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# Applying an integrated logistics network design and optimisation model: the Pirelli Tyre Case

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The aim of the present paper is to provide an application to a real life supply chain context (i.e. the Pirelli Tyre European logistics network) of an integrated logistics network design and optimisation model. Starting from the analysis of supply chain under study and of the configuration problem to be solved, we identified the most suitable approach: a mixed integer linear programming optimisation model endowed with a series of guidelines for gathering and processing all the data necessary to set-up and run the model. The application of the selected integrated design and optimisation model to the Pirelli Tyre case allowed obtaining significant cost savings related to three different service level scenarios. Thus, the applied model could be profitably implemented by supply chain and logistics managers for optimising various operating contexts. Moreover, the exemplified data mapping section represents a useful guideline, which can be applied by practitioners to gather and handle the high volume of data necessary for running the model in a real-life context. In conclusion, being the current state of the art particularly wanting of exhaustive supply chain design models, the implemented integrated approach represents a significant contribution to the existing body of knowledge on supply chain configuration.

Keywords: supply chain design, spreadsheet programs, linear programming, data mapping

# Applying an integrated logistics network design and optimisation model: the Pirelli Tyre Case

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## 1. Introduction and background

In recent years supply chains have witnessed a restless evolution, due to impressive changes of the world economy and of the competitive environment. In particular, an ever-growing pressure on service level (Gunaserakan et al., 2008) concurrently with a global competition, which causes reduction of the price of goods and services (Jammernegg and Reiner, 2007; Christopher, 2007; Jahene et al., 2009), drive companies in seeking the optimal topological configuration of their supply chain, especially those ones characterised by a global supply chain with numerous subsidiaries in different worldwide locations. In fact, nowadays the supply chain design issue, i.e. the definition of the number, size and location of the supply chain nodes (Canel and Khumawala, 2001; Teo and Shu, 2004; Simchi-Levi et al., 2005; Zhang et al., 2008), is proving itself to have great importance for companies to gain cost effectiveness and competitiveness (Ballou, 2005). In order to address this issue, these days supply chain managers need decision support tools which allow to easily, more accurately and more frequently configure/re-design logistics networks (Melachrinoudis and Min, 2007; Melo et al., 2009).

For responding to this requirement, the logistics network configuration problem has been widely addressed by means of a number of different methodological approaches, including genetic or heuristic methods, simulation methods and, as foremost approach, linear programming (Gargeya and Meixell, 2005; Truong and Azadivar, 2005; Chopra and Meindl, 2007). Generally speaking, linear programming is characterised by some limitations (Sharma, 2006): first of all, it is necessary that both the objective function and the constraints are linear. Then, linear programming is not the most suitable technique for considering the effect of time and uncertainty and the model parameters are usually considered as constant in the optimisation horizon. Moreover, linear programming is not suitably applicable when in a multi-objective problem the objective function includes different measures for the diverse objectives. With linear programming, any model which tends to be as more realistic as possible entails the solution of an impressive amount of calculations, hence requiring powerful computer systems, and not always such complex models have a possible solution. Notwithstanding its limitations, its wide adoption and use are due to the fact that it allows for easily developing solvers, which enable solutions for the network configuration problems to be obtained, taking into account a series of objectives and constraints (Sharma, 2006). Moreover, this kind of solvers can be easily implemented by means of spreadsheet software packages, so as they can be used in a very effective way for analysing logistics and supply chain issues and creating different scenarios for deriving the optimal values of variables such as, for instance, facility number and size (Smith, 2003).

For these reasons, in the present case study, which concerns with the re-configuration of the European Pirelli Tyre supply chain, we decided to apply linear programming and, in particular, the mixed integer linear programming model we proposed in a previous work (Creazza et al., 2011). We decided to choose our model since, on the one hand, it is able to deal with multi-commodity and multi-layer supply chains as well to consider service level constraints and, on the other hand, it is provided with data gathering and processing guidelines. According to us, such characteristics make our model actually suitable for addressing the supply chain configuration problem in real-life cases.

The present paper is organised as follows: an introduction of Pirelli Tyre and of its operating context is provided in paragraph 2.1, along with a description of the as-is configuration of its European logistics network (paragraph 2.2). Afterwards, we describe the implementation of the optimisation model and of the data mapping procedure to the Pirelli Tyre case (paragraph 2.3). The model is validated in paragraph 3, while the results of the entire implementation process are illustrated in paragraph 4. A series of concluding remarks and managerial implications deriving from the present study are discussed in paragraph 5.

## 2. The Pirelli Tyre Case

The objective of a logistics network configuration problem is to find a minimal-cost configuration of the logistics network able to satisfy product demands at specified customer service levels. The integrated logistics network configuration model proposed by the authors (Creazza et al., 2011) encompasses all these issues and it is accompanied by data gathering and processing guidelines, which allow it to be practically implemented. As a consequence, we applied our model to re-configure the Pirelli European logistics network.

### *2.1 Pirelli Tyre: the company*

Pirelli Tyre is a multinational automotive tyre manufacturer, headquartered in Italy, member of the Pirelli & C. Group. Its product range includes a wide variety of tyres, from commodity products to motorsport special tyres, and it can be subdivided in three main categories: car, motorcycle and truck tyres. Each of them is characterised by different features, basically regarding quality and product density (volume/weight ratio). Pirelli's customers can be subdivided in two main groups: original equipment manufacturers (OEM customers, represented by automotive manufacturers) and replacement customers (technical assistance centres for automobiles, garages, fast fitters, tyre wholesalers, retail shops). OEM customers basically receive direct shipments from plants, following a make-to-order policy. Replacement customers, which approximately demand 65% of the overall annual Pirelli's production volume, require a high service level in terms of short delivery times. Consequently, in order to replenish these customers (more than 40,000 delivery points located on the entire European area) with small size and frequent orders, Pirelli has built a logistics network composed by a series of Regional Distribution Warehouses, where a stock to serve a specific market area is held.

With respect to the European market, Pirelli Tyre is challenged in increasing the cost-efficiency of its supply chain, with the aim to gain competitive advantage in a business environment characterised by a growing pressure on cost control and ever stricter service level requirements. The Pirelli Tyre European logistics network is a 2-echelon network composed by a series of production plants, a set of regional distribution warehouses and a number of delivery points. In particular, in the configuration problem the company needs to optimise the set of regional distribution warehouses (in terms of number, size and location) and the network linkages (i.e. the linkages between plants and warehouses, and warehouses and delivery points), but without modifying the production network, which the company considers as given in the medium term horizon.

Before presenting the details of the Pirelli Tyre case, we would like to inform the reader that all the numerical data shown in the paper have been entirely disguised for strict confidentiality reasons.

### *2.2 The current Pirelli Tyre European logistics network*

In the current Pirelli Tyre European logistics network six product-focused production plants, 15 regional distribution warehouses and approximately 40,000 delivery points are present (for a scheme of the European Pirelli Tyre logistics network see Figure 1).

Figure 1. Current configuration of the European Pirelli logistics network

The products of the different plants basically differ for quality and product density, the regional distribution warehouses are served by plants through full truck loads (FTL) and, finally, the delivery points are supplied by the regional distribution warehouses according to a single sourcing policy. In details, the regional distribution warehouses are owned and run by third-party logistics service providers (3PL) and Pirelli has signed with them three-year logistics outsourcing contracts. The physical distribution process from the regional distribution warehouses to the each single delivery point is generally performed by means of less than truck load deliveries (LTL), often through the network of transit points run by the 3PLs. It is worth to remind that this last section of the physical distribution process is out of the scope of the present work, not being under Pirelli's direct responsibility.

As far as the objectives given by Pirelli Tyre to the re-design activity, they are represented by:

- defining the regional distribution warehouses (named as $RDW_h$) to be included into the new logistics network configuration (such $RDW_h$ must be selected among the 15 current ones and 9 other further potential locations. The choice of the potential locations has been driven by the geographical distribution of Pirelli's customer demand concurrently with the analysis of the best locations in the European logistics real estate market);
- defining which of the activated $RDW_h$ must serve which delivery points;

so as to minimize the overall logistics and distribution cost connected to the network, i.e. the sum of the primary and secondary distribution costs as well as of the warehousing cost (given, in turn, by the sum of housing and handling costs).

