# Movement generation and trip distribution for freight demand modelling applied to city logistics

## Guido Gentile [1], Daniele Vigo [2]

[1] *Università di Roma "La Sapienza", Dipartimento di Ingegneria Civile Edile e Ambientale*
*Via Eudossiana 18 - 00184 Roma, Italy, guido.gentile@uniroma1.it*
[2] *Università di Bologna, Dipartimento di Ingegneria dell'Energia Elettrica e dell'Informazione*
*"Guglielmo Marconi"*
*Viale Risorgimento, 2 - 40136 Bologna, Italy, daniele.vigo@unibo.it*

**Abstract**

The quantification of the freight movements disaggregated by supply chain occurring in each traffic zone for the urban delivery of goods and that of the corresponding Origin-Destination trip tables is essential to evaluate the effects of any city logistic policy in terms of vehicle congestion and polluting emissions through the assignment of truck flows on the road network.

In this paper we propose two innovative demand models: the first one for movement generation, the second one for trip distribution. The movement generation is addressed through an extension of the category index model, which takes into account the hierarchy in the classification system of the economic activities, thus avoiding aggregating the many existing classification codes into pre-specified groups. The trip distribution is addressed through an adaptation of the gravity model, which takes into account that deliveries are organized in tours.

This approach has been successfully applied to the case of Emilia-Romagna Region in Italy, where an extensive campaign of surveys has permitted to calibrate both models for several towns and cities with various dimensions and vocations.

*Keywords:* urban delivery of goods, estimation of freight O-D matrices, category index model with hierarchy, gravity model with tours.

## 1. Introduction

City logistics is concerned with the efficient transport of products from industrial and stocking sites to retail local units, and then to offices and houses. To better understand the problem, it is worth examining the physical itinerary of important items, such as grocery and household articles, which generally make up more than one third of the total freight traffic in urban areas (see, e g. Strauss-Wieder et al, 1989 or Danielis et al., 2010). Since the main focus of this paper is the distribution within city centers affected by relevant congestion problems, that in many cases have a dominant retailing vocation, we simplify our description by considering only transportation of goods towards shops. The goods are transported to the shops in the city by: private carriers, the manufacturing

companies themselves or the shops in own account; logistic service providers, each owning a large fleet of vehicles to provide the delivery service(such as third and fourth-party logistics providers, 3PL and 4PL), autonomous transporters, small operators often owning a single truck. Along this journey, transshipment may occur at logistic centers, located near or within the city, where load rearrangement is performed; here the goods are dropped off from heavy trucks, possibly stocked, and then transferred to smaller vehicles for the distribution in town. These flows of goods are organized into different *supply chains* depending on their characteristics and service requirements, e.g., fresh foods, frozen foods, dry foods, household articles (Browne and Gomez, 2011; Danielis et al., 2013). In the last step, which is not addressed in this paper, the goods are purchased by final consumers who personally bring them home.

City logistics may be analyzed by two different points of view, each one rising different problems. For logistic agencies the most relevant aspect is that of minimizing the shipment industrial costs. Therefore, one of the main issue is that of finding the optimal routes to be used by the vehicles providing the delivery service. Vehicle Routing Problems (VRPs) have been extensively studied in the context of Operations Research and several algorithms have been proposed in the literature (for recent surveys see: Toth and Vigo, 2002; Cordeau et al., 2007, Golden et al., 2008). Vehicle routing models are highly disaggregated and require fine-grained data on demand distribution and on the service specifications. The existing tools for pickup and delivery planning are conceived for supporting the operational management of a city logistic service, or for analyzing mid-term problems such as fleet sizing.

For the Public Administrations the most important aspect is instead that of moderating the social costs generated by freight mobility in the urban area. These are primarily connected with the impact on traffic congestion of the vehicles circulating for delivery tours, as well as with the road capacity reductions caused by the stationary vehicles for loading or unloading operations, often caused by illegal parking of private cars in double line or on dedicated delivery bays (see e.g., Routhier, 2002, and FREILOT, 2012). In the following we will call such loading and unloading operations also *movements*. Then the problem consists either in positioning new logistic centres or in establishing effective policies for the regulation of freight traffic. This latter option may be implemented by imposing temporal and/or spatial limitations to the circulation and/or parking of trucks as well as by creating dedicated stopping areas to let freight vehicles perform the movements.

The quantification of freight demand in terms of movements and flows on each link of the road network due to the urban delivery of goods is essential for evaluating the effects of any city logistic policy. In the following we briefly review the main approaches that were proposed in the literature to model the transport of goods in the urban case. For a detailed survey the reader is referred to Anand et al. (2012), Comi et al. (2012), Gonzalez-Feliu and Routhier (2012), Gonzalez-Feliu et al. (2012), Holguín Veras et al. (2012), as well as to the extensive bibliography compiled by the Oak Ridge National Laboratory (2004) for the Freight Model Improvement Program.

In general, the demand models used in the context of freight distribution can be classified into three main types: gravity (Hutchinson, 1974; Ogden, 1992; Taylor, 1997; He and Crainic, 1998; Gorys and Hausmanis, 1999), spatial price equilibrium (Oppenheim, 1995; Nagurney, 1999), and input-output (Harris and Liu, 1998; Marzano and Papola, 2004). In all these cases, the resulting O-D matrices can be adjusted to match truck link flows. The above approaches seem to be more suitable for regional and

national planning, than to the context of urban freight shipment, since many factors (e.g. historical traditions, city structure) beside accessibility influence the location of shops. Note also that such models refers mainly to the distribution step, whereas those used in the context of people's movements generally refers to the demand generation at origins or consider integrated approaches. Few practical implementations of demand models for urban freight distribution, such as that described in this paper, are available nowadays and are reviewed in the next Section 1.

Gravity models may be further divided into truck-based and commodity-based approaches. Truck-based models (Zavettero and Waseman, 1981; Habib, 1985; Ogden, 1977; Slavin, 1976) yield a direct estimation of trip rates, but suffer transferability problems. Although the average quantities of consumed goods per inhabitant usually do not vary too much from one city to another in a same country, the organization of logistics in terms of shop and truck dimensions may indeed differ considerably. This observation, which is consistent with the survey results used in our study is also addressed by Gerardin et al. (2000), and Gonzalez-Feliu et al. (2013).

Commodity-based models (Taniguchi and Thompson, 1999, 2003, 2006; Holguin-Veras and Thorson, 2000) estimate the quantity of goods sold in each traffic zone (which is strictly correlated to the number of employees in the commerce sector), under the assumption that consumer demand (which is instead related to the number of residents) must be satisfied, thus reproducing the process of acquisition and consumption of goods. As a counterpart, commodity-based models require a loading model to convert the tons of goods into the number of vehicle trips (Noortman, 1984, for example, uses a fixed share of the truck capacity, which may vary according to the commodity type, although such a simplification is not acceptable for most of the goods travelling in the urban context, as observed by Button and Pearman, 1981), and to take into account complementary empty trips (as described, for example, in: Hautzinger, 1984; Holguín-Veras and Thorson, 2003a, 2003b; Holguín-Veras et al., 2005).

In addition to trucks and commodities, alternative units to describe freight transport are also routes (see, e.g., Sonntag, 1985 or Hunt and Stefan, 2007), trips (Ogden, 1992; Bera and Rao, 2011) and movements as used in this paper, in the Freturb software (see Routhier and Aubert, 1999) and in Nuzzolo et al. (2012), among others.

In practice, most demand models for urban freights are based on the same "four-steps" sequential approach (generation, distribution, modal split, and assignment) used for passenger transport. For example, the demand generation and attraction of every supply chain is first determined for each traffic zone through a regression model, then a gravity model for distribution is applied to obtain an Origin-Destination (O-D) matrix to be assigned on the road network taking into account access restrictions, while mode choice usually reduces to the vehicle dimensioning which depends strongly on the supply chain.

This classical approach involves two open questions. The first one is intrinsic in the approximation introduced by arbitrarily aggregating the many different economic activities into a few groups of categories. The second one lays in the fact that many deliveries are performed by a commercial vehicle within the same tour, so that before assigning the demand flows to the network one has to transform the pickups and deliveries into an O-D matrix of direct truck trips. Both issues will be addressed in this paper and new solutions will be proposed. In particular, our main contributions are two innovative demand models: the first one for movement generation, the second one for trip distribution. The movement generation is addressed through an extension of the

category index model, which takes into account the hierarchy in the classification system of the economic activities, thus avoiding to aggregate the many existing classification codes into pre-specified groups. The trip distribution is addressed through an adaptation of the gravity model, which takes into account that deliveries are organized in tours.

The paper is organized as follows. In the next section, we outline the overall approach underlying the proposed models. In Section 2 we describe the generation model, whereas in Section 3 we describe the distribution model. Finally, Section 4 presents the application of the methodology to the city of Bologna, capital of the Emilia-Romagna Region. Section 5 draws some conclusions.

## 2. The overall approach for impact evaluation

The quantification of the external effects produced by freight mobility in urban areas is currently an important field of research but, in contrast to what happened with people mobility, no consolidated methodology of analysis is yet available. In order to fill this gap some attempts were recently carried out in Europe. The information collected from some German towns within the Bestufs Project, financed by the European Union, led to the Wiver model (Meimbresse and Sonntag, 2001), now integrated within the Viseva software package (Friedrich et al., 2003). Other examples of practical models are the Good Trip model (Boerkamps and Van Binsbergen, 1999) developed in The Netherlands, and the VENUS software (Janssen and Vollmer, 2005) produced by IVV Aachen.

