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1 Executive Summary

1.1 Description

Definition of the tools to optimise the processes and activities of the Supply Chain considering the supply chain network optimization, highly constrained routing problems, material flow planning and inventory optimization.

The tools and methods resulting from this Deliverable will be used to provide solutions and perform tests in *Task 4.3 Solution Test and Simulation*.

1.2 Applied Methodology

In this Deliverable we primarily describe the supply chain analysed by the project, which is a two-echelon supply chain. We thus provide a deep literature review on the optimization problems related to the two-echelon supply chain structure, with an improvement of the existent notation. Afterwards, a set of optimization problems is proposed to represent the SUCCESS urban construction logistics and a correspondence between the optimization problems and the simulation scenarios defined in WP4 is given. The consider optimization problems are Two-echelon Facility Location Problems, Two-echelon Stochastic Facility Location Problems, Two-echelon Allocation Problems, Capacitated Vehicle Routing Problems, and Inventory vs Transport Problems.

In the following part of the Deliverable, we provide a detailed description for the mathematical models for the set of proposed optimization problems. For each of them we describe the solving algorithms used, the required input, and the resulting output.

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2 A Two-echelon Supply Chain

A supply chain is a system of organizations, people, activities, information, and resources involved in moving a product or service from supplier to customer. Supply chain activities involve the transformation of natural resources, raw materials, and components into a finished product that is delivered to the end customer. In sophisticated supply chain systems, used products may re-enter the supply chain at any point where residual value is recyclable. Supply chains link value chains. (Nagurney (2006)).

Into the supply chain, the transportation of freights takes place between an origin and a destination. It can be depicted as transportation among a set of different stages (e.g., intermediate depot, production plants, consolidation centers, etc.) between the first origin (e.g., the row material suppliers, etc.) and the last destination (e.g., the customers). This representation of the supply chain is normally referred to as *multi-echelon distribution system*.

In our contexts, construction sites are located into urban centers, and most of transports take place in urban areas, thus we will consider urban freight distribution. In the last years, urban freight distribution has been deeply studied in order to deal with its main drawbacks: congestion and environmental issues, like air pollution, noise, increase of waiting times or difficulty in finding a parking lot. Thus a new discipline, City Logistics, has been developed to decrease those inconveniences and tackle those problems related to freight transport in urban areas. In Europe, some real City Logistics applications have been developed, most of them proposing an alternative transportation system which realizes an urban freight distribution service, in some cases combined with a specific normative and restrictions. These systems are usually based on one or more Urban Consolidation Centers (UCC), which are intermediary platforms where freight, arriving from different locations outside the city, are organized into smaller and less polluting vehicles that will be able to satisfy the request of freights transport inside the urban areas. These distribution systems are examples of multi-echelon distribution systems and, in particular, of *two-echelon distribution systems*.

The two-echelon distribution systems are a special case of multi-echelon systems were the network is divided into two subnetworks, called *echelons*, built upon three set of stages. In the majority of the two-echelon systems, the freights start their journey from the first stage vertices, called *depots* (that can be a production plants, suppliers, etc.), and then move to intermediate facilities called *satellites* where storage, consolidation, and transshipment operations can take place (e.g. UCCs). Eventually, freights are distributed to the last stage vertices, the *customers*. The two echelons are two subnetworks normally furnished with one fleet of vehicles each. The first echelon includes the depots and the satellites and the network between them. The second echelon

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includes the satellites and the customers, and the network between them. See Figure 1 for a graphical representation.