### *2.3 The implementation of the optimisation model and of the data mapping section*

In this paragraph we aim at recalling the main specifications and characteristics of the adopted mixed integer linear programming model, with particular reference to the Pirelli operating context, and we aim at describing how, for the Pirelli Tyre case, we applied the data mapping procedure.

The input data of the optimisation model selected for the application are the following:

- 6 production plant ($P_p$) originating the logistics flows, with their geographical location (i.e. latitude and longitude) all over the European continent, and manufactured type of product;
- a set of 15 current regional distribution warehouses ($RDW_h$) and 9 further potential $RDW_h$, with their geographical location all over the European continent, maximum floor space size, inventory turnover ratio and throughput capacity;
- 42,455 delivery points (to be aggregated in a set of Aggregated Delivery Points - $ADP_j$) to be served, with their geographical location, service level requirements;
- the demand characteristics (annual amount of required products) of each delivery point (to be aggregated in the $ADP_j$).

The model is aimed at minimising the overall logistics cost (primary and secondary distribution costs and warehousing costs), fulfilling a required service level, by setting the values of the following decision variables:

- a Boolean decision variable ($k_h$) for selecting which $RDW_h$ out of the potential locations must be activated;
- a Boolean decision variable ($k_{h,j}$) for determining which $RDW_h$, if activated, must serve which $ADP_j$.

In designing our model, we considered the following model variables and parameters:

- $cs_{h,j}$ is the unit secondary distribution cost for shipping one unit of product along one unit of distance (i.e. according to the commonly adopted transportation rates, this is the cost for shipping one kilogram of product for one kilometre) from $RDW_h$ to $ADP_j$ [€/kg·km];
- $d_{h,j}$ is the distance between $RDW_h$ and $ADP_j$ [km];
- $D_j$ is the annual demand of $ADP_j$ [kg/year];
- $cw_h$ is the unit housing cost [€/m$^2$·year];
- $S_j$ is the average space utilisation index connected to the products requested by $ADP_j$ [kg/m$^2$];
- $ITR_h$ is the average yearly inventory turnover ratio characterising the products requested by $ADP_j$ [1/year];
- $ch_h$ is the unit handling cost for $RDW_h$ [€/kg];
- $cp_{p,h}$ is the primary distribution cost for a full truck load shipment from $P_p$ to $RDW_h$ [€/FTL shipment];
- $m_{p,j}$ is the percentage of $D_j$ fulfilled by means of products supplied by $P_p$;
- $LC_p$ represents the average full truck load capacity for a FTL shipment from $P_p$ [kg/FTL shipment].

It is particularly opportune to mention that the unit secondary distribution cost is a unit transportation rate calculated on the basis of a series of fixed costs (e.g. truck depreciation, road taxes) and variable costs (e.g. fuel and lubricants, tyres, maintenance costs, road tolls), which are allocated to each unit of product to be delivered, according to the distance to be covered in a shipment and to the amount of products transported in that shipment. In order to practically derive the value of $cs_{h,j}$, please refer to section 2.3.4. Obviously, the definition of this variable is based on the assumption that the secondary distribution cost is directly dependent on the distance to be travelled and on the quantity to be shipped. This is a realistic assumption for the considered context but also from a general perspective, since it is a very common practice that the distribution rate defined by the majority of transport service providers is based on the abovementioned factors (i.e. distance and loaded quantities).

Other assumptions in the definition of the model variables concern $S_j$ and the product mix. With respect to $S_j$, we assumed that its value is almost exclusively depending on the required products' space utilisation index (essentially deriving from the product density and from its physical configuration) and not on the features of the warehouse. We deem this is a valid assumption since we are studying a context where the tyres are stored in specific metal cages and the stock piling is limited to 5 levels due to safety and stability requirements.

As regards the product mix, we considered the percentage of product volumes manufactured by the various plants and required by the delivery points (and thus by the $ADP_j$) equal to the one of the previous years. This is a strong assumption since it considers that the demand is not going to significantly vary in the considered time horizon and that there is no production relocation on different plants by Pirelli Tyre (here it is important to recall that the different plants are product focused).

The model's objective function, representing the minimisation of the annual overall logistics cost, is shown by expression 1 (where, if the overall number of Regional Distribution Warehouses *H* and the overall number of Production plants *P* are given, the overall number of Aggregated Delivery Points *J* is not defined yet at this point, since the model needs to be operationalized, as it will be explained in section 2.3.1):

$$\min \left( \begin{array}{l} \sum_{h=1}^{24} \sum_{j=1}^{J} cs_{h,j} \, d_{h,j} \, k_{h,j} \, D_j + \sum_{h=1}^{24} \sum_{j=1}^{J} \frac{cw_h \cdot k_{h,j}}{ITR_h} \cdot \frac{D_j}{S_j} + \\ + \sum_{h=1}^{24} \sum_{j=1}^{J} ch_h \cdot k_{h,j} \cdot D_j + \sum_{h=1}^{24} \sum_{p=1}^{6} cp_{p,h} \cdot \frac{\sum_{j=1} m_{p,j} \cdot k_{h,j} \cdot D_j}{LC_p} \end{array} \right) \quad (1)$$

The constraints of the mixed integer linear programming model are given by the following expressions:

$$\sum_{h=1}^{24} k_{h,j} = 1 \quad \forall j \tag{2}$$

$$k_{h,j} \le I_{h,j} \cdot k_h \quad \forall h, j \tag{3}$$

$$k_{h,j} = bin \quad \forall h, j \tag{4}$$

$$k_h = bin \quad \forall h \tag{5}$$

$$\sum_{j=1}^{J} k_{h,j} \cdot \frac{D_j}{S_j \cdot ITR_h} > 4{,}000 \quad \forall h \tag{6}$$

Expression 2 represents the single sourcing policy constraint (each $ADP_j$ can be served by a single $RDW_h$ only). Expression 3 represents the service level requirement constraint: the linkage between a $RDW_h$ and an $ADP_j$ exists only if that activated $RDW_h$ allows goods to be delivered to that $ADP_j$ within a given time (the Boolean variable $I_{h,j}$ allows modelling this condition). Expressions 4 and 5 constrains the decision variables $k_{h,j}$ and $k_h$ respectively to be Boolean variables and expression 6 constraints the minimum size of a $RDW_h$ to be activated (the minimum size is set equal to 4,000 square metres since this represents the typical minimum plot size offered by logistics service providers, on whom Pirelli relies for its warehousing activities).

After having described the optimisation model adopted in the Pirelli Tyre case, in the following pages we present the numerical implementation of the data mapping procedure, whose guidelines are summarized in Table 1 (including the steps, the processing instructions, the sources of information along with the suggested support tools necessary for completing the model operationalisation and finally the parameterized variables).

Table 1. Summary of the data mapping steps, processing instructions, suggested support tools and parameterised variables

### *2.3.1 Definition of the $ADP_j$ and the aggregation of customer's demand*

With reference to the $ADP_j$ to be used in the model, they are obtained by clustering, according to a geographical basis, the destination points characterising the Pirelli Tyre European logistics network. Hereinafter, due to simplicity reasons (being Austria the first market area represented in Figure 1) the definition of the Austrian $ADP_j$ geographical aggregation is described (see Table 2, where the characteristics of the nine Austrian $ADP_j$ in terms of NUTS3 clusters they refer to, demand and location are depicted).

Table 2. The Austrian $ADP_j$

The Austrian 1,972 delivery points are firstly grouped according to the NUTS coding (*Nomenclature des Unités Territoriales Statistiques*, Nomenclature of Territorial Units for Statistics, proposed by Eurostat in 1988). Three different levels of aggregation are present in the NUTS codes, based on the number of inhabitants per aggregated cluster. As suggested in Creazza et al., (2011), we chose the most disaggregated codes (NUTS3), and we obtained 35 NUTS3 areas characterising the Austrian territory, i.e. from AT111 to AT342. For instance, all the delivery points located in Graz belong to the cluster corresponding to the NUTS3 code AT221. For each of the abovementioned clusters, the demand is calculated as the sum of the demands (in kilograms of products) of all the delivery points which belong to that specific cluster, i.e. to the corresponding NUTS3 area. In the Austrian case, nine clusters only (i.e. AT112, AT123, AT126, AT130, AT211, AT221, AT312, AT323 and AT332) are characterised by a not null demand. They correspond to the $ADP_j$ used in the mixed integer linear programming model for representing the Pirelli Austrian market. The location of each of the nine $ADP_j$ is obtained by geographically referencing on the ArcGIS™ software package the demand data of the delivery points belonging to the corresponding cluster. Moving from this data, ArcGIS™ is able to calculate the geographical coordinates of the cluster's centre of gravity, which are assigned to the corresponding $ADP_j$.