The French Government promoted the development at the Laboratoire d'Economie des Transportes in Lyon of the Freturb model (Routhier and Aubert, 1999; Ambrosini and Routhier, 2004, Routhier and Toilier, 2007). In this latter case, the statistical analysis of the data collected through surveys performed in three important cities (Marseilles, Bordeaux and Dijon) produced an overall model that allows for evaluating a set of impact indicators, based on the average number of movements made by each category of economic activity as a function of the employees. Demand generation in Freturb is related to all premises since also end-users movements are considered. For example, to evaluate the occupation of parking slots for freight movements it is assumed that the total number of stopping hours spent within a given traffic zone is the sum, over all categories of shops and vehicle types, of the products among: a) the number of premises belonging to that category present in the zone; b) the number of movements each shop generates for that type of vehicle; c) the average duration of such movements; and d) an equivalence factor typical of the vehicle, for example, related to the travelled distance or the number of stops.

In this paper we present a new model for the analysis of urban freight demand and the evaluation of its external effects, which originates from the intensive collaboration between the authors and the Council on Transportation of the Emilia-Romagna Region in Italy. There, an extensive survey has been promoted in the years 2004-5, partially financed by European Projects CityPorts and Merope, on the logistic activities in ten (out of fourteen) towns with more than 50,000 inhabitants. Almost all surveys have been performed according to the methodology developed within the CityPorts Project, where the phenomenon of urban freight shipment is faced from different points of view, thus including specific interviews to: commercial local units, logistic operators, and truck drivers. The surveys collected more than 1700 interviews to shops and other relevant premises (covering between 1% and 10% of the overall universe), 80 logistic

operators and more than 3500 vehicles (see Section 4 for additional details on the surveys). Each interview collected detailed information of the characteristics of the movements (regular and irregular) that interested the premise for all possible Supply Chain in a time horizon of a week, leading to several hundreds of movements analyzed for each surveyed town. The result is an extensive and homogeneous data source that represents an interesting modeling opportunity.

The CityPorts Project proposes a methodological framework for the planning of initiatives to support city logistics, such as new transshipment infrastructures or regulatory policies. Any specific *logistic action* affects only a subset of Traffic Zones (TZ) and of Supply Chains (SC). Its relative impact can then be measured through the so called *TZ-SC matrix* (Gentile and Vigo, 2006), whose generic element yields the total number of, say annual, movements for a given supply chain in a certain traffic zone. For example, access restrictions to freight vehicles may be applied to the city center and not to other zones, while a logistic center may serve only a part of the whole town and some supply chains. Therefore, the overall impact of a logistic action may be easily determined by computing the total number of movements that it "covers" on the TZ-SC matrix. Figure 1 gives an illustration of a TZ-SC matrix and of the mapping of logistic actions on the matrix: LA1 is a SC-specialized distribution center (DC) serving several zones, LA2 is a non-specialized DC serving a single zone.
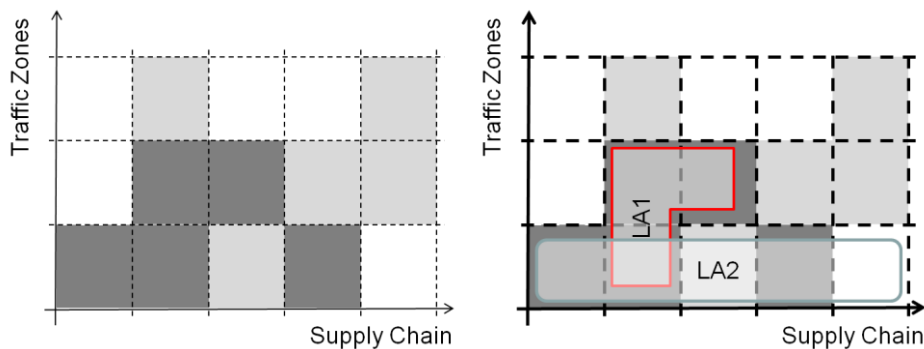


Figure 1. Example of Traffic Zones-Supply Chain (TZ-SC) matrix (right) where different colors represent levels of movements or congestion. On the left there is an example of mapping of Logistic Actions on the TZ-SC matrix.

The determination of the TZ-SC matrix as well as its use as a starting point to obtain the Origin-Destination matrices of truck flows, distinguished by SC, that can be assigned on the road network, will be addressed in the remainder of this paper by proposing specific generation and distribution models. These two models aim, respectively, at finding the movements generated by each traffic zone for each SC, and the direct truck trips between the zones containing two consecutive vehicle stops, taking into account the structure of the delivery tours. To this end it should be considered that: a) each local unit (e.g., shop, office …) generates movements belonging to several supply chains; b) local units are classified in the available databases according to a hierarchic code that identifies with successive specifications the sector of economic activity (e.g., the NACE system adopted in Europe, and the NAICS system adopted in North America); c) the generated movements are organized into truck tours that begin

and end at given portals (logistic centers, or access roads to town) and may serve local units in several traffic zones.

The CityPorts surveys that we used as a base for the development and tuning of our models confirmed the above remarks. Several SCs were identified a priori according to their relevance in the movements of towns under study, the important of which are:

- Clothes and accessories
- Food (subdivided into Fresh, non Fresh and Frozen as separate SCs)
- Household and electrics
- Newspapers
- Pharmaceuticals
- Wholesale and department stores
- Other non specialized retail
- Services
- Documents
- Reverse logistics

For each surveyed premise where an local unit is located, the questionnaire collected all data on the movements it possibly generated for each such SCs within a weekly time horizon. Thus the NACE code of the local unit may provide a link between premises and movement generation for different SCs.

The main difficulty of performing a statistical analysis to determine the number of movements for each SC generated by every type of activity is represented by the fact that, generally, the classification systems include hundreds of different codes (e.g., in the NACE system they are more than 1500). Therefore, the activity codes are typically partitioned into groups, or *categories*, and an average for each group is retrieved from a sample of local units. However, when many categories are defined one cannot expect the sample to cover uniformly and satisfactorily each group. In our case, this happened because of the relatively limited size of the sample for each town dictated by the available budget for the survey activities.

Category index models are an evolution of the above simple aggregation approach. The main idea is to take into consideration the correlation among categories, if present, so as to provide a better estimate for groups that are not adequately covered by the sample. The classical case is when the categories are defined on the basis of several discrete attributes (continuous variables can be handled by defining suitable intervals), and the correlation among categories arises naturally from having the same value for some attribute. In our case, apparently there is only one attribute available, namely the activity code; however, we can consider the single digits forming the code as separate attributes, each one identifying a successive specification of the economic sector.

In this paper we introduce a new demand generation model for the determination of urban freight movements that extends the category index approach, thus avoiding any a-priori aggregation of activity codes into a predefined number of groups. The proposed model is based on the explicit consideration of the tree-based structure adopted by most classification systems for local units, that typically include a progressive level of disaggregation represented by the subsequent digits in the code associated with each economic activity. We then assume that the correlation among categories depends on their topological relationship by exploiting the hierarchical structure of one explanatory attribute: the activity code. More specifically, the main assumption is that the number of movements generated by a given activity code is correlated with those generated by

activity codes that are associated with its descendant and ascendant nodes in the classification tree, i.e., those representing its disaggregation or aggregation.

   The second contribution of this paper is a distribution model that implements the gravity paradigm in the case of urban freights, taking into account the average number of deliveries made along shipping routes of each supply chain. Every route of a vehicle serving a certain supply chain is assumed to begin at some portal, make a specific number of stops to perform the deliveries (or the pickups, in the case of reverse logistics), and end at the same portal. Therefore every section of the tour between two successive stops, including the first and the last leg from and to the portal respectively, shall be associated with a direct trip in the O-D matrix from the traffic zone of the previous stop to the traffic zone of the following stop. In other words, each movement occurring in a given traffic zone shall be associated with one direct trip that terminates in that zone and with another direct trip that originates in the same zone. These tours are associated with the different portals proportionally to their relative importance, measured for example by the truck traffic that they generate. Then, the number of direct trips originating and terminating at each portal is equal to the number of tours associated with it. The probability that a tour leaving a given zone will reach another zone through a direct trip is assumed to decrease with the distance on the network between the two zones, for example measured by the generalized travel cost, thus implementing the gravity paradigm.

   The two demand models, along with a classical assignment model, have been integrated into a software tool called CityGoods (Gentile and Vigo, 2007), and were calibrated with the data of the Emilia-Romagna surveys. CityGoods provides a GIS interface, illustrated in Figure 2, that allows for creating a scenario by importing the road network and the Traffic Zones in shape format as well as the database of the universe of local units, of the SC descriptions and of the survey. Once the scenario is created the software allows for the determination and calibration of the generation and distribution models and the execution of the assignment of traffic flows to the road network. In the following sections we describe in detail the two models and report the results of the application of CityGoods to the case of Emilia-Romagna. Once defined and calibrated the models may be stored to be used for subsequent analyses on the same or other towns.
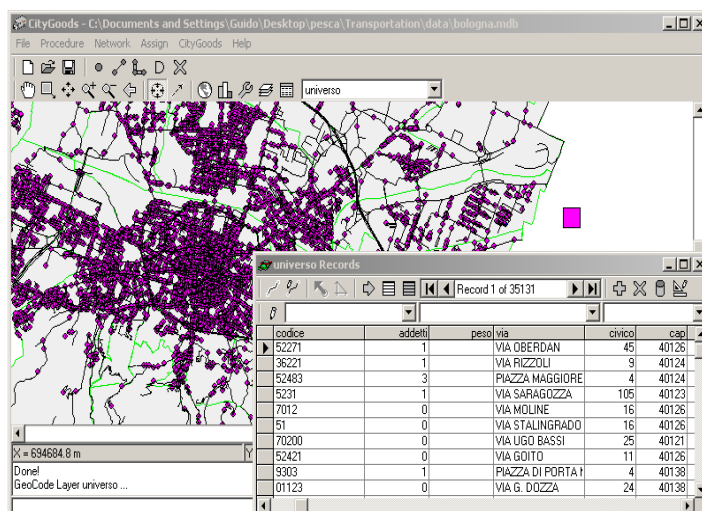
Figure 2. Screenshot of CityGoods software showing the distribution of the universe.