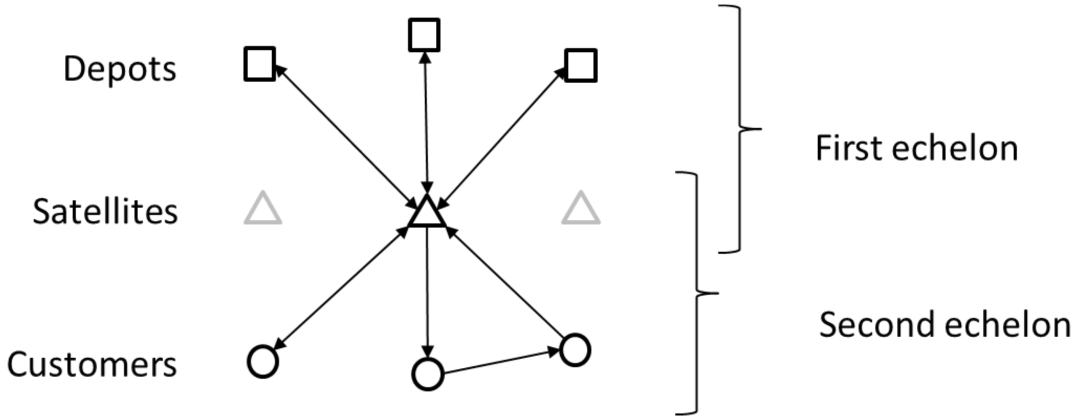

Figure 1 Two-echelon distribution system representation

We described the case in which freights are delivered from depots to customers. However the case where products are picked up from the customers and then carried to the satellites and to the depots can be similarly described considering the opposite direction of shipping. The situation where both pickups and deliveries are considered simultaneously is slightly more complex, but can be described on the same two-echelon network depicted previously.

3 Literature review on two-echelon Problems

3.1 Three Classes of two-Echelon Problems

In the last decades the two-echelon related problems have been studied in detail in order to better represent the supply chain, especially concerning City Logistics and UCCs. Among the large number of papers appeared in the last years that claim solving two-echelon problems, we detected three main classes of problems:

1. The *two-echelon facility location/location-allocation problems*: 2E-FLPs;
2. The *two-echelon capacitated vehicle routing problems*: 2E-VRPs (2E-CVRPs);
3. The *two-echelon location-routing problems*: 2E-LRPs.

In Class 1, the decisions to be made are related to the location and, sometimes, allocation in at least one of the two echelons. In this case there is no real routing and the routing part is represented by the costs of return trips. In Class 2 the location and sometimes the allocation of facilities is decided previously and the routing part is the main subject of optimization. In Class 3 all the strategic (location), tactical (allocation), and operational (routing) decisions are considered at the same time. Class 3 is justified by the fact that

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considering these decisions as separated can ease the solving method but provides poor quality solution (see, e.g., Salhi and Rand (1989)).

Class 1 and Class 2 include NP-hard problems (see, e.g., Gary MR, Johnson DS. (1979)) because they are the generalization of two NP-hard problems: the Facility Location Problem (FLP) and of the Capacitated Vehicle Routing Problem (CVRP), respectively. Class 3 represents the two-Echelon Location-Routing Problems (2E-LRPs), a generalization of the Location-Routing Problem (LRP) where two level of distribution are considered, and thus Class 3 denotes a NP-hard class of problems as well, being LRP a generalization of well-known NP-hard problems such as CVRP and FLP.

3.2 An Improved Notation

In the following, we will use the notation presented by Laporte (Location-routing problem, in Golden *Vehicle routing problems: methods and studies* (1988)) and improved by Crainic et al. (*Location-routing models for two echelon freight distribution system design* (2011)). In particular, we will denote the problems by using $\lambda/M_i/\ldots/M_{\lambda-1}$, where λ is the number of stages (number of echelons plus one) and the M_i represent the characteristic of each echelon *i*. If M_i = R then for stage *i* just return trips to vertices (a trip that goes from the starting vertex to its destination and back to starting vertex) are considered, while if M_i = T in echelon *i* routes (that is a path that starts from a vertex, that can visit one or more vertices, and then comes back to the starting vertices) are considered. For each echelon, if the R or the T are overlined, then it means that location decision have to be made at that echelon.