Applying this procedure to the entire European Pirelli Tyre network (composed by 42,455 delivery points), we obtained 976 NUTS3 areas, which represent the clustered demand of the aggregated delivery points (ADPj).

*2.3.2 Definition of the product mix*

As far as the product mix is concerned, it is necessary to define the various $m_{p,j}$ percentages, which can be calculated according to expression 7:

$$m_{p,j} = \sum_{k=K'}^{\tilde{K}} \frac{m_{p,k} \cdot d_k}{D_j} \quad \forall j \ \ \forall p \tag{7}$$

where:

- $m_{p,k}$ is the percentage of the delivery point demand ($d_k$) represented by the product manufactured by $P_p$ and
- $D_j$ is the $ADP_j$ demand.

However, it should be remarked that in the Pirelli Tyre case the products mix requested by each delivery point, i.e. the percentages according to which the delivery points' demands are split among the different product-focused plants ($m_{p,k}$), is not known. For this reason, we consider the following assumption: if the $RDW_h$'s demand is satisfied by the different plants $P_p$ according to the percentages $M_{p,h}$ and the k-th delivery point in the as-is configuration of the Pirelli European logistics network is served by the h-th RDW, then the demand of that delivery point inherits from that specific $RDW_h$ the product mix percentages according to which its demand is fulfilled from the different plants $P_p$. Hence, we calculate the percentages $m_{p,j}$ according to equation 8:

$$m_{p,j} = \frac{\sum_{k=K'}^{\tilde{K}} \sum_{h=1}^{24} M_{p,h} \cdot d_k \cdot I_{k,h}}{D_j} \quad \forall p, \forall j \qquad (8)$$

where $I_{k,h}$ is a Boolean variable whose value is 1 if in the as-is configuration of the logistics network the k-th delivery point receives products from that specific considered $RDW_h$, 0 otherwise and K' and $\tilde{K}$ are the indexes of the generic delivery point within a generic $ADP_j$.

With reference to the Austrian territory, Table 3 shows, for each $ADP_j$ representing the Pirelli Tyre Austrian market, the number of delivery points served (in round brackets) and the kilograms of products supplied (in square brackets) by each $RDW_h$.

Table 3. Sourcing features of the Austrian territory

As shown in Table 3, all the delivery points included into each Austrian $ADP_j$ are served by $RDW_1$ only, i.e. by the $RDW_j$ located in Gumtransdorf – AT (see Figure 1). As a consequence, by applying equation 8 the equality shown by expression 9 for $ADP_2$ can be obtained.

$$m_{p,2} = \frac{\sum_{k=28}^{107}\sum_{h=1}^{15} M_{p,h} \cdot d_k \cdot I_{k,h}}{D_2} = \frac{\sum_{k=28}^{107} M_{p,1} \cdot d_k \cdot 1 + \sum_{k=28}^{107}\sum_{h=2}^{15} M_{p,h} \cdot d_k \cdot 0}{D_2} = \\ = \frac{M_{p,1} \cdot \sum_{k=28}^{107} d_k \cdot 1}{D_2} = \frac{M_{p,1} \cdot D_2}{D_2} = M_{p,1} \quad \forall p \tag{9}$$

An expression similar to expression 9 can be written for all the Austrian $ADP_j$. In particular, it is possible to surmise that each of them is characterized by percentages $m_{p,j}$ exactly equal to the percentages $M_{p,h}$ characterizing $RDW_1$, i.e. to the percentages according to which the generic production plant $P_p$ serves the Gumstrandorf RDW. Due to the data provided by Pirelli Tyre for the quantities of products that $RDW_1$ yearly receives from each plant, the $m_{p,j}$ percentages characterizing the Austrian $DP_j$ can be calculated and they are depicted in Table 4.

Table 4. $m_{p,j}$ percentages characterizing the Austrian $ADP_j$

*2.3.3 Definition of the primary transportation cost*

The other elements necessary for running the model and concurring in determining the primary transportation costs are represented by the unit cost per FTL shipment ($cp_{p,h}$) from a $P_p$ to $RDW_h$ and the average FTL transport capacity ($LC_p$, expressed in kg/FTL shipment). We obtained the various rates per delivery (from each plant to each Pirelli existing $RDW_h$) from the contracts signed by the company with its providers for the considered cases and by means of a benchmarking activity involving the best-in-class transport service providers for the other potential locations not included in the current Pirelli Tyre logistics network. $LC_p$ was derived considering the quantity (expressed in kilograms) that can be loaded on a trailer according to an average product mix, as indicated in the transport accounting sheets provided by the company itself. In Table 5 we report the values of $cp_{p,h}$ for each considered $RDW_h$.

Table 5. $cp_{p,h}$ values for the considered $RDW_h$

As abovementioned, all values in the analysis have been disguised for confidentiality reasons. In particular, in this case we set as a fictitious measure the value "1" for the cost for connecting $P_4$ (Settimo Torinese) to $RDW_{14}$ (Novara): the other values are multiples of this baseline value.

In Figure 2 we include the values of $LC_p$ for the Pirelli Tyre case (with reference to the 15 existing $RDW_h$). As further information, it is worth to specify that $LC_p$ values are influenced by the loaded product type (being Pirelli Tyre products characterised by different product density values) and by the particular load weight restrictions applied by the various countries hosting Pirelli's warehouses and plants.

Figure 2. $LC_p$ values (in tons) for the Pirelli Tyre case

*2.3.4 Definition of the secondary distribution cost*

With reference to the secondary distribution cost, it is necessary to first derive the unit cost to ship a kilogram of tyres from a certain $RDW_h$ to a certain $ADP_j$. It can obtained from the secondary distribution cost function of each single $RDW_h$, which, in turn, is derived from the $RDW_h$ transport accounting sheet and from the quantities of product (in kilograms) yearly shipped. Hereinafter, the definition of the secondary distribution cost for $RDW_1$, located in Gumstrandorf – AT (see Figure 1), and the calculation of the unit secondary distribution costs to connect $RDW_1$ to each $ADP_j$ are shown. Tables 6 and 7 respectively represent a portion of the transport accounting sheet and a sample of the quantities shipped from $RDW_1$ during the year 2008.

Table 6. Portion of the transport accounting sheet related to $RDW_1$

Table 7. Shipped quantities from $RDW_1$ to Wien and Stockerau

It is possible to see from such tables that, in the Pirelli Tyre case, the transport accounting sheet reports the transport rates (€/kg) for different weight ranges and destinations. In this case as well, the values have been disguised for confidentiality reasons.

In particular, for each destination indicated in Table 6, the average €/kg rate weighted on the actual shipped quantities per weight range (Table 7) can be calculated. Then, by dividing each rate by the distance between the corresponding destination and $RDW_1$, the related €/kg·km rate is obtained (see Table 8).

Table 8. €/kg·km rates from $RDW_1$ to Wien and Stockerau

Finally, by plotting the values of all the €/kg·km rates (i.e. not only the ones reported in Table 8) against the distance and performing a regression analysis on such points, the cost function is derived. It is important to underline that this cost function is valid for distance ranges comprised between 50 and 700 km. In Figure 3 the cost function for $RDW_1$ is depicted (such a cost function is the one obtained by using not disguised values of tariffs and shipped quantities).

Figure 3. Secondary distribution cost function for $RDW_1$

Moving from the function depicted in Figure 3, it is possible to derive the secondary distribution costs for connecting each $ADP_j$ to $RDW_1$. To do this, it is necessary to calculate the Euclidean distance between $RDW_1$ and each $ADP_j$ moving from their geographical coordinates and to multiply such a distance by the circuity factor corresponding to the country the $ADP_j$ belongs to. The circuity factor is a multiplier used to convert and correct estimated distances into approximate actual travel distances (Ballou et al., 2002). Circuity factors are expressed by means of an average and a standard deviation values and for instance for the Austrian country the average circuity factor is equal to 1.34, with a standard deviation equal to 0.18. Entering in the cost function depicted by Figure 3 with the adjusted distances allows the €/kg·km rates referring to the couples given by $RDW_1$ and each $ADP_j$ to be obtained. Finally, the unit secondary distribution cost (in Euros) for moving one kilogram of products from $RDW_1$ to each $ADP_j$ is obtained by multiplying such rates by the adjusted distances between $RDW_1$ and each $ADP_j$. Table 9 shows this calculation with reference to the nine Austrian $ADP_j$.