## 3. The generation model

In this section we describe a generation model aimed at the estimation of the number of movements produced by each local unit for freight deliveries (or residuals pick-ups) of different supply chains. It should be noted that in the case of urban logistics the movement generators are actually the destinations of the goods, i.e., the shops, if we refer to shipments, whereas in modeling passenger demand the traffic generators are typically the origins, i.e., the homes, if we refer to morning commuters; the opposite is true if we consider collection activities and afternoon return trips.

As introduced in the previous sections, the model is an extension of a category-index approach whose main characteristic is that it does not require any a-priori aggregation of the economic activities into categories. In classical models generation is indeed based either on mean values or on a-priori aggregations of activities into categories, often using standard aggregation patterns from the literature that map into each such category sets of codes of the activity classification system adopted by most countries to identify the economic activities in census statistics.

Our model explicitly associates movement generation to a fine-grained classification, such as that informing the activity classification systems. Such systems have normally a hierarchic structure, topologically represented by a tree structure, which reflects the progressive disaggregation of economic sectors into sub-sectors. More specifically, each disaggregation level is associated with an additional digit of the code that identifies the economic activity in the system. For example, the Italian specification of the NACE system, called ATECO, identifies 15 main categories further disaggregated into sub-categories with up to five hierarchic levels. The main assumption of this fine-grained approach is that a correlation exists between the movement generated by activities whose codes are belonging to the same branch of the classification tree. Once the movement generation is determined for each code of the tree it is easy to re-aggregate them into a-priori categories. The computational validation on the Emilia-Romagna sample data, described later in this section, shows that our approach is not only simple and fast to be applied but it provides considerably more accurate results than classical methods from the literature.

### 2.1 Detailed description of the generation models

We now give the formal description of two variants of the generation model. For the sake of simplicity we refer our analysis to generic movements, although in practice we shall build a specific model for each SC, given that every category may produce movements of several SCs. To this end, we simply must add a SC-related index to all movement variables in the formulas reported below.

Given an economic activity classification system, the topological relationship between a sub-category and its immediate aggregation in the higher level is clearly unique, i.e., each sub-category is originated from the disaggregation of a single category. Hence, as previously observed the classification system may be suitably represented as a tree $T = (C, B)$, i.e., an acyclic oriented graph, where the set $C$ includes a node for every category plus a special *root* node $r$. The latter is the only node with no entering branches, while all the other nodes have a single entering branch. The final nodes of the branches exiting from the root represent the main categories, which can be considered

independent from each other in terms of any relevant feature. The hierarchic relationships among economic activities within the classification system are represented by the set of branches, $B$, each connecting a category with one of its sub-categories. More precisely, each node $i \in C\text{-}\{r\}$ is associated with another node, called *father*, which represents its immediate higher level in the hierarchic structure and is denoted by $f(i) \in C$. Therefore, the set of branches constituting the tree is $B = \{(i, j): j \in C\text{-}\{r\}, i = f(j)\}$. The *predecessors* $P(i)$ of node $i \in C\text{-}\{r\}$, are the nodes included in the unique path in $T$ connecting the root node $r$ with node $i$, except the root itself but including $i$, i.e., $P(i) = \{r, \ldots, f(f(i)), f(i), i\}\text{-}\{r\}$. Similarly, the *successors* $S(i)$ of node $i \in C$ are all the nodes whose predecessors include $i$, except node $i$ itself, i.e., $S(i) = \{j \in C: i \in P(j)\}\text{-}\{i\}$. The *children*, $FS(i)$ of node $i \in C$ are the nodes whose father is $i$, i.e., $FS(i) = \{j \in C: f(j) = i\}$. The *leaves $L$* of the tree are the nodes having no children, i.e., $L = \{i \in C: FS(i) = \varnothing\}$. This mathematical representation of a classification system is exemplified in Figure 3.

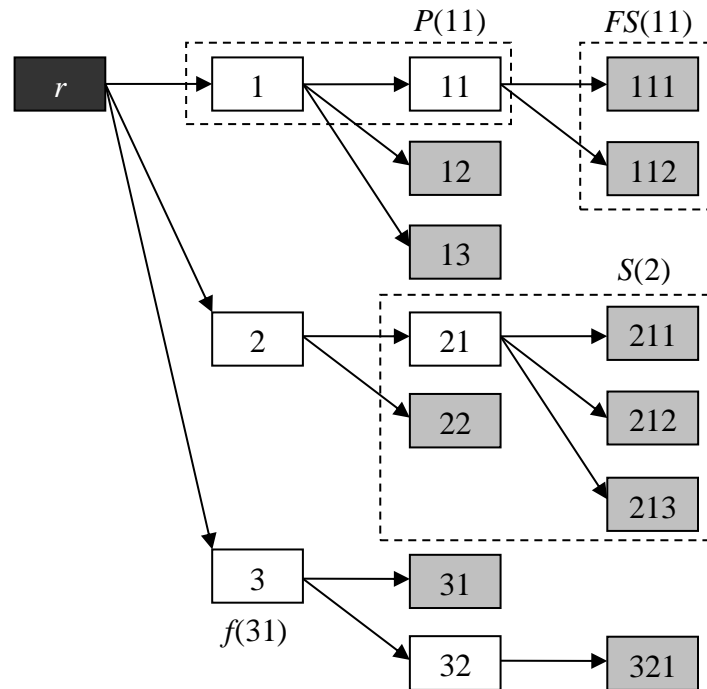

Figure 3. Graph representation of a classification system. The root is black, the leaves are grey.

Given the *universe U* of local units that are present in the specific area under analysis, each node $i \in C\text{-}\{r\}$ is associated with the *probability* $\beta_i$ that it is the child of his father $f(i)$, to be evaluated as follows. Each local unit $u \in U$ is characterized by a category $c(u) \in C$. Let $\omega_i$ be the number of local units in the universe belonging to the category associated with node $i \in C$:

$$\omega_i = \sum_{u \in U} B(c(u) = i) , \tag{1}$$

where $B(x) = 1$, if $x = $ TRUE, 0, otherwise, and $\Omega_i$ be the number of local units belonging to any category associated with a successor of node $i$ and with $i$ itself, that is:

$$\Omega_i = \omega_i + \sum_{j \in S(i)} \omega_j = \omega_i + \sum_{j \in FS(i)} \Omega_j . \tag{2}$$

Then, the probability $\beta_i$ is computed as:

$$\beta_i = \Omega_i / \sum_{j \in FS(f(i))} \Omega_j = \Omega_i / (\Omega_{f(i)} - \omega_{f(i)}) \ . \tag{3}$$

The number of local units $\Omega_i$ and the probabilities $\beta_i$ may be computed in linear time by visiting the tree in reverse topological order, i.e., from the leaves up to the root. We can then define the *relationship* $\psi_{ji}$ of any successor $j \in S(i)$ of node $i \in C$ with $i$ itself as the probability that $j$ is the descendant of $i$, expressed as a product of conditional probabilities at nodes:

$$\psi_{ji} = \prod_{h \in P(j)-P(i)} \beta_h \ . \tag{4}$$

The main assumption of the generation model we propose is that the number of movements associated with a given activity code of the classification system, i.e., with a given node of the tree, is correlated with the number of movements generated by the codes of its predecessors and successors nodes. To specify the form of this correlation, we assume that a non-negative number of movements $m_j$ is associated with each branch of the tree $(f(j), j)$, $j \in C-\{r\}$. Then, the number of movements $M_i$ generated by the generic node $i \in C$ in the reference period (e.g. one year) is obtained by adding two different terms: $H_i$ , given by the sum of the movements associated with the branches entering each predecessor $j \in P(i)$ of $i$, and $W_i$ , given by the sum of the movements associated with the branches entering each successor $j \in S(i)$ of $i$ suitably weighted by their relationship $\psi_{ji}$ with $i$.

In other words, the main output of the model are the number of movements $M_i$ produced by each node of the tree, which are correlated among each other due to the hierarchic structure of the classification system. But the relevant independent variables to be estimated are the number of movements $m_j$ associated with each branch of the tree, that express the contribution to the demand generation common to node $j$ and to all and only its successors. Indeed, each branch of the tree represents an additional specification of economic activity that identifies a category, and thus contributes with a specific number of movements to its demand generation as well as to those of all the sub-categories obtained through its further disaggregation. Based on the above assumptions any portion of the classification system relative to each main category is independent from the others in terms of movement generation.