Integrating this notation and the classes we selected previously, we can state that Class 1 includes problems like $3/\overline{R}/R$, $3/R/\overline{R}$, and $3/\overline{R}/\overline{R}$. Class 2 includes problems like 3/T/T. Class 3 includes problems like $3/T/\overline{T}$, $3/\overline{T}/T$, and $3/\overline{T}/\overline{T}$. In the classification provided by Cuda et al. (2015) they do not consider as 2E-LRPs those problems that do not deal with routing at both echelons, but we think it is relevant to include these problems in Class 3. In particular the following problems: $3/R/\overline{T}$, $3/\overline{R}/T$, $3/\overline{R}/\overline{T}$, $3/T/\overline{R}$, $3/\overline{T}/R$, and $3/\overline{T}/\overline{R}$, even if not all of them are covered by the literature.

The presented notation has also been used by Cuda et al. (2015), but we think it lacks in representing all the many features appeared in the body of literature regarding the two-echelon problems. Thus, we represent the many features into the current notation by providing an improved notation for the two-echelon problems. In the following, we report the features that can be treated in two-echelon problems each one represented by a letter.

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Table 1 Classification of features of two-echelon problems

Symbol	Meaning
D	if direct shipping are allowed between depots and customers
P	if pickup and deliveries are considered simultaneously in at least one of the echelons
W	if some type of time window is considered in one of the echelons
C	if cross-docking synchronization is considered
N	if non-homogeneous vehicles are considered in one of the echelons
S	if some information is stochastic or dynamic
I	if some kind of inventory is considered
O	if multi commodity problem
B	if multi period problem
E	if multi depot problem
J	if multi objective problem
X	if maximum duration for the routes is imposed in one of the echelons

If one feature is considered in one problem, according to the improved notation, the corresponding letter will be positioned in round brackets after the current notation of the problem. For example, 3/T/T(PW) would represent a two-echelon vehicle routing problem with pickup and delivery and time windows.

3.3 Survey on two-Echelon Problems

In the following we present a detailed, if not exhaustive, literature review on the two-echelon problems, starting from the subdivision in the three main classes we previously proposed.

3.3.1 Class 1: Facility Location, Location-allocation problems: 2E-FLPs

3.3.1.1 3/R/$\overline{R}$

3.3.1.1.1 Melachrinoudis, Min (European Journal of Operations Research 2000): 3/R/$\overline{R}$ (BEJ)

The authors solve a multi period problem where location and relocation of facilities is considered. Existing facilities can be closed while new ones can be opened respecting the budget and considering operating costs, setup costs, and also incentives. The considered problem is multi objective including the maximization of the profit in the time horizon, the minimization of distance and

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operating time, the maximization of aggregated local incentives during the time horizon that are evaluated as a qualitative measure. The authors solve the proposed multi objective MILP model by making use of LINGO.

3.3.1.1.2 Li, Li, Zhang, Zhou (PLOS ONE 2016): $3/R/\overline{R}$ (SIE)

The authors propose a 2E-FLP where the satellites must be located. Multiple depots, stochastic demands, and inventory are also considered. They provide a MILP formulation that minimizes the cost of opening facilities, of inventory, of transportation, and the CO_2 emission tax charges. This charge is computed as proportional to the product quantities and the travel distances. They solve the formulation directly with the use of LINGO.

3.3.1.1.3 Santoso, Ahmed, Goetschalckx, Shapiro (European Journal of Operational Research 2005): $3/R/\overline{R}$ (SOE)

The authors propose a Stochastic Programming 2-stage model and solution algorithm for solving a supply chain network design problem under uncertainty of a realistic scale. They integrate a sample average approximation scheme with an accelerated benders decomposition algorithm. They test their algorithm on two real world instances.

The authors have multiple types of facilities, multiple commodity, and capacitated facilities. They consider costs, demands, supplies and capacities as stochastic parameters. The penalty for not responding to demands can be seen as the cost of outsourcing the unmet demand. In the first stage the authors decide the location of the facilities; in the second stage they decide the processing and transportation after the realization of the scenarios paying a penalty in case outsourcing is needed.