Table 9. Calculation of the secondary distribution costs for connecting $RDW_1$ to the Austrian $ADP_j$

*2.3.5 Definition of the housing and handling costs*

For deriving the housing cost we needed the value of $S_j$ and $ITR_h$ in order to transform the annual flow of goods (kg/year) into required warehouse floor space, along with the unit warehousing cost ($cw_h$), expressed in €/$m^2$·year.

$S_j$ and $ITR_h$ values were provided by Pirelli Tyre for each $ADP_j$ and $RDW_h$. In particular, $S_j$ values are almost exclusively depending on the required products' space utilisation index (essentially deriving from the product density and from the physical configuration of each stock keeping unit), since we are considering in the present study a set of similar and equivalent warehouses (potential and activated), while $ITR_h$ can be considered as a standard average value for the new potential $RDW_h$ while for the existing $RDW_h$ the current values apply.

With respect to the $cw_h$ values, they were found in the contracts signed by Pirelli Tyre with warehousing companies, for each of the $RDW_h$ currently present in the Pirelli logistics network. As for the other locations, it was necessary to contact primary logistics real estate companies (e.g. Cushman&Wakefield, Jones Lang LaSalle and CB Richard Ellis) which provided a series of documents including the values of the annual rent per square metre for the potential sites we considered in the study. With reference to Gumstrandorf, i.e. to the current Austrian RDW, the annual rent is equal to 60 €/$m^2$·year. For Brno and Katowice, i.e. for two potential $RDW_h$, such cost is equal respectively to 48 €/$m^2$·year and 36 €/$m^2$·year.

With regards to the handling cost, we needed the handling unit cost $ch_h$, which, similarly to the housing cost, was derived from the contracts signed by Pirelli Tyre with service providers for the already preset $RDW_h$ and from a survey of the handling rates applied by logistics service providers for the potential considered locations. With reference to Gumstrandorf, the current applied handling rate is equal to 0,059 €/kg; with reference to Brno and Katowice the handling rate is equal respectively to 0,050 €/kg and 0,056 €/kg.

*2.3.6 Definition of the service level*

As far as the service level is concerned, in the Pirelli Tyre case we considered three different scenarios: the first (S1) where all the $ADP_j$ must be served within 24 hours, the second (S2) where all the $ADP_j$ must be served within 36 hours and the third (S3) where all the $ADP_j$ must be served within 48 hours. In particular, to fill in the row of Table 9 corresponding to $RDW_1$, i.e. to the Gumstrandorf $RDW_h$, in the scenario S1 it is necessary to derive, by means of Microsoft MapPoint 6.0™, the area reachable within 24 hours from $RDW_1$ (i.e. the $RDW_1$ 24-hour isochronal zone), considering an average driving speed of 60 km/hours and 4 hours driving stops every 8 hours. Once such an isochronal zone has been drawn, it is possible to verify which NUTS3 areas are completely included in there and which lie outside this zone (see Figure 4). Then, in the possible origin-destination matrix the cells corresponding to the ADP $_j$ that refer to the former NUTS3 areas should be set to 1, to 0 the others (see Table 10 for an example focused on the Austrian RDW and including the Austrian, Hungarian, Czech and Slovakian $ADP_j$).

Figure 4. NUTS3 areas covered within 24 hours from $RDW_1$

Table 10. Example of a service level origin-destination matrix

**3. Model validation**

After having completed the data mapping section implementation, it was then possible to solve the configuration problem for the Pirelli Tyre European logistics network.

First of all, we decided to test the adherence of the model as well as of the input data by deriving the overall logistics costs of the current configuration of the Pirelli Tyre European logistics network (i.e. the sum of transportation costs and of the warehousing costs). To this aim we set the decision variables $k_h$ and $k_{h,j}$ so as to replicate the logistics network structure depicted in Figure 1. The model provides an overall logistics cost very similar to actual figures for year 2008, with a difference equal to only -0,9%. Such a result allows for proving the adherence of the model objective function and of the input data to the Pirelli logistics cost function and context respectively. On the other side, in more general terms, it demonstrates the effectiveness of the proposed data mapping section.

With regard to the development of the model, we had to confront some critical points in order to match the real dynamics of the considered operating environment. In fact, some choices regarding the model variables were immediately induced by the modelisation process (e.g. primary transportation cost and the handling cost). On the other hand, other choices such the unit secondary distribution cost required a series of iterations in order to derive a meaningful approximation: we initially started by considering an average distribution rate based on weight ranges for the shipments from $RDW_h$ to $ADP_j$ from the transport accounting reports. However, by deeply analysing the reports, we understood that the rates we previously obtained were strongly depending on the shipped quantities along the various linkages between $RDW_h$ and $ADP_j$, since they were closely referred to those specific transport linkages. Then, since in our modelisation it is evident that the transport leg set changes from a configuration to another, it is generally unfeasible to directly apply the cost values present in the transport accounting reports for assessing the overall secondary distribution cost. For these reasons, we had to derive for each $RDW_h$ a function of the travelled distance expressing the secondary distribution unit cost. Such a function is derived by means of a regression analysis which allows for obtaining the best fitting curve interpolating the €/kg rate per each single destination, weighted on the basis of the shipped volume for each weight range, divided by the distances between the corresponding destinations and the considered RDWh.

## 4. Outcomes of the optimisation process

In the present section we report the results of the optimisation process applied to the Pirelli Tyre case and we then propose a sensitivity analysis aimed at evaluating the robustness of the solution obtained for Scenario 2, as it will be explained.

### *4.1. Numerical results*

We exploited the mixed integer linear programming model to solve the configuration problem. In particular, by using Lindo What's Best? 9.0™ software, the values of $k_h$ and $k_{h,j}$ which minimise the overall logistics cost function in the three different service level scenarios (S1, S2 and S3) are found. Table 11 synthesises the results obtained for the configuration problem in each scenario and compares them with the *as-is* configuration of the Pirelli Tyre European logistics network (the base case), in terms of number of activated $RDW_h$ and of percentage reduction of each cost item of the overall logistics cost. For the three considered optimisation processes, the average computational time was about 2,400 seconds (on a 1.3 GHz chipset machine with 512 RAM DDR).

Table 11. The outcomes of the implementation of the optimisation model (consider as 100% the overall logistics cost of the base case)

In particular, it is possible to observe how the service level constraint influences the total logistics cost. It is interesting to notice how for a very high service level (S1, i.e. delivery time within 24 hours) the number of warehouses resulting from the optimisation is the same as for the base case, even though 3 warehouses out of 15 change (i.e. they are not the same warehouses as before). The saving (equal to 4%) arises from the selection of an optimised set of $RDW_h$ and of linkages between the logistics network nodes so as to reduce each single item of the overall logistics cost. In S2 (i.e. delivery time within 36 hours), which allows broader reachable geographical zones within a wider time window due to a less strict service level constraint, 14 $RDW_h$ are activated. In this case the optimisation allows for a higher saving (equal to 7%). Of course, the saving concerning the warehousing cost is to be ascribed to the fact that a wider time window allows selecting a more efficient set of $RDW_h$, in terms of unit warehousing costs, compared to current ones. In scenario S3 (i.e. delivery time within 48 hours) the model returns a configuration for the Pirelli Tyre European logistics network equal to the one returned in the case of scenario S2. This is probably due to the fact that the savings in the warehousing costs obtainable by the selection of a more efficient set of $RDW_h$ (due to the fact that, with an even wider allowed time window, a lower number of warehouses could be potentially activated) are more than compensated by the consequent increases in the primary and secondary distribution costs to connect $RDW_h$ with more distant $P_p$ and $ADP_j$, due to the lower number of activated $RDW_h$ and to the deriving increased distance between the nodes of the network.