In formal terms, we assume that for each $i \in C$ it is:

$$M_i = H_i + W_i \ , \tag{5}$$

where

$$H_i = \sum_{j \in P(i)} m_j \ , \tag{6}$$

$$W_i = 0, \text{ if } i \in L, \text{ and } W_i = \sum_{j \in S(i)} \psi_{ji} \cdot m_j \ , \text{ otherwise.} \tag{7}$$

To clarify the physical interpretation of the model we can observe that: a) the number of movements generated by a leaf is given by the sum of the movements associated with the branches entering its predecessors; b) the correlation among two leaves is given by the sum of the movements associated with the overlapping branches in the two paths connecting the root to them; c) a node which is not a leaf synthesizes all the leaves in its successors, indeed it generates the average number of movements relative to the leaves in its successors weighted by the relationship of each leaf with it.

Assertions a) and c) are formally expressed by the following equations:

$$M_i = \sum_{j \in P(i)} m_j \ , \ i \in L, \tag{8}$$

$$M_i = \sum_{j \in S(i) \cap L} \psi_{ji} \cdot M_j \ , \ i \in C-L. \tag{9}$$

While (8) derives directly from the model (5)-(7), (9) could be easily proved through a recursive argumentation.

For the two contributions, respectively, we can state the following local and recursive formula:

$$H_r = 0 \ , \ H_i = m_i + H_{f(i)} \quad i \in C\text{-}\{r\} \ , \tag{10}$$

$$W_i = 0, \ i \in L \ ; \ W_i = \sum_{j \in FS(i)} \beta_j \cdot (m_j + W_j), \ i \in C\text{-}L \ . \tag{11}$$

Indeed, it is:

$$H_i = m_i + \sum_{j \in P(f(i))} m_j \ , \tag{12}$$

$$W_i = \sum_{k \in FS(i)} \beta_k \cdot \sum_{j \in S(k) \cap L} \left(\prod_{h \in P(j)-P(k)} \beta_h\right) \cdot \left(m_k + \sum_{h \in P(j)-P(k)} m_h\right) \ . \tag{13}$$

The triangular system (10) can be solved by processing the nodes in topological order, while the triangular system (11) can be solved by processing the nodes in reverse topological order. On this basis the model can be solved in linear time.

The system (5)-(7) expressing the dependent variables $M_i$ in terms of the independent variables $m_j$ is linear. Therefore we can also write:

$$M_i = \sum_{j \in C} \pi_{ij} \cdot m_j \ , \ i \in C \ , \ \text{in compact form } \boldsymbol{M} = \boldsymbol{\pi} \cdot \boldsymbol{m} \ , \tag{14}$$

where $\pi_{ij}$ represents the unit contribution of $m_j$ to $M_i$ , which can be determined as follows.

Three different cases may occur:
a)   $j \notin P(i) \cup S(i)$ , then $\pi_{ij} = 0$;
b)   $j \in P(i)$ , from (6) we have that $\pi_{ij} = 1$;
c)   $j \in S(i)$ , from (7) we have that $\pi_{ij} = \psi_{ji}$.

The matrix $\boldsymbol{\pi}$ can be computed directly from the probabilities $\beta_i$ without introducing explicitly the relationships $\psi_{ji}$ as shown in the algorithm presented below.

```
π = 0
for each i∈C
        ψ = 1
        j = i
        until j = r
                ψ = ψ · βj
                πij = 1
                j = f( j)
        loop
next i
```

The formulation as a linear system turns out to be useful for the calibration of the model. Let $y_q$ be the movements generated by the generic element $q \in Q$ of the sample $Q \subseteq U$. The calibration process can be addressed by solving the following least square problem through the algorithm NNLS - Non-Negative Least Squares of (Lawson and Hanson, 1995):

$$\min\{\|\mathbf{y} - \boldsymbol{\Pi} \cdot \mathbf{m}\|^2 \colon \mathbf{m} \geq \mathbf{0}\} \ , \tag{15}$$

where $\boldsymbol{\Pi} = [\boldsymbol{\pi}_{c(1)}{}^{\mathrm{T}} , \ \ldots \ , \boldsymbol{\pi}_{c(q)}{}^{\mathrm{T}}, \ \ldots \ , \boldsymbol{\pi}_{c(|Q|)}{}^{\mathrm{T}}]^{\mathrm{T}}$, $\boldsymbol{\pi}_i$ is the generic $i$-th row of matrix $\boldsymbol{\pi}$, with $i \in C$, and $\mathbf{y} = (y_1 , \ \ldots \ , y_q , \ \ldots \ , y_{|Q|})^{\mathrm{T}}$. The proposed model introduces many parameters to be determined. However, in practice the number of movements associated with a branch is left to zero by the calibration process whenever no element of the

sample requires to introduce that specific disaggregation for distinguishing its category from those in the rest of the sample. In such a case, the number of movements generated by that category is equal to the number of movements generated by its father.

The proposed model can be considered a particular application of the category index approach, since for each economic activity we deduce the rate of freight movements produced for every supply chain by averaging the sample data through a procedure that introduces a correlation among the activity codes of the categories, taking into account the hierarchic structure of the classification system.

As previously described, this model does not exploit any information about the local unit other than its activity code to explain the magnitude of the generation phenomenon. A major improvement can then be achieved by considering some attribute expressing the dimension of the local unit, such as the number of employees or the available selling surface. The proposed approach is easily extended to obtain a linear model with respect to a given *size function* (see Ben Akiva and Lerman, 1985) $E$ as follows:

$$M_i + E \cdot X_i = \sum_{j \in C} \pi_{ij} \cdot (m_j + E \cdot x_j) \, , \, i \in C \, ,$$

in compact form $\mathbf{M} + E \cdot \mathbf{X} = \boldsymbol{\pi} \cdot (\mathbf{m} + E \cdot \mathbf{x})$ . (16)

In this version of the model the variable $M_i$ expresses the minimum number of movements that local units of the category associated to node $i \in C$ generate in any case regardless of their dimension, whereas $X_i$ expresses the additional number of movements generated per each dimension unit, while the variables $m_i$ and $x_i$ referred to the branches entering node $i$ allow to express the correlation among $\mathbf{M}$ and $\mathbf{X}$, respectively, in terms of independent variables.

The calibration problem becomes:

$$\min\{\|\mathbf{y} - [\boldsymbol{\Pi}, \mathrm{diag}(\mathbf{E}) \cdot \boldsymbol{\Pi}] \cdot [\mathbf{m}^{\mathrm{T}}, \mathbf{x}^{\mathrm{T}}]^{\mathrm{T}}\|^2 : \mathbf{m} \geq \mathbf{0}, \mathbf{x} \geq \mathbf{0}\}.$$ (17)

where $E_u$ is the dimension attribute of the generic local unit $u \in U$, and $\mathbf{E} = (E_1 , \ldots , E_q , \ldots , E_{|Q|})^{\mathrm{T}}$ are the dimension attributes of the sample $Q$.

Once we have calibrated our disaggregated model, which allows to associate a number of generated movements to each local unit given its economic activity and possibly its dimension, the application to a study area typically requires to aggregate the movements generated by all local units present in a single traffic zone $z \in Z$, where $Z$ denotes the set of zones in which the study area is partitioned. Let $z(u) \in Z$ be the zone where the generic unit $u \in U$ is located. Since each local unit generates a yearly number of movements $M_{c(u)} + E_u \cdot X_{c(u)}$ , the total number of movements $D_z$ generated in the generic traffic zone $z \in Z$ is:

$$D_z = \sum_{u \in U: z(u) = z} M_{c(u)} + E_u \cdot X_{c(u)} \, .$$ (18)

### 2.2 Validation

The proposed model has been validated on a dataset of 315 surveys carried out in the framework of the CityPort European Project to assess the movements produced by retail shops (i.e., the sub-tree rooted at code 52 of the NACE tree) in the city center of Bologna, Italy. The validation has been performed by randomly choosing a subset of the surveys, including 5%, 10%, 20%, or 50%, of the whole sample. Our model without size function factors (e.g., employees), is calibrated on the complementary fraction of the sample (i.e., the remaining 95%, 90%, 80% and 50% samples not in the validation set), and the output is compared with the actual values. This process is repeated 1000 times for each size of the sample subset and only total movements are considered for the

comparison; indeed a model based solely on the activity code may not provide an accurate estimation for the single shop. This is consistent with the actual need of proving the quality of the method at a rather aggregated level, since in practice it will be applied to estimate the movements generated by all shops of a given traffic zone.

The average of the percentage relative gap, defined as |*sample - model*| / *sample ·100*, in terms of total generated movements (depicted by white bars in Figure 4) decreases from 16.4% for 5% of the validation sample (16 shops) down to 7.1% for 50% of the validation sample (157 shops). As expected, the average number of generated movements tends to become more stable for larger populations of shops. In any case, the goodness to fit shown by the model can be considered satisfactory, since a relative gap of 10% in demand modeling is suitable for most applications. Moreover, the distribution of the relative gap (without taking the absolute value) among the random samples (depicted by white diamonds in Figure 6), shows that for most of the experiments the result lays within the interval [-20%, +20%], which also assesses good robustness of the model.

To investigate the convenience of the proposed hierarchic approach with respect to a classical category index model, we extended the validation analysis to a simple aggregation of local units and to the trivial model where all shops are aggregated into one group. This latter yields the mean of the calibration sample, and is taken as the basis for the comparison. As to the simple category aggregation, given the coding associated with classification system, we defined separate categories each corresponding to a different value of the third digit of the activity code, as it is frequently done in practice. : The main results are reported in Figure 5, where the $\rho^2$ (rho square) indicator is defined as the complement to one of the ratio between the relative gap of a model and the relative gap of the basis: $\rho^2 = 1$, identifies a perfect model, whereas $\rho^2 = 0$, identifies a useless model which is not better than the basis.