3.3.1.1.4 Chang, Tseng, Chen (Transportation Research Part E 2007): $3/R/\overline{R}$ (DSIO)

In this paper the authors present a Decision Support System for logistic planning in preparation of flood emergency. The flood emergency logistic problem with uncertainty is formulated as a 2-stage stochastic model. The decisions that are made consider location, inventory, and allocation. The problem is made of multiple different vertices representing different facilities and demand points, but it can be seen as a two-echelon supply chain. A clusterization in groups and rescue regions is performed. The stochastic part is represented by the demand and the shortage cost for not satisfying the demands is considered. They solve the proposed models to optimality with Sample Average Approximation.

3.3.1.1.5 Contreras, Cordeau, Laporte (2011): $3/R/\overline{R}$ (SOE)

The authors study stochastic hub location problems where the uncertainty is associated to demands and costs. The decisions to be made are the location

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of the hubs and the allocation of the origins and destinations to the hubs. One or two hubs can be used by the same delivery, to do so they make use of pseudo-route variables. They propose 3 versions of the problem: with stochastic demands, with stochastic dependent transportation costs, with stochastic independent costs. They propose a Monte Carlo simulation based algorithm that integrates a sample average approximation scheme with benders decomposition algorithm to solve the stochastic independent transportation costs problem.

3.3.1.2 $3/\overline{R}/\overline{R}$

3.3.1.2.1 Wu, Chu, Yang, Zhou, Zhou (International Journal of Production Research 2016): $3/\overline{R}/\overline{R}$ (E)

In this paper the authors solve a 2E-FLP where both depots and satellites must be located, and the depot must be sized. The authors propose an MILP formulation for the problem, a lagrangean relaxation, and new valid inequalities. They also provide an upper bound by proposing a hybridation between simulated annealing and tabu search algorithms.

3.3.1.2.2 Hinojosa, Puerto, Fernandez (European Journal of Operations Research 2000): $3/\overline{R}/\overline{R}$ (OBE)

The authors consider a multi period, multi commodity, multi depot location-allocation problem where both depots and satellites must be located and allocated. There are facilities already opened that can be closed in one period (but once closed they cannot be opened again) and new facilities can be opened at some period (but cannot be closed inside the considered time horizon). The objective function accounts for transportation costs and operating costs for time period and unit of product. The authors propose a MILP model and describe a lagrangean relaxation with dual ascent method to solve the problem, while making use of a constructive heuristic algorithm to find feasible solutions.

3.3.1.2.3 Tragantalerngsak, Holt, Ronqvist (European Journal of Operations Research 2000): 3/R/R(E)

The authors propose a lagrangean relaxation based branch-and-bound for the location-allocation problem where decision on number, location, flows, and assignments must be made on both depots and satellites.

3.3.1.2.4 Sadjady, Davoudpour (Computers & Operations Research 2012): $3/\overline{R}/\overline{R}$ (NIOE)

The authors solve a multi commodity, multi vehicle two-echelon location-allocation problem where both depots and satellites must be located and sized. They consider different types of transportation, with different costs and times. In the objective function they consider opening and operating costs for

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facilities, transportation costs, lead time costs, and inventory costs. The authors present a MILP model and solved it by proposing a lagrangean based heuristic algorithm.

3.3.1.2.5 Alhaj, Svetinovic, Diabat (Resources, Conservation and Recycling 2016): 3/ $\overline{R}$ / $\overline{R}$ (SIE)

The authors present a two echelon location-inventory problem with stochastic demands and considering the reduction of carbon emissions. Both the depots and the satellites must be located: the satellites locations are non-dependent on the stochastic scenarios, while the location of depots and the inventory decisions depend on the scenarios. The authors propose a MILP model and solve it with GAMS.