It is important to underline that the overall warehouse floor space does not change in the considered scenarios, even if the number of activated $RDW_h$ varies in the different analysed cases: in fact, the overall required warehouse floor space depends on the flows of products through the logistics network and on the values of $S_j$ and $ITR_j$, which are connected to the $ADP_j$ overall demand product mix, which does not vary as well in the different considered scenarios.

### *4.2. Sensitivity analysis*

In order to discuss the robustness of the obtained solution, we used the developed model to perform a sensitivity analysis. We took as a reference the network configuration obtained from the optimisation of Scenario 2. As a matter of fact, the resulting logistics network configuration is the lowest one and the service level characterising Scenario 2 is the one Pirelli Tyre has to assure in its real-life context. In particular, we used as benchmark variable the overall logistics cost and we modified the values of significant model variables and parameters (selected by discussing their relevance with Pirelli Tyre). We ran the model and we derived the new optimal logistics network configuration (named as "new solution") connected to the changed input variables (and the corresponding value of the overall logistics cost). Then, we calculated the overall logistics cost connected to the original logistics network configuration in Scenario 2 (named as "original solution") due to the changes in the values of the input variables. We measured the robustness of "original solution" by calculating the percentage difference between the overall logistics costs connected to "original solution" and to "new solution". The relevant model variables and parameters we considered in the sensitivity analysis were:

- $cw_h$ and $ch_h$ values referred to a potential $RDW_h$ located in Kassel (Germany). As a matter of fact Pirelli Tyre was awaiting for receiving an offer from a logistics service provider whose warehouse is placed in Kassel. Since in "original solution" Kassel was not activated, in the sensitivity analysis we considered only a reduction of its $cw_h$ and $ch_h$ values. Pirelli Tyre suggested that the reduction of these value could range from 5% to 10%;
- product mix: Pirelli Tyre wanted to know the impacts of the relocation of the production of certain products from one or more production plants to another. In particular, the relocations of a 10% and a 15% of product volumes were tested. For confidentiality reasons, in this paper we do not report the details of the plants potentially involved in the production relocation.

The results of the sensitivity analysis are depicted in Table 12, as a % value of the base case configuration overall logistics cost (which is considered equal to 100%).

Table 12. The outcomes of the performed sensitivity analysis

As it is possible to see from Table 12, the maximum percentage difference between the overall logistics costs connected to "original solution" and to "new solution" (taking as a reference the optimal cost, i.e. the one related to "new solution") is equal to 0.35% (corresponding to Variation "-10% $cw_h$ & $ch_h$ ($RDW_h$ Kassel)"). Consequently, we are able to affirm that the logistics network configuration obtained for Scenario 2, besides being the most realistic one in terms of considered service level constraints and the most cost-efficient one, it is also remarkably robust.

## 5. Concluding remarks

The present paper addresses a topical and current supply chain issue, i.e. supply chain configuration and optimisation, by means of a case study. In particular, a design and optimisation model for logistics and distribution networks, based on mixed integer linear programming (see Creazza et al., 2011), was applied to a real-life supply chain (the Pirelli Tyre European logistics network).

In detail, we exhaustively implemented the integrated approach we proposed in our previous work, starting from the gathering of the input data necessary for running the optimisation model. To accomplish this task, we relied on the data mapping procedure, composed of different sub-sections, which allowed obtaining the values of all the required parameters, substantially reducing the complexity of the data mapping and processing activity, which is considered as a relevant, difficult and time-consuming operation in real-life contexts (Carlsson and Ronnqvist, 2005).

Then, after having implemented the model (parameterized with the data previously obtained) on a spreadsheet software package, we succeeded in applying it to the Pirelli Tyre European logistics network, which is characterised by a high complexity level (being a multi-product and multi-stage supply chain with more than 40,000 nodes) and by service level as a pre-eminent critical success factor. In particular, based on the comparison of the outcomes of the model with budgetary data, the model proved to be accurate and adherent to the actual figures. Then, we solved the configuration problem for Pirelli Tyre, obtaining significant results in terms of saving, compared to the as-is configuration, with different scenarios of service level constraints. In fact, in any of the considered cases, the savings resulting from the implementation of the proposed method (i.e. the developed mapping section and integer linear programming model) are significant (see Table 10). Such a result allows for proving the usefulness of the proposed method in the Pirelli context and in addition it demonstrates, in more general terms, the effectiveness of the proposed method for configuring multi-item, multi-layer logistics networks.

We believe that the model we implemented in the present case study could be profitably applied by supply chain and logistics managers for optimising operating contexts characterised by similar features compared to the considered one. Moreover, the exemplified data mapping section could represent a useful guideline, which can be successfully applied by practitioners to gather and handle the high volume of data necessary for running the model in a real-life context. In more general terms, being the current state of the art particularly wanting of exhaustive configuration models, i.e. models dealing with real-life complexity and practically implemented in realistic contexts and including the data mapping section as well (see for examples the scientific contributions analysed by Melo et al., 2009), we believe that the implemented integrated approach could represent a significant contribution to the existing body of knowledge on supply chain configuration.

Furthermore, our proposed approach, besides being an optimisation tool for configuring/redesigning supply chains, represents also a useful instrument for performing scenario and what-if analysis.

In fact, the proposed model can be exploited by supply chain managers for analysing the variations of the supply chain performance (i.e. the overall logistics cost) with reference to the changes of the key parameters of the model. For instance, they could assess the overall logistics cost in function of the unit cost value modifications. In this way, they could build a sort of managerial cockpit where monitoring the supply chain performance in function of the variation of the key parameters of the model, by running the optimisation model in a changed environment.

On the other hand, supply chain managers, by modifying themselves the values of the Boolean decision variables (without running the model), can easily evaluate the impact of their decisions concerning the activation of different $RDW_h$ and/or the sourcing policy (i.e. the allocation of the logistics flows from the various $RDW_h$ to the $ADP_j$) on the supply chain performance. In this way, for instance, supply chain managers could consider the outcomes of the what-if analysis as a basis for negotiating the service level the sales & marketing wants to ensure to their customers.

Moving from this statement, supply chain managers could similarly assess the risk connected to disruptions of a certain production plant or of a RDW. In fact, they could simulate the shut down of a production plant/RDW or else the reduction of the production capacity of a production plant. By running the model excluding a $P_p$ or a $RDW_h$, or else modifying their specific features, the model is able to provide a simulation on how the logistics flows get redistributed in the network according to the changed context conditions, deriving the resulting overall logistics cost. In this case, supply chain managers modify by themselves such values and then they should run the optimisation model and assess the impact of such variations on the supply chain configuration and on the supply chain performance. This what-if scenario analysis of the behaviour of the supply chain allows to quantify the effect on the overall logistics cost, i.e. the variation of the supply chain performance from its as-is optimised network configuration value in each considered scenario.

Still, the proposed integrated approach presents some limitations which should be critically discussed. In fact, even if the provided data mapping guidelines allow for an easier and more structured operationalisation of the model, our model necessitates a considerable amount of reliable and sound data to be elaborated (e.g. the data necessary for determining the secondary distribution cost). Then, our proposed approach can be used in those contexts where production plants are product focused and where it is possible to clearly identify and define an unambiguous equivalent product unit (e.g. tons or pallets or kilos), since the $LC_p$ values and the required warehouse floor space depend on this equivalent product unit. Finally, with respect to the modelling features, our approach is not time-dependent, even if, by allowing the possibility to handle a definitely higher computational complexity and longer computational times, it could be made time-dependent: this represents one of our aims as a further research on this theme, along with the development of a multi-location layer mixed integer linear programming model for considering the redesign and the optimisation of production-distribution networks.

