}$).

3.2. Transport and Logistic cycles

In the field of logistics and transport, there are many aspects to consider for economic efficiency. These aspects are defined and mitigated by the connections between the physical points inside the city and, upstream, with the physical points of production. There is a remarkable amount of scientific literature and a great deal of experimentation that has taken place internationally. These works allow us to design the best solutions considering the variables present today: that is, time and cost variables (Letnik et al., 2018; Taniguchi et al., 2018; Veličković et al., 2018; Gonzalez-Feliu, 2019). A schematization that includes the main components of the whole process from production to consumption by end users has been proposed by Russo and Comi (2010), which highlight all the meta-routes of the goods with the different decision makers: manufacturers, retailers, and end consumers.

In this paper, the interest is in the energy impact of city logistics and therefore, as said, in the relationship between energy and transport/logistics. It immediately becomes clear that the interaction between the two systems takes place in the vehicles used for the various phases of travel and at the physical nodes where the different storage and transhipment activities take place. Thus, in general attention must be paid to the two crucial elements: nodes and vehicles.

For the *nodes*, the elements to be considered on an urban scale in addition to the residences of citizens for e-commerce deliveries, are: pick-up points, urban logistic hubs, delivery bays and retailers.

For *vehicles*, the overall energy impacts must be considered, starting from the main component which is given by consumption. The role of the motorisation of the vehicles used becomes central. With the most recent evolutions of vehicles on the market, that is, with the increasingly important presence of electric vehicles, the traditional separation between storage and consumption cannot be maintained because the problem of batteries is, probably, the most important for electric vehicles. Therefore, it is necessary to analyse the different methods of calculating consumption.

It is necessary here to recall the theme of the different conditions of optimality for companies interested in economic optimum and for the public decision-maker who is interested in the optimum relative to congestion reduction. With Agenda 2030 in action, this optimum must include both economic components and environmental, and therefore energy components. For the public decision maker to make companies participating in the energy-environmental optimal they can introduce elements such as emission trading allowances between countries, or very simple elements such as access to vehicles of specific emission classes.

The problem is to bring the costs for the community within the costs of the users. In this hypothesis, the equations of the theory of transport systems expressed in classical form can be used (Cantarella et al., 2019). In this case, the link flow function cost of the group of relationships defining the supply must be rewritten considering the environmental exchange components:

$$\boldsymbol{c} = c\,(\boldsymbol{f}) \tag{2}$$

Considering *eq. (1)*, the link flow function can be expressed, omitting $\boldsymbol{\lambda}$, as:

$$\boldsymbol{c} = c(\boldsymbol{f}) + e\,(\boldsymbol{f}) \tag{3}$$

It should be noted that the interactions between Transport and ICT can be integrated into the formulation of cost functions, *eq. 2*, without changing the structure of the formulation of both equilibrium and dynamic assignment (Russo and Comi, 2021; Comi and Russo, 2022). However, the interactions between Transport and Energy play differently because most of the impacts occur to non-users.

4. Vehicles and nodes impacts

4.1. Evaluation emission models

The elements of city logistics at the intersection of the energy system and transport system are the vehicles and nodes of the integrated system. The environmental indicator that allows one to measure the impact of this interaction on the environment and on the climate is the carbon footprint (CF). This indicator has been developed internationally and today is the reference measure for the evaluation of the different products and processes of human activities. The use of CF allows us to trace the different emissions of the various chemical compounds that affect the climate to a single indicator. In fact, carbon dioxide is certainly the gas that most affects, but there are others with considerable impacts, such as methane, some sulphur compounds, and other elements derived from hydrocarbons. Each of these elements is translated by means of appropriate CO_2 equivalence parameters. Therefore, this makes it possible to use CO_2, or more properly CF, as an indicator of climate impact. The correct evaluation of CF requires a detailed analysis of each product and/or process with the identification of the various factors of the components.

For the nodes, the problem of emissions arises in the construction of buildings and systems, which must be done considering the most advanced techniques of green building and green architecture. An important role of nodes is to realize them in order to have energy autonomy through adequate renewable energy systems.

The issue of proper emission assessment is becoming increasingly important for vehicles. In a simplistic approach, it may appear that switching from the vehicle with a heat engine to the one with an electric engine will reduce the emissions to zero. This is certainly true when considering the emissions produced by the moving vehicle. If all the emissions due to the production of electricity are considered, the problem takes on very different contours.

On this basis, three main evaluation methods are considered (FFC, 2021). The first refers to the emissions produced by the vehicle with all its equipment when the vehicle is operational, this method is called “tank to wheel”. The second considers the emissions already considered in the first method and those relating to the entire production process of the energy used from production. The method is called “well to wheel”, i.e., from the primary source to its final use. The third method, called Life Cycle Assessment (LCA), considers all the emissions produced over the entire life cycle by all the components of the vehicle, thus including both the emissions related to the energy consumed for the movement (starting from its production), and the energy necessary for the production of the vehicle in all its components, for the life of the vehicle until the end of life and any final recovery.