As far as the relative gap is concerned, all three models that we examined proved to be suitable for many engineering applications, especially at high aggregation levels. This result tells us that sophisticated generation models (e.g. consumer acquisition based models), which typically require lots of expensive data (either in terms of modeling efforts or in terms of survey costs), have a hard life proving to be really better than simple models, that already have sufficient quality. However, as expected, the aggregation is better than the mean, and the hierarchic model is better than the aggregation. This is true regardless the validation sample, although the differences among the three model decrease with its size. In conclusion, the proposed model is better than simple ones, without requiring additional data, since there is no explanatory variable other than the activity code.
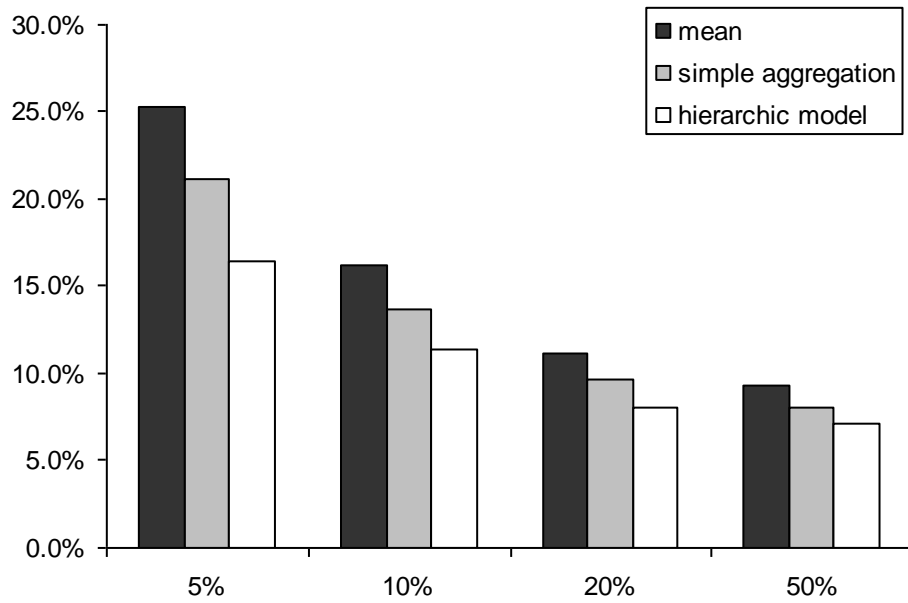
Figure 4. Fitting of the hierarchic model, compared to the simple aggregation and the mean, in terms of the average relative gap for increasing shares of the validation sample.
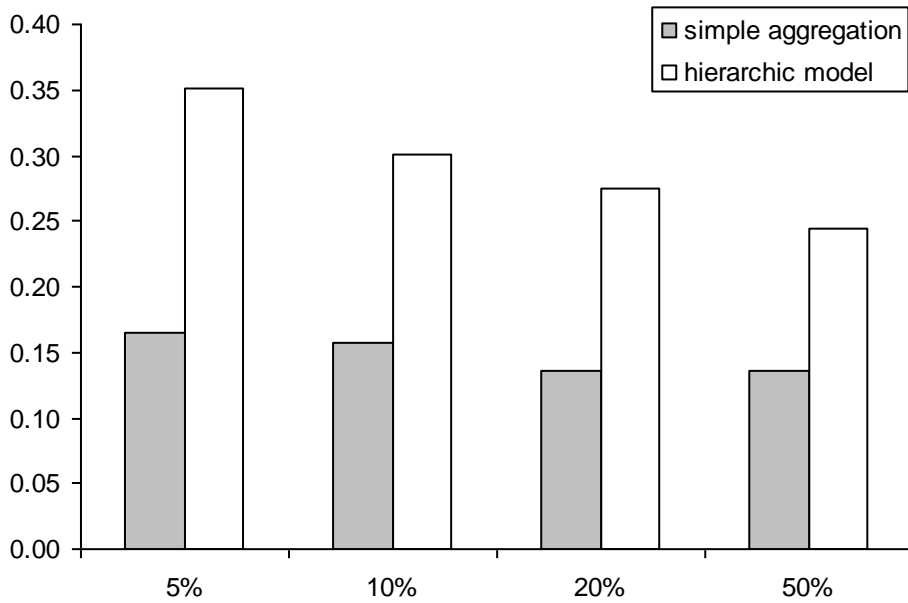


Figure 5. Improvement of the fitting obtained by the hierarchic model and by the simple aggregation with respect to the mean, in terms of the rho square for increasing shares of the validation sample.
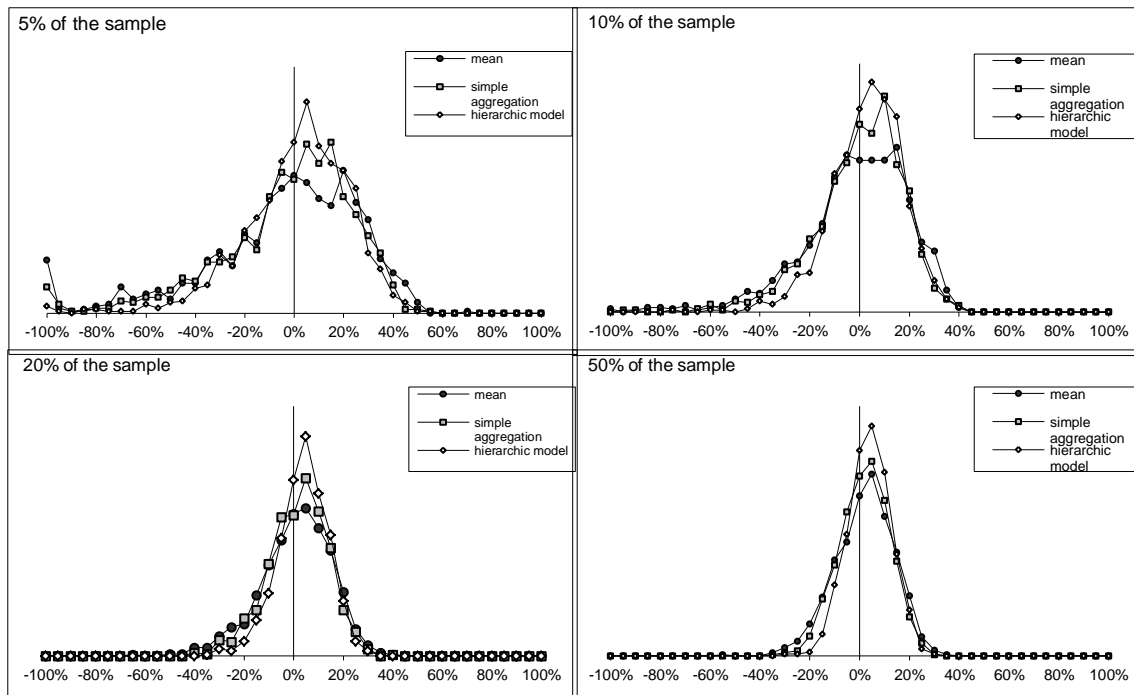
Figure 6. Statistical distributions of the relative gap obtained with the three models, for increasing shares of the validation sample.

## 4. The distribution model

The distribution model proposed in this paper repeatedly applies a gravity model so as to better approximate the main characteristic of urban freight shipment. In this case, the direct trips that vehicles perform from one point of the study area to another without intermediate stops do not satisfy a specific mobility demand to travel from one origin to a destination, as in the transport of passengers, but are merely the legs of a delivery or collection tour between two consecutive movements (loading or unloading operations). Moreover, the movements occurring at local units, i.e., the intermediate stops of the tours, are densely located within the urban environment, whereas the pickup movements occurring at logistic centers are much more dispersed in a wider territory, being often out of town or even further away in other cities close to the production centers. To simplify the analysis, it is preferable to define a limited number of tour terminals, called *logistic portals*, located at the town boundaries along the main routes followed by the trucks to enter the city, or at logistic centers within the study area. Each portal is associated with a weight to represent its relative importance, given for example by the average number of commercial vehicles passing that road section or leaving that logistic center.

Also in this case we will discuss the model for generic movements, without distinguishing them by supply chain in the notation. However, specific distribution models that allow for the O-D matrix estimation of a particular supply chain may be easily obtained by adding the required index to all formulas reported below.

Given a set $N$ of node centroids that act as generators and attractors of freight traffic, the gravity model allows to determine a matrix of, say yearly, truck flows $F_{od}$ travelling from each origin $o \in N$ to each destination $d \in N$, based on the trips $G_o$ generated by each

origin $o \in N$ and the trips $A_d$ attracted by each destination $d \in N$. The main explanatory variable of the gravity model is the LoS (Level of Service) matrix of generalized travel cost $C_{od}$ from each origin $o \in N$ to each destination $d \in N$, which may in turn be expressed by a linear combination of suitable attributes weighted by coefficients to be calibrated.