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Table 1. Summary of the data mapping steps, processing instructions, considered variables and suggested support tools

| Data mapping steps | Processing instructions | Information data input and sources | Suggested support tools | Parameterized variables |
|---|---|---|---|---|
| Aggregation of customers' demand | - Aggregate the various delivery points k basing on the NUTS3 coding into Aggregated Delivery Points ($ADP_j$).<br>- Sum the demand of the single delivery points included in each $ADP_j$.<br>- Determine the geographical coordinates of the centre of gravity of each $ADP_j$ weighted on the basis of the demand of each delivery point included in the cluster. | The various delivery points k, gathered from company's delivery database. | ArcGIS™ | $ADP_j$ |
| | | Single demand and geographical coordinates of the various delivery points k, gathered from company's delivery database. | ArcGIS™ | $ADP_j$ demand ($D_j$) and geographical coordinates |
| Product mix definition | - Define the product mix required by each $ADP_j$ from the various $P_p$, as the weighted average of the product mix required by each single delivery point k on the ADPj (which the delivery point k belongs to) overall demand | The mix of products manufactured by a specific $P_p$ and required by the single delivery point k, gathered from the company's accounting sheets, $D_j$. | Excel™ | Product mix ($m_{p,j}$) |
| Primary transportation cost per FTL shipment and FTL capacity definition | - Calculate the average transportation cost of FTL shipments ($cp_{p,h}$)<br>- Calculate the average FTL capacity ($LC_p$) | Transportation cost of each FTL shipment occurred in the last year for each linkage $P_p$-$RDW_h$., gathered from contracts with logistics providers.<br>Amount of products transported in each FTL shipment occurred in the last year for each linkage $P_p$-$RDW_h$., gathered from transport accounting sheets | Excel™ | $cp_{p,h}$ and $LC_p$ |
| Unit secondary distribution cost | - For each $RDW_h$, calculate the weighted average unit secondary distribution rate for linking $RDW_h$ to each $ADP_j$ on the amount of products shipped in each of the predefined weight ranges.<br>- For each $RDW_h$, calculate the Euclidean distance to each connected $ADP_j$, correcting it by the circuity factor corresponding to the country the $ADP_j$ belongs to.<br>- For each $RDW_h$, divide the weighted average unit secondary distribution rates for linking $RDW_h$ to the different $ADP_j$ by the distance between $RDW_h$ and the corresponding $ADP_j$ (obtaining a €/kg·km rate)<br>- For each $RDW_h$, plot the values of all the €/kg·km rates against the distance.<br>- For each $RDW_h$, perform a regression analysis deriving the function expressing the unit secondary distribution cost ($cs_{h,j}$). | The currently applied transport rates (expressed in €/kg per destination) gathered from company's transport accounting sheets. Geographical coordinates of $ADP_j$ and $RDW_h$ returned by ArcGIS™. Circuity factors, gathered from Ballou et al. (2002). | Excel™ and ArcGIS™ | $cs_{h,j}$ |
| Housing cost definition | - For each potential location perform a benchmark activity for estimating the unit housing cost ($cw_h$) | The sources of $cw_h$ are logistics real estate companies for the potential locations and the company's contracts | | $cw_h$ |

| | | | | |
|---|---|---|---|---|
| | | for the existing locations. | | |
| Handling cost definition | - For each potential location perform a benchmark activity for estimating the unit handling cost ($ch_h$) | The sources of $cw_h$ are handling service providers for the potential locations and the company's contracts for the existing locations. | | $ch_h$ |
| Service level requirement definition | - Define a required delivery time for each $ADP_j$.<br>- From each $RDW_h$ draw the isochronal zone for the various required delivery times, considering the average driving speeds and other factors such as the driving stops imposed by regulations.<br>- Verify which $ADP_j$ completely lie within the isochronal zone for each $RDW_h$.<br>- Fill in each cell ($I_{h,j}$) of the origin-destination matrix with 1 if the correspondence between each $RDW_h$ and each $ADP_j$ is verified, with 0 otherwise. | $RDW_h$ and $ADP_j$ geographical coordinates returned by ArcGIS$^{TM}$, driving speeds and number and frequency of driving stops, gathered from local and international regulations. Delivery times gathered by service level specifications. | Excel$^{TM}$ , MapPoint$^{TM}$ and ArcGIS$^{TM}$ | $I_{h,j}$ |

Table 2. The Austrian $ADP_j$

| $ADP_j$ | NUTS3 cluster | $ADP_j$ demand [kg] | $ADP_j$ geographical coordinates X coordinate | Y coordinate |
|---|---|---|---|---|
| $ADP_1$ | AT112 | 95,009 | 131,116 | -237,154 |
| $ADP_2$ | AT123 | 465,655 | 48,041 | -204,049 |
| $ADP_3$ | AT126 | 297,091 | 100,847 | -183,598 |
| $ADP_4$ | AT130 | 503,437 | 102,108 | -198,224 |
| $ADP_5$ | AT211 | 403,415 | -75,938 | -375,822 |
| $ADP_6$ | AT221 | 764,405 | 29,379 | -319,175 |
| $ADP_7$ | AT312 | 1,201,131 | -63,222 | -194,536 |
| $ADP_8$ | AT323 | 450,261 | -133,736 | -248,635 |
| $ADP_9$ | AT332 | 503,743 | -276,214 | -304,616 |

Table 3. Sourcing features of the Austrian territory

| $ADP_1$ | $ADP_2$ | $ADP_3$ | $ADP_4$ | $ADP_5$ | $ADP_6$ | $ADP_7$ | $ADP_8$ | $ADP_9$ |
|---|---|---|---|---|---|---|---|---|
| $RDW_1$ (27) [95,009] | $RDW_1$ (107) [465,655] | $RDW_1$ (65) [297,091] | $RDW_1$ (119) [503,437] | $RDW_1$ (102) [403,415] | $RDW_1$ (189) [764,405] | $RDW_1$ (275) [1,201,131] | $RDW_1$ (121) [450,261] | $RDW_1$ (167) [503,743] |
| $RDW_2$ to $RDW_{15}$ (0) [0] | | | | | | | | |

Table 4. $m_{p,j}$ percentages characterizing the Austrian $ADP_j$

| | p=1 (UK) | p=2 (DE) | p=3 (RO) | p=4 (IT) | p=5 (TR) | p=6 (ES) |
|---|---|---|---|---|---|---|
| $\forall j$ $(1 \le j \le 9)$ | 14% | 18% | 8% | 31% | 20% | 9% |

Table 5. $cp_{p,h}$ values for the considered $RDW_h$

| | $P_1$-Carlisle | $P_2$-Breuberg | $P_3$-Slatina | $P_4$-Settimo T. | $P_5$-Izmit | $P_6$-Manresa |
|---|---|---|---|---|---|---|
| $RDW_1$ – Guntramsdorf (AT) | 16,29 | 8,86 | 6,90 | 12,16 | 18,00 | 18,55 |
| $RDW_2$ – Effretikon (CH) | 15,71 | 8,29 | 14,00 | 8,56 | 26,50 | 13,50 |
| $RDW_3$ – Moscow (RU) | 43,35 | 37,00 | 33,00 | 44,00 | 49,50 | 53,55 |
| $RDW_4$ – Izmit (TR) | 35,05 | 19,48 | 15,25 | 26,00 | 0,50 | 6,45 |
| $RDW_5$ – Miramas (FR) | 15,02 | 12,25 | 17,00 | 10,55 | 28,00 | 10,00 |
| $RDW_6$ – Saint Witz (FR) | 7,88 | 8,46 | 16,00 | 12,71 | 25,50 | 11,05 |
| $RDW_7$ – Msczonow (PL) | 16,15 | 10,40 | 12,90 | 16,80 | 25,00 | 21,79 |
| $RDW_8$ – Athens (GR) | 31,30 | 35,27 | 13,00 | 24,00 | 18,00 | 36,20 |
| $RDW_9$ – Eskilstuna (SW) | 12,42 | 22,20 | 24,00 | 31,86 | 48,00 | 29,43 |
| $RDW_{10}$ – Subirats (ES) | 16,15 | 13,85 | 21,10 | 11,33 | 38,00 | 1,20 |
| $RDW_{11}$ – Sesena (ES) | 20,85 | 20,54 | 23,50 | 14,50 | 37,00 | 2,00 |
| $RDW_{12}$ – Otzberg (DE) | 9,07 | 0,80 | 12,00 | 9,18 | 22,00 | 12,37 |
| $RDW_{13}$ – Barton (UK) | 0,50 | 16,64 | 24,50 | 23,50 | 33,90 | 21,50 |
| $RDW_{14}$ – Novara (IT) | 13,77 | 8,00 | 12,50 | **1,00** | 14,50 | 6,97 |
| $RDW_{15}$ – Aprilia (IT) | 18,78 | 14,24 | 15,00 | 5,00 | 19,00 | 14,20 |
| $RDW_{16}$ – Brussels (BE) | 9,05 | 5,50 | 16,00 | 13,40 | 21,50 | 13,20 |
| $RDW_{17}$ – Brno (CZ) | 16,68 | 8,00 | 7,47 | 14,02 | 18,08 | 17,88 |
| $RDW_{18}$ – Kassel (DE) | 9,55 | 2,86 | 12,00 | 14,00 | 20,50 | 14,85 |
| $RDW_{19}$ – Stoccarda (DE) | 13,45 | 2,86 | 12,85 | 11,00 | 21,00 | 13,00 |
| $RDW_{20}$ – Zaragoza (ES) | 18,12 | 17,74 | 22,46 | 15,20 | 30,51 | 4,39 |
| $RDW_{21}$ – Lyon (FR) | 9,56 | 8,75 | 14,72 | 5,99 | 23,79 | 7,58 |
| $RDW_{22}$ – Piacenza (IT) | 11,96 | 9,83 | 14,23 | 2,78 | 16,45 | 10,50 |
| $RDW_{23}$ – Bologna (IT) | 19,60 | 12,60 | 13,14 | 3,29 | 15,58 | 9,00 |
| $RDW_{24}$ – Katowice (IT) | 15,75 | 8,20 | 9,50 | 15,00 | 20,00 | 19,50 |