For the definition modalities, the third includes the second, which in turn includes the first. Therefore, it is useful to recall the main elements of the LCA. However, the LCA model does not consider an important element such as the increase in emissions related to the increase in overall energy consumption potentially covered by non-renewable sources. Considering this further increase in emissions, it is useful to recall some results obtained by comparing different classes of vehicles (FFC, 2021). The vehicles are first classified into: subcompact, intermediate, high-end. Each of these classes is in turn segmented according to the type of engine in: *gasoline*; *methane*; *HEV – hybrid electric vehicle*, commonly known as full hybrid, it is partly similar to MHEV (mild) technology. The electric engine is recharged by the internal combustion engine and regenerative braking, the battery performance allows us to drive in all-electric mode for short distances and up to certain low speeds. *PHEV, plug-in hybrid electric vehicle*, they can reach speeds of up to 130 km/h and distances of up to 40 km using only electric power. The battery can be recharged both from a combustion engine and from an external source. *BEV, battery electric vehicle*, i.e. exclusively with a battery-powered electric motor, which is recharged via an external power source, *hydrogen*.

For each segment, annual emission values in kg of CO_2 were evaluated using the three methods, TTW, WTW, LCA, also considering incremental electricity generation. It emerged that BEV vehicles have the lowest value of all, of course, if you consider the TTW method. The situation is more complex if the other types of measurement are considered (FFC, 2023). Among small cars, the BEV has an overall impact of 1044 compared to 1039 for the PHEV. This shows that vehicles equipped with dual engines can have qualified environmental performance. Among the averages, BEV has the lowest overall value. Among high-end vehicles, the BEV has a value of 1646 which is higher than the value 1603 obtained by the methane vehicle.

4.2. Life Cycle Assessment

The LCA method is formalised at international level to assess the overall impact of a product or process on climate. The method is specified by the standards:

- ISO 14040 (2006), Environmental Management, Life Cycle Assessment, Principles and Framework;
- ISO 14044 (2006), Life Cycle Assessment, Requirements and Guidelines;
- ISO/TS 14072 (2014), Requirements and guidelines for the life cycle assessment of organisations;

Based on ISO standards, the development of an LCA study is divided into 4 steps:

- Definition of the objectives and scope of the study, i.e., which products are being studied;
- Life Cycle Inventory, which consists of data collection and calculation procedures to quantify the incoming and outgoing flows relevant to the objective and the field of application;
- Life Cycle Impact Assessment, which aims to assess the extent of possible environmental impacts, calculating specific category indicators for each damage;
- Life Cycle Interpretation, which is the phase in which the results of phases 2 and 3, analysis and evaluation, are combined to present them in a manner congruent with the defined objective, with the final aim of highlighting the limitations and providing recommendations.

The LCA method allows the estimation of direct and indirect emissions throughout the life cycle of a product and/or process. LCA, according to what has been seen, is standardised internationally and is therefore the main tool to be able to compare vehicles, infrastructural nodes, organizational processes of city logistics carried out in different contexts. The approach allows the evaluation of CF produced by different vehicles to be performed. The results obtained are significant even with the same vehicle. It has been found that feeding with a mixture of ethanol-bio and gasoline, the reduction of CF, compared to fuelling only gasoline, can exceed 50%. Such a result, if confirmed by further investigation, could foster research in cleaner combustion fuels instead of electrification, for example.

5. Conclusion

The theme developed in this paper is that of the relationship between the transport system and the energy system in the frame of city logistics. The theme is developed starting from the definition of the SDGs of the Agenda 2030 that pay attention to both economic and environmental components. Then, the basic elements of the energy cycle and the transport/logistics cycle are recalled, highlighting the overlapping areas and, therefore, the two elements on which the two cycles intersect: vehicles and interchange nodes. The indicator that is considered is always the carbon footprint. The analysis of the current situation of vehicles in production highlights the complexity of the problem since there is no type of engine that always and in any case dominates all the others. In addition, there is the related problem of distances that vehicles can cover autonomously with different engines.

Different considerations emerge from the work carried out. The first concerns the need to increase the production of renewable energy in transhipment centres in order to be able to power the vehicles that use them. The second concerns research to be developed considering models that study not only cost efficiency but also energy impacts. A further direction of research derives from the previous one and provides for the possibility of developing models that consider the components of energy, transport and ICT, in a smart perspective. These are the most important challenges on the desk.

Therefore, the presented work is of interest to researchers in the sector, but also to technicians of public administrations who are planning interventions for the control of the distribution of goods at an urban scale. Therefore, based on the proposed review on the lessons learnt, the framework for identifying the potential new policies/measures that can be implemented to pursue the goals of sustainability should be clearer to policy makers. Besides, it is one of the first contributions as well as the first steps towards the promotion of an integrated system description where new and expansive patterns of thinking are nurtured, where collective aspiration is set free, and where people are continually learning to see the whole together (Senge, 2023). A pioneering attempt in city logistics has been carried out by Toiler et al. (2018).

From the considerations made above and recalling the state of the development of the Transport-ICT interaction available in the literature, it is possible to identify a research development roadmap. The first link, where to move, is to include, in the TSM standard equations, the cost functions updated with the available vehicles, considering both the TTW consumption and the distances allowed by batteries and tanks, as indicated in this paper. The next link is to use the TSM equations rewritten in the previous step but with the advancement for dynamic conditions, using emerging ICT technologies. These two steps allow us to model the integration between the three pillars of the smart city: Transport-Energy-ICT. Having the complete formulations allows us to evaluate ex-ante the actions and measures to be implemented for the pursuit of the SDGs of Agenda 2030.

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