By definition, we have:

$$\sum_{d \in N} F_{od} = G_o \, , \; \forall o \in N \, , \tag{19}$$

$$\sum_{o \in N} F_{od} = A_d \, , \; \forall d \in N \, , \tag{20}$$

which also imply that the total generation and attraction are equal:

$$\sum_{o \in N} G_o = \sum_{d \in N} A_d = \sum_{o \in N} \sum_{d \in N} F_{od} \, . \tag{21}$$

The functional form of the gravity model is:

$$F_{od} = a_o \cdot b_d \cdot G_o \cdot A_d / \lambda(C_{od}) \, , \; \forall od \in N \times N \, , \tag{22}$$

where $G_o$ and $A_d$ play the role of the masses, while the monotonic function $\lambda(C_{od})$ of generalized travel costs plays the role of the square distance. In our analysis we have considered the following impedance function:

$$\lambda(C_{od}) = \exp(\gamma \cdot C_{od}) \, , \tag{23}$$

where $\gamma$ is a parameter to be calibrated. The generalized travel costs can be, for instance, those of the shortest paths on the road network computed with respect to the link costs obtained through a traffic assignment model.

In a origin-constrained model the structural coefficients $a_o$ have to be consistent with equation (19), while $b_d$ is set to 1, so that we have:

$$a_o = 1 / [\sum_{d \in N} A_d / \lambda(C_{od})] \, , \; \forall o \in N \, . \tag{24}$$

In a destination-constrained model the structural coefficients $b_d$ have to be consistent with equation (20), while $a_o$ is set to 1, so that we have:

$$b_d = 1 / [\sum_{o \in N} G_o / \lambda(C_{od})] \, , \; \forall d \in N \, . \tag{25}$$

In a doubly-constrained model the structural coefficients $a_o$ and $b_d$ have to be consistent with both equations (19) and (20), so that we have, respectively:

$$a_o = 1 / [\sum_{d \in N} b_d \cdot A_d / \lambda(C_{od})] \, , \; \forall o \in N \, , \tag{26}$$

$$b_d = 1 / [\sum_{o \in N} a_o \cdot G_o / \lambda(C_{od})] \, , \; \forall d \in N \, . \tag{27}$$

The non-linear system defined by (26)-(27) can be conveniently seen as a fixed point problem that turns out to be a contraction, i.e., it can be easily solved by initially setting the coefficients to arbitrary values, e.g. $a_z = b_z = 1$ for each zone $z \in N$, and then calculating (26)-(27) iteratively until convergence is achieved. The above solution approach is also adopted in Bablu and Sanat Kumar (2006), where the doubly-constrained gravity model is formulated as an equivalent minimization problem.

In our case, the set of centroids is partitioned into two subsets, namely the set $Z$ of traffic zones and the set $P$ of logistic portals, so that formally we have: $N = Z \cup P$, $Z \cap P = \varnothing$. The urban freight shipping from the portals to the local units is performed by vehicles that leave from a specific portal, visit some units possibly located in more than one zone, and return to the same portal. Therefore, the same vehicle may perform during one tour not only a trip from a portal, origin of the freight, to a single zone, destination of the freight, and backward, but also trips within such zone or even between different zones.

We are interested here in estimating the number of direct trips between centroids, but not in deriving the actual structure of vehicle routes which, being the result of VRP

algorithms, is out of the scope of the demand oriented methodology proposed in this paper. However, the gravity model is not conceived to yield O-D flows that satisfy the topological constraints of tours. To force such a structure we will consider a sequence of gravity models, each one representing implicitly a further stop of the delivery tour.

From the generation model we know the total number of movements $D_z$ occurring in each zone $z \in Z$. Moreover, we assume to known the average number $\mu$ of movements per route, for example as a result of a specific survey. The total number of performed tours will then be:

$$R = \sum_{z \in Z} D_z / \mu . \tag{28}$$

Each portal $p \in P$ is associated with a weight $w_p$ that represents its relative importance. We can therefore compute the number of tours $R_p$ headed at portal $p$ as:

$$R_p = R \cdot w_p / \sum_{s \in P} w_s . \tag{29}$$

Clearly, the average number $\mu$ of movements per route and the weight $w_p$ of each portal $p \in P$ are specific characteristics of each supply chain.

In the proposed model M1, the flow of vehicles in terms of direct O-D trips results from the contribution of the successive legs of delivery tours, which are implicitly represented by each loop of the following iterative algorithm.

**F = 0**
**for each** $o \in N$
   **if** $o \in P$ **then** $G_o = R_o$ **else** $G_o = 0$
   **if** $o \in Z$ **then** $A_o = D_o$ **else** $A_o = 0$
**next** $o$
**until** $A_d = 0 \; \forall d \in N$
   **for each** $od \in N \times N$
      $X_{od} = G_o \cdot [A_d / \lambda(C_{od})] / \sum_{j \in N} [A_j / \lambda(C_{oj})]$   *first and intermediate leg*    (30)
      **next** $o$
   **for each** $d \in N$
      $Q_d = \sum_{o \in N} X_{od}$
      **if** $Q_d > A_d$ **then**
         **for each** $o \in N$
            $X_{od} = X_{od} \cdot A_d / Q_d$                    (31)
               **next** $o$
         **end if**
      **next** $d$
   **for each** $od \in N \times N$
      $F_{od} = F_{od} + X_{od}$
      $A_d = A_d - X_{od}$
      $G_o = G_o - X_{od}$
      $G_d = G_d + X_{od}$
      **next** $od$
**loop**
**for each** $o \in N$
   **if** $o \in P$ **then** $A_o = R_o$ **else** $A_o = 0$
**next** $o$
**for each** $od \in N \times N$
   $X_{od} = a_o \cdot b_d \cdot G_o \cdot A_d / \lambda(C_{od})$    *last leg*    (32)

$$F_{od} = F_{od} + X_{od}$$

**next** $od$

The probability that the next stop of any tour carries out a movement in zone $d \in Z$ is given by the origin-constrained model expressed by equation (30), where, at each step of the algorithm, the generation is the number of trucks present at centroid $o \in N$, while the attraction is the number of deliveries to be still covered in $d$. If the sum $Q_d$ of the resulting movements exceed the deliveries to be still covered in zone $d \in Z$, then only a share of the vehicles are moved there, as implied by (31).

As far as the first leg is concerned, the generation $G_o$ is then equal to the number of tours $R_o$ headed at each portal $o \in P$ and is null for each zone $o \in Z$, while the attraction $A_o$ is equal to the total number of movements $D_o$ of each zone $o \in Z$ and is null for each portal $o \in P$. To take into account the last legs of the delivery tours needed for going back to the portal, i.e., to represent the empty trips, we consider the doubly-constrained model (32), where the attraction $A_o$ is equal to the number of tours $R_o$ headed at each portal $o \in P$ and is null for each zone $o \in Z$, while the generation $G_o$ of each centroid $o \in N$ is that resulting at the end of the main cycle.

Instead, for $\gamma \to \infty$, the model can be regarded as an approximate solution to the corresponding VRP with the relaxation that the number of stops per route is satisfied only on average; indeed in this case the gravity model is a solution to the corresponding transportation problem (Bablu and Sanat Kumar, 2006).

In the following alternative model M2 the latter relaxation is removed, under the simplifying assumption that each movement occurring at zones has the same probability to be the $k$-th stop of the delivery tour that performs it, for $k = 1$ to $\mu$:

**F** = **0**
**for each** $o \in N$
   **if** $o \in P$ **then** $G_o = R_o$ **else** $G_o = 0$
   **if** $o \in Z$ **then** $A_o = D_o / \mu$ **else** $A_o = 0$
**next** $o$
**for each** $od \in N \times N$
   $X_{od} = a_o \cdot b_d \cdot G_o \cdot A_d / \lambda(C_{od})$    *first and last leg*             (33)
   $F_{od} = F_{od} + X_{od}$
   $F_{do} = F_{do} + X_{od}$
**next** $od$
**for each** $o \in N$
   **if** $o \in Z$ **then** $G_o = D_o / \mu$ **else** $G_o = 0$
**next** $o$
**for each** $od \in N \times N$
   $X_{od} = a_o \cdot b_d \cdot G_o \cdot A_d / \lambda(C_{od})$    *intermediate legs*         (34)
   $F_{od} = F_{od} + X_{od} \cdot (\mu-1)$
**next** $od$

The probability that the first stop (and symmetrically the last stop) of any delivery tour carries out a movement in zone $d \in Z$ is given by the doubly-constrained model (33), where the generation $G_o$ is equal to the number of tours $R_o$ headed at each portal $o \in P$ and is null for each zone $o \in Z$, while the attraction $A_o$ is equal to the number of first (or

last) stops $D_o$ / μ of each zone $o \in Z$ and is null for each portal $o \in P$. The probability that the intermediate $k$-th stop, $k \in [2, μ]$, of any tour carries out a movement in zone $d \in Z$ is given by the doubly-constrained model (34), with symmetric generation and attraction equal to the number of $k$-th stops $D_o$ / μ to occur at each zone $o \in Z$ and null for each portal $o \in P$. Since these (μ-1) gravity models are identical to each other, we compute one of them and multiply the resulting O-D flows by (μ-1) times.

It is interesting to observe that, for μ → 1, the number of tours tends to the total number of movements so that the proposed model collapses into a classical gravity model between origin portals and destination zones (and back), without direct trips among zones.