Table 6. Portion of the transport accounting sheet related to $RDW_1$

| Tariffs [€/kg] | | Weight ranges [kg] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Destinations (zip code) | Dist. [km] | ≤20 | 20-50 | 50-100 | 100-200 | 200-300 | 300-500 | 500-1000 | 1000-2000 | 2000-3000 | 3000-5000 | >5000 |
| Wien (10) | 28 | 1,50 | 1,04 | 0,80 | 0,69 | 0,61 | 0,56 | 0,34 | 0,19 | 0,15 | 0,11 | 0,10 |
| Wien (11) | 31 | 1,50 | 1,04 | 0,80 | 0,69 | 0,61 | 0,56 | 0,34 | 0,19 | 0,15 | 0,11 | 0,10 |
| Wien (12) | 34 | 1,75 | 1,21 | 0,93 | 0,80 | 0,71 | 0,66 | 0,39 | 0,25 | 0,19 | 0,14 | 0,11 |
| Stockerau (20) | 56 | 1,75 | 1,21 | 0,93 | 0,80 | 0,71 | 0,66 | 0,39 | 0,25 | 0,19 | 0,14 | 0,11 |
| Stockerau (21) | 44 | 1,75 | 1,21 | 0,93 | 0,80 | 0,71 | 0,66 | 0,39 | 0,25 | 0,19 | 0,14 | 0,11 |
| Stockerau (22) | 54 | 1,75 | 1,21 | 0,93 | 0,80 | 0,71 | 0,66 | 0,39 | 0,25 | 0,19 | 0,14 | 0,11 |
| Stockerau (23) | 43 | 1,75 | 1,21 | 0,93 | 0,80 | 0,71 | 0,66 | 0,39 | 0,25 | 0,19 | 0,14 | 0,11 |
| Stockerau (24) | 40 | 1,75 | 1,21 | 0,93 | 0,80 | 0,71 | 0,66 | 0,39 | 0,25 | 0,19 | 0,14 | 0,11 |
| Stockerau (25) | 11 | 1,75 | 1,21 | 0,93 | 0,80 | 0,71 | 0,66 | 0,39 | 0,25 | 0,19 | 0,14 | 0,11 |
| Stockerau (26) | 19 | 1,75 | 1,21 | 0,93 | 0,80 | 0,71 | 0,66 | 0,39 | 0,25 | 0,19 | 0,14 | 0,11 |
| Stockerau (27) | 36 | 1,75 | 1,21 | 0,93 | 0,80 | 0,71 | 0,66 | 0,39 | 0,25 | 0,19 | 0,14 | 0,11 |
| Stockerau (28) | 41 | 1,75 | 1,21 | 0,93 | 0,80 | 0,71 | 0,66 | 0,39 | 0,25 | 0,19 | 0,14 | 0,11 |

Table 7. Shipped quantities from $RDW_1$ to Wien and Stockerau

| Shipped quantities [kg] | Weight ranges [kg] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Destinations (zip code) | ≤20 | 20-50 | 50-100 | 100-200 | 200-300 | 300-500 | 500-1000 | 1000-2000 | 2000-3000 | 3000-5000 | >5000 |
| Wien (10) | 1,128 | 4,781 | 5,929 | 5,681 | 3,719 | 5,607 | 8,739 | 7,398 | 1,162 | 1,707 | |
| Wien (11) | 1,864 | 7,047 | 7,237 | 4,998 | 4,148 | 6,281 | 2,962 | 5,149 | 3,660 | | |
| Wien (12) | 2,788 | 11,331 | 16,775 | 17,274 | 11,975 | 15,971 | 22,180 | 21,943 | 22,596 | 6,751 | 13,256 |
| Stockerau (20) | 389 | 1,149 | 1,904 | 1,737 | 1,156 | 1,284 | 1,558 | 4,815 | 1,076 | 3,758 | |
| Stockerau (21) | 200 | 1,185 | 1,826 | 1,607 | 2,177 | 565 | 1,866 | 735 | 1,163 | | |
| Stockerau (22) | 189 | 1,043 | 1,403 | 1,363 | 1,439 | 1,319 | 983 | 3,528 | | 1,902 | |
| Stockerau (23) | 705 | 3,204 | 4,453 | 4,706 | 2,290 | 1,730 | 3,017 | 2,975 | | 1,529 | |
| Stockerau (24) | 346 | 1,402 | 2,892 | 3,136 | 845 | 1,255 | 1,270 | | 2,051 | 1,476 | |
| Stockerau (25) | 660 | 2,562 | 2,754 | 1,859 | 1,155 | 878 | 1,801 | 1,538 | | | 12,704 |
| Stockerau (26) | 234 | 1,104 | 1,690 | 2,301 | 728 | 1,547 | 873 | | | 5,725 | |
| Stockerau (27) | 570 | 1,904 | 2,314 | 2,804 | 2,388 | 1,395 | 1,613 | 1,558 | 1,063 | | |
| Stockerau (28) | 50 | 335 | 729 | 597 | 938 | 324 | 3,173 | 3,756 | 2,449 | 2,155 | |

Table 8. €/kg·km rates from $RDW_1$ to Wien and Stockerau

| Delivery point code | 10 | 11 | 12 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Weighted €/kg rate | 0.5547 | 0.6446 | 0.5402 | 0.5020 | 0.6903 | 0.5630 | 0.7274 | 0.6826 | 0.4721 | 0.5514 | 0.7386 | 0.3783 |
| Distance [km] | 28 | 31 | 34 | 56 | 44 | 54 | 43 | 40 | 11 | 19 | 36 | 41 |
| €/kg·km rate | 0.0198 | 0.0208 | 0.0159 | 0.0090 | 0.0157 | 0.0104 | 0.0169 | 0.0171 | 0.0429 | 0.0290 | 0.0205 | 0.0092 |

Table 9. Calculation of the secondary distribution costs for connecting RDW1 to the Austrian $ADP_j$

| | Geographical coordinates | | Distance [km] from $RDW_1$ | €/kg·km rate | Secondary distribution cost – |
|---|---|---|---|---|---|
| | X coordinate (**A**) | Y coordinate (**B**) | (**C**=(1.34*((Xcoord$_{RDW}$-A)$^2$+(Ycoord$_{RDW}$-B)$^2$)$^{1/2}$)) | (**D**=0.1139*C$^{-0.843}$) | $cs_{hj}$ [€/kg] (**E**=D*C) |
| $ADP_1$ | 131,116 | -237,154 | 41.72018462 | 0.004898755 | 0.20437698 |
| $ADP_2$ | 48,041 | -204,049 | 82.11961096 | 0.002767392 | 0.227257147 |
| $ADP_3$ | 100,847 | -183,598 | 44.72164489 | 0.004620001 | 0.206614054 |
| $ADP_4$ | 102,108 | -198,224 | 25.36079057 | 0.007454066 | 0.189041012 |
| $ADP_5$ | -75,938 | -375,822 | 326.4862257 | 0.000864135 | 0.282128103 |
| $ADP_6$ | 29,379 | -319,175 | 173.7299387 | 0.001471084 | 0.255571301 |
| $ADP_7$ | -63,222 | -194,536 | 231.4147293 | 0.001155135 | 0.267315286 |
| $ADP_8$ | -133,736 | -248,635 | 326.9859552 | 0.000863021 | 0.282195727 |
| $ADP_9$ | -276,214 | -304,616 | 528.4611897 | 0.000575714 | 0.304242497 |