The model calibration, i.e., the estimation of the impedance parameter γ, can be performed by maximizing the likelihood, which is defined as the joint probability that the model associates to the (independent) *events* revealed in the sample. In this case, the event is a vehicle performing a particular tour. The generic tour $k \in K$ of the sample $K$ is a sequence of μ($k$) zones {$z(1, k)$, $z(2, k)$, ... , $z(μ(k), k)$} and a portal $p(k)$. The probability $η_k(γ)$ that the model associates to such a tour is:

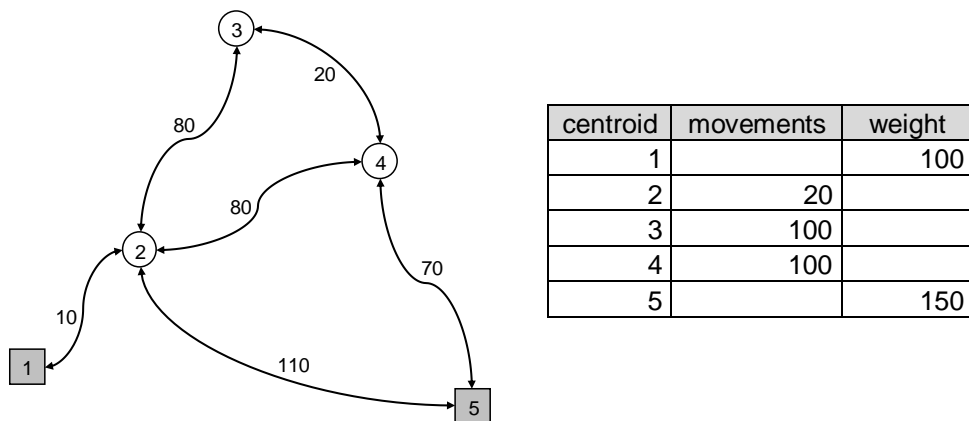$$η_k(γ) = F_{p(k)\,z(1,k)} / D_{p(k)} \cdot F_{z(1,k)\,z(2,k)} / D_{z(1,k)} \cdot ... \cdot$$
$$F_{z(μ(k)-1,k)\,z(μ(k),k)} / D_{z(μ(k)-1,k)} \cdot F_{z(μ(k),k)\,p(k)} / D_{z(μ(k),k)} \,, \tag{35}$$

where the dependency from γ is implicit in the flow model (22) through (23). The parameter shall then be determined by solving the following unconstrained nonlinear optimization problem with one variable:

$$\max\{\textstyle\sum_{k \in K} \log(η_k(γ)): γ \in \mathfrak{R}\} \,, \tag{36}$$

which we suggest to address simply by determining the objective function values for a suitable interval of γ values through fixed steps.

We illustrate the behavior of the two models M1 and M2 by means of a simple numerical example, depicted in 7, that includes two logistic portals (nodes 1 and 5) and three zones (nodes 2, 3 and 4). The figure reports the results obtained with two different levels of the coefficient γ (low 0.01 and high 1), which show the relevance of the impedance parameter in the trip distribution model. By its nature, model M2 tends to spread more the flows between centroids. In the high case γ = 1 travel impedances force the flow distribution towards a sort of vehicle routing solution with minimal logistic costs.
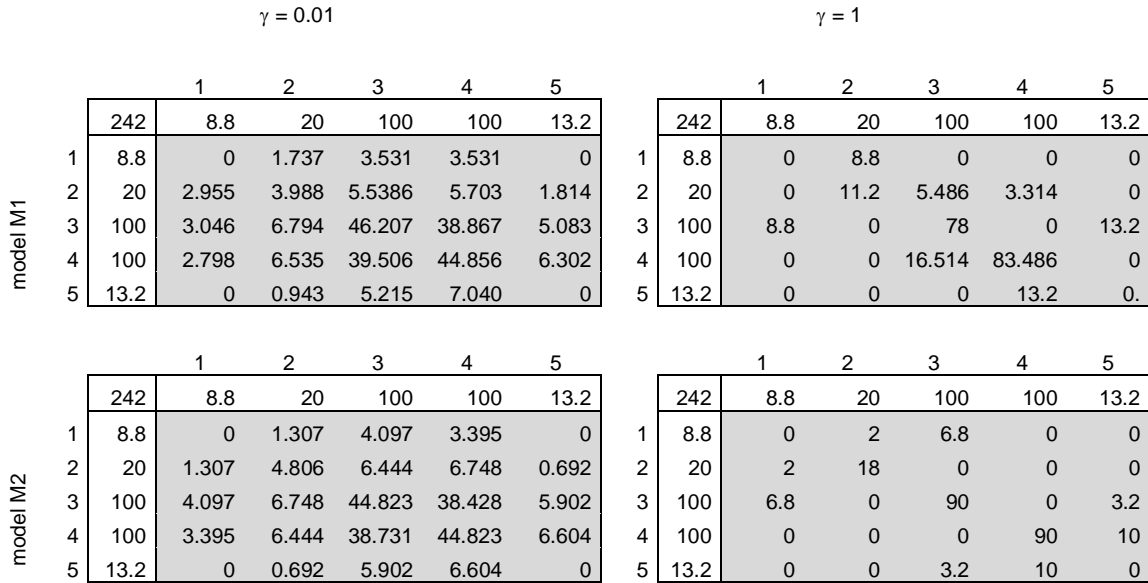


| centroid | movements | weight |
|---|---|---|
| 1 |  | 100 |
| 2 | 20 |  |
| 3 | 100 |  |
| 4 | 100 |  |
| 5 |  | 150 |

γ = 0.01

**model M1**

|   | | 1 | 2 | 3 | 4 | 5 |
|---|------|-------|-------|--------|--------|-------|
|   | 242  | 8.8 | 20 | 100 | 100 | 13.2 |
| 1 | 8.8  | 0 | 1.737 | 3.531 | 3.531 | 0 |
| 2 | 20   | 2.955 | 3.988 | 5.5386 | 5.703 | 1.814 |
| 3 | 100  | 3.046 | 6.794 | 46.207 | 38.867 | 5.083 |
| 4 | 100  | 2.798 | 6.535 | 39.506 | 44.856 | 6.302 |
| 5 | 13.2 | 0 | 0.943 | 5.215 | 7.040 | 0 |

γ = 1

|   | | 1 | 2 | 3 | 4 | 5 |
|---|------|------|------|--------|--------|------|
|   | 242  | 8.8 | 20 | 100 | 100 | 13.2 |
| 1 | 8.8  | 0 | 8.8 | 0 | 0 | 0 |
| 2 | 20   | 0 | 11.2 | 5.486 | 3.314 | 0 |
| 3 | 100  | 8.8 | 0 | 78 | 0 | 13.2 |
| 4 | 100  | 0 | 0 | 16.514 | 83.486 | 0 |
| 5 | 13.2 | 0 | 0 | 0 | 13.2 | 0. |

**model M2**

|   | | 1 | 2 | 3 | 4 | 5 |
|---|------|-------|-------|--------|--------|-------|
|   | 242  | 8.8 | 20 | 100 | 100 | 13.2 |
| 1 | 8.8  | 0 | 1.307 | 4.097 | 3.395 | 0 |
| 2 | 20   | 1.307 | 4.806 | 6.444 | 6.748 | 0.692 |
| 3 | 100  | 4.097 | 6.748 | 44.823 | 38.428 | 5.902 |
| 4 | 100  | 3.395 | 6.444 | 38.731 | 44.823 | 6.604 |
| 5 | 13.2 | 0 | 0.692 | 5.902 | 6.604 | 0 |

|   | | 1 | 2 | 3 | 4 | 5 |
|---|------|------|------|------|------|------|
|   | 242  | 8.8 | 20 | 100 | 100 | 13.2 |
| 1 | 8.8  | 0 | 2 | 6.8 | 0 | 0 |
| 2 | 20   | 2 | 18 | 0 | 0 | 0 |
| 3 | 100  | 6.8 | 0 | 90 | 0 | 3.2 |
| 4 | 100  | 0 | 0 | 0 | 90 | 10 |
| 5 | 13.2 | 0 | 0 | 3.2 | 10 | 0 |

Figure 7. O-D matrices resulting from the application of models M1 and M2 to a simple example for low and high values of the coefficient γ. Travel impedances are reported next to links.

## 5. The case of Emilia-Romagna Region

The models presented in the previous sections have been developed and preliminarily validated within a study about city logistics for the Emilia-Romagna Region, located in northern Italy. Emilia-Romagna has about 4 Million inhabitants and a surface of 22,000 square Km. Given its geographical position, the region plays a central role in the North-South communication system and is characterized by several mid-size towns with various economic and industrial vocations: from the mainly tourist town of Rimini to the industrial harbor of Ravenna, from the capital Bologna with one of the oldest universities in the world to the towns of river Po valley that combine agriculture with middle-size mechanical and hi-tech industries.

Since a long time, the regional authority of Emilia-Romagna has been very active in the investigation and planning of mobility in the region and in the more recent years has devoted an increasing attention to freight mobility. In particular, within two European Research projects of the InterReg Program, denominated CityPorts and Merope, and other initiatives directly sponsored by the regional authority itself, a large and systematic survey regarding the urban freight movements has been undertaken in 2004 for ten out of the thirteen towns of the region with more than 50,000 inhabitants. These surveys were performed according to a homogeneous interview scheme and included specific questions for demand generators (shops and other economic activities located in the urban area), demand attractors (distribution centers and shipping companies), and on-road interviews to truck drivers.

Ten towns were surveyed (Bologna, Cesena, Ferrara, Forlì, Modena, Parma, Piacenza, Ravenna, Reggio Emilia, and Rimini) collecting more than 1700 interviews to shops and other relevant premises (covering between 1% and 10% of the overall universe), 80 logistic operators and more than 3500 vehicles. For example, the survey at premises for the town of Bologna that we used for the testing of the model we propose is made up by

315 interviews at shops and relevant premises, which represent about 1% of the large universe of more than 30000 units. For smaller towns the coverage is much larger: Ravenna has about 170 interviews which cover more than 6% of the universe of less than 2800 premises. Each interview collected detailed information of the characteristics of the movements (regular and irregular) that interested the premise for all possible Supply Chain in a time horizon of a week, leading to several hundreds of movements analyzed for each surveyed town. More details on the whole data set and its organization can be found in (Regione Emilia Romagna, 2005).

The initial purpose of the survey was to improve the knowledge on freight distribution activities in Italian towns by obtaining information disaggregated over the main supply chains so as to support the impact analysis of infrastructures and policies. The richness of the data that have been collected was indeed very promising, reporting on the freight movements generated by a given economic activity with respect to different supply chains and with many information on commercial vehicles, time windows, parking habits, delivery features, etc. However, the available funds have considerably limited the size of the samples, hence making impossible its direct statistical use, and motivating the development of an appropriate modeling tool that would allow for the extension of the observations to the universe in a structured way.

As previously mentioned, the quantity and quality of logistic information associated with the observed sample is very rich, whereas very little is available for the whole universe, that is census data reporting the localization of each economic activity, its category code according to the ATECO/NACE classification system, and its size measured in terms of employees (but in many cases not highly reliable). An extensive preliminary testing and validation of the demand generation and distribution models presented in this paper has been performed during the years 2005-06 on various towns by using these data for the calibration. In particular the analysis has considered 6 supply chains and has allowed to determine the average number of freight movements generated yearly in each traffic zone of the town and the specific O-D matrices of freight vehicles serving each such supply chain, which are then assigned to the road network jointly with private cars.

As an example of the output, Figure 8 depicts the total number of movements and their disaggregation over the different supply chains for the town of Bologna. The figure clearly shows the different behavior of the various zones both in terms of overall number of movements and of their subdivision over the different supply chains. In addition, Figure 9 shows the localization of the logistic portals for the distribution model and Figure 10 depicts the flow chart of trucks on road links determined with the distribution and assignment models.
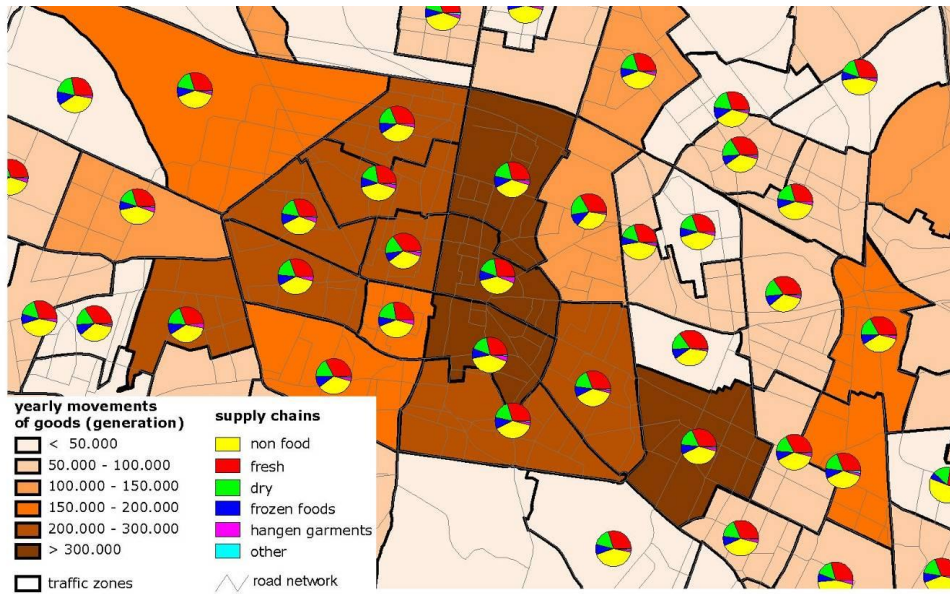
Figure 8. Plot of the Z-S matrix, for the town of Bologna.
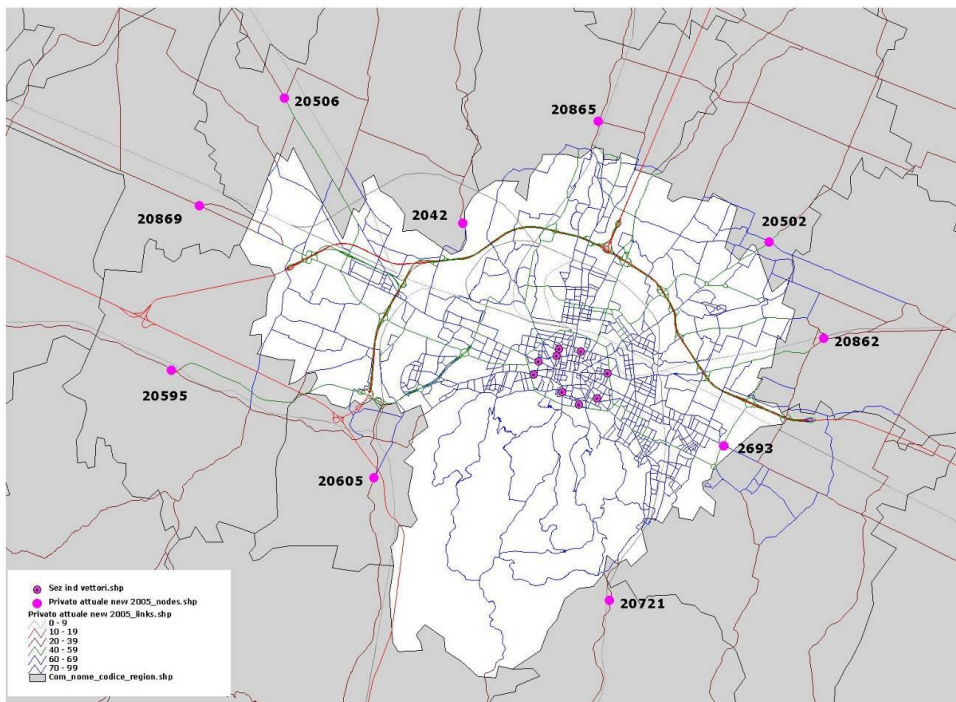


Figure 9. Localization of the logistic portals for the application of the distribution model to the municipal area of Bologna (in white).
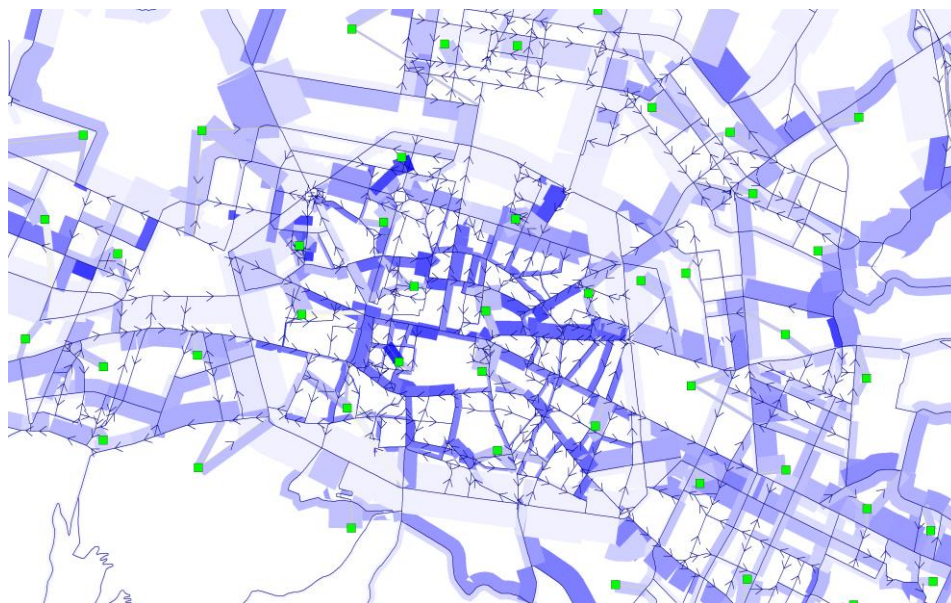
Figure 10. Flow chart of trucks, for the town of Bologna.

The calibration of the generation and distribution models using the rich database of Emilia-Romagna Region has made available a set of models for different city typologies, from small to middle size, with various urban structures, which are representative of most Italian and European towns. The proposed demand models, along with a standard traffic assignment model to load the truck flows on the road network, have been incorporated within an overall GIS-based software tool, called CityGoods (see Figure 2)that is currently used by the regional authority.

## 6. Conclusions

In this paper we have introduced new models that are able to describe generation and distribution of freight movements in urban areas. The main characteristic of the generation model is its direct use of the hierarchical structure informing the classification system of the economic activities to introduce a correlation among movement production of the various activities codes, disaggregated by supply chains. The approach does not require an a-priori mapping of the economic activities into supply chains and fits very naturally with the scarce data available for the universe of potential freight generators, producing fine-grained information that proved to be reliable when aggregated for traffic zones. The distribution model incorporates another important issue of urban freight shipment related to the fact that vehicle tours are headed out of the urban area and make several intermediate stops in town, whose number depends on the specific supply chain.

The proposed models represent a sound and practical tool that fits within well-established modeling paradigms and requires easily available data, such as census information on the economic activities and commercial street networks, that favor its usability by practitioners and decision makers.

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