Table 10. Example of a service level origin-destination matrix

| | ADP$_j$ | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** |
| **Scenario 1** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| **Scenario 2** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 |
| **Scenario 3** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |
| | **ADP$_j$** | | | | | | | | | | | | | | |
| | **16** | **17** | **18** | **19** | **20** | **21** | **22** | **23** | **24** | **25** | **26** | **27** | **28** | **29** | **30** |
| **Scenario 1** | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| **Scenario 2** | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| **Scenario 3** | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

Table 11. The outcomes of the implementation of the optimisation model (consider as 100% the overall logistics cost of the base case)

| **Scenario** | **Base Case (24-36 hours)** | **S1** | **S2** | **S3** |
|---|---|---|---|---|
| Activated RDW | 15 | 15 | 14 | 14 |
| Primary distribution cost [%] | 44 | 43 | 44 | 44 |
| Secondary distribution cost [%] | 33 | 31 | 32 | 32 |
| Housing cost [%] | 9 | 9 | 5.5 | 5.5 |
| Handling cost [%] | 14 | 13 | 11.5 | 11.5 |
| **Total cost [%]** | **100** | **96** | **93** | **93** |

Table 12. The outcomes of the performed sensitivity analysis

| **Variation** | **Solution** | **Overall Logistics Cost [%]** | **Notes** |
|---|---|---|---|
| -5% cw$_h$ & ch$_h$ (RDW$_h$ Kassel) | "new" | 92.82 | - RDW$_h$ Kassel activated<br>- Computational time*: 2,557 s |
| | "original" | 93 | - RDW$_h$ Kassel not activated |
| -10% cw$_h$ & ch$_h$ (RDW$_h$ Kassel) | "new" | 92.68 | - RDW$_h$ Kassel activated<br>- Computational time*: 5,632 s |
| | "original" | 93 | - RDW$_h$ Kassel not activated |
| +10% of production relocated from | "new" | 94.42 | - RDW$_h$ Kassel activated |
| | "original" | 94.56 | - RDW$_h$ Kassel not activated |
| +15% of production relocated from one or more plants to Plant p | "new" | 94.44 | - RDW$_h$ Kassel activated<br>- Computational time*: 2,126 s |
| | "original" | 94.57 | - RDW$_h$ Kassel not activated |

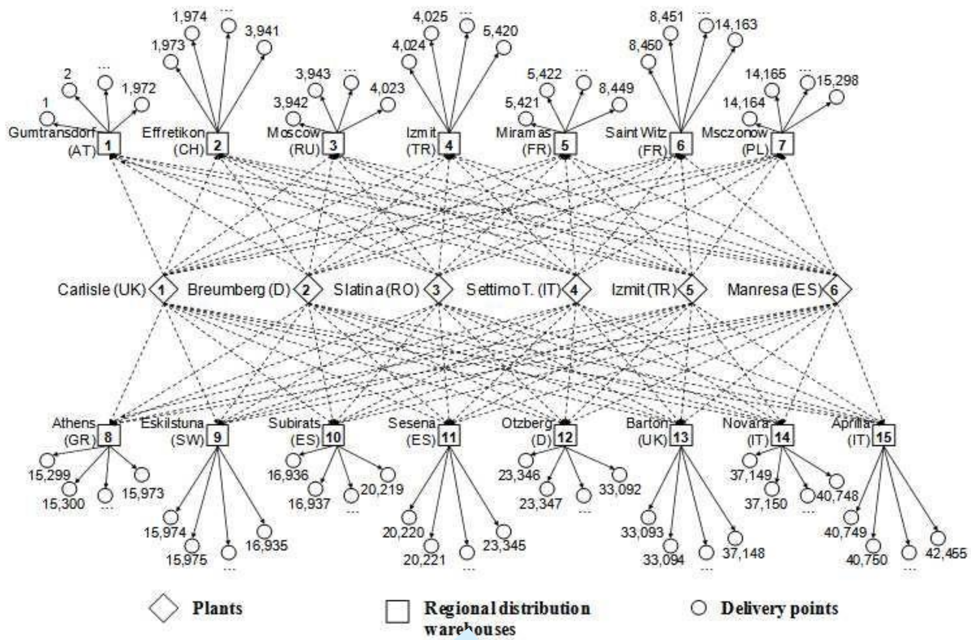
** The model was run on a 1.3 GHz chipset with 512 Mb DDR RAM*

Figure 1. Current configuration of the European Pirelli logistics network

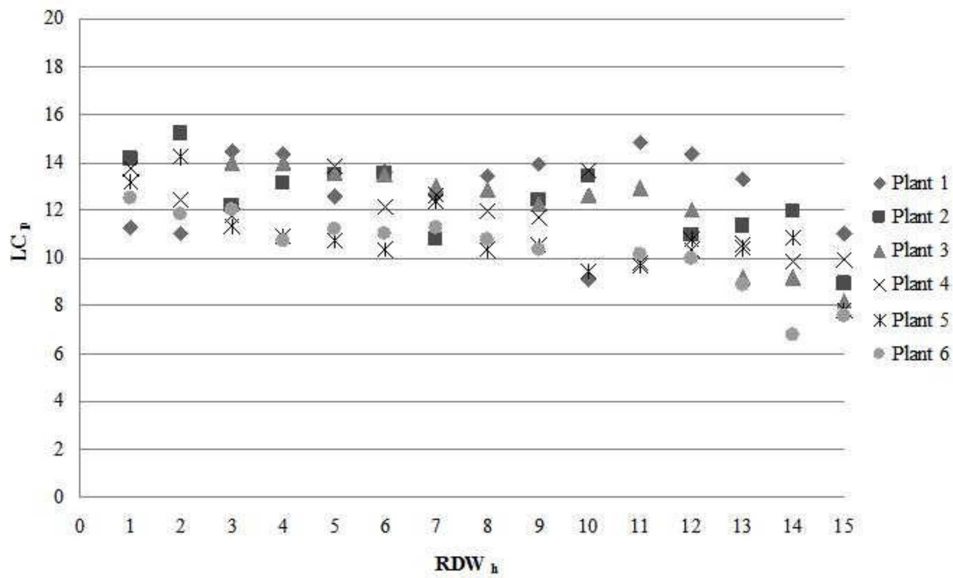
Figure 2. $LC_p$ values (in tons) for the Pirelli Tyre case

Figure 3. Secondary distribution cost function for $RDW_1$

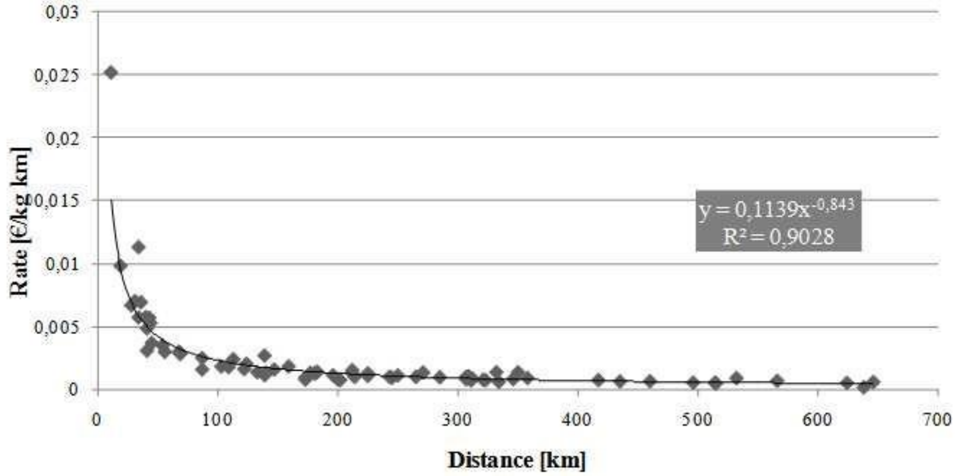
Figure 4. NUTS3 areas covered within 24 hours from $RDW_1$




272x175mm (72 x 72 DPI)




252x147mm (72 x 72 DPI)




245x126mm (72 x 72 DPI)


215x146mm (72 x 72 DPI)