3.3.1.2.6 Pishvaee, Jolai, Razmi (Journal of Manufacturing Systems 2009): 3/R/R(PSE)

The authors present a 2-stage stochastic programming model for an integrated forward and revers logistics network. They consider one product, multiple depots, reverse and forward transportation, but a single period. Uncertainty is in almost all the parameters. They consider 4 types of points, but the problem can be seen as a two-echelon one. The authors decide to open and locate production/recovery centres, distribution centres, and disposal centres, and the material transportation. They solved the stochastic MILP formulation by making use of LINGO.

3.3.1.3 4/R/ $\overline{R}$ / $\overline{R}$

3.3.1.3.1 Jayaraman, Pirkul (European Journal of Operations Research 2001): 4/R/ $\overline{R}$ / $\overline{R}$ (OE)

In this paper the author propose a 3-echelon problem, but both the problem and the solution methods applied are in line with the rest of the literature, thus we decided to consider it in this survey. The authors firstly propose a MILP formulation for the problem and then propose a heuristic algorithm that uses solutions derived from lagrangean relaxation. They consider production costs for producing the materials from different row materials at the first echelon in addition to operating and traveling costs.

3.3.1.3.2 Shankar, Basavarajappa, Chen, Kadadevaramath (Expert Systems with Applications 2013): 4/R/ $\overline{R}$ / $\overline{R}$ (OEJ)

This paper presents a 3-echleon location-allocation problem that includes more than one commodity in the first echelon. The problem is multi objective with one component that considers opening costs, operating costs for the facilities, and transportation costs, while the other component evaluates a fill rate for the facilities. The authors solved the model with swarm optimization algorithms.

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3.3.1.4 *Stochastic Facility Location*

The Facility location into the supply chain can be treated more in detail. We recall to the reader that we can have three types of problems, in this case:

- P-median problem: p-facilities have to be selected to minimize the total distance (weighted).
- Uncapacitated facility location: when the number of facilities has to be decided (UFLP).
- Capacitated facility location problem: each facility has its maximum demand that can be supplied.

The simplest versions of these three types have in common: Single period planning horizon; Deterministic parameters (demands and costs); One product; One type of facility; Location-allocation decision. However, some extensions that are interesting for the Project point of view can be considered: multiple periods, stochastic components, different type of facilities, different type of echelons, direct shipping from one or more echelons, multiple commodities, reverse logistics, etc.

In this document we set our interest on the stochastic facility location problems. These problems can be solved with both exact and heuristic approaches. Among the exact approaches typically used in the literature we have the following:

- Branch-and-bound have been very popular, sometimes combined with lagrangean relaxation and with heuristics for bounds.
- Decomposition techniques have also been used due to the form of the problem that welcomes these methods.
- Direct use of optimization solvers

Among the Heuristic approaches, the most commonly used in literature are lagrangean relaxation and linear programming based heuristics.

In the following we report a literature review on the stochastic facility location problems that are not included into the two-echelon literature review.

3.3.1.4.1 Snyder, Daskin, Teo (European Journal of Operational Research 2007)

The authors present a stochastic location model with risk pooling. Where risk pooling means that the variability of the demand decreases with the decrease of the inventory stock. They consider location, transportation, and inventory and propose a 2-stage model where each scenario has its probability. The objective is to locate distribution centres and set inventory levels to minimize total expected cost.

The authors discuss the multi commodity and multi period version. They propose an exact algorithm based on lagrangean relaxation and a greedy heuristic for upper bound. If the gap is not 0 after this, they move to the optimal solution

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tank to a branch-and-bound. Both demands and costs are considered stochastics.

3.3.1.4.2 Gabor and Ommeren (Operations research letters 2006)

The authors propose a 2-approximation algorithm for the probabilistic version of the facility location problem with stochastic demands. In this model the inventory is also considered.

3.3.1.4.3 Lieckens and Vandaele (Computers & Operations Research 2007)

The authors continue the traditional reverse logistic network models (with facility location) with a queueing model, presenting a mixed integer non-linear problem for a single product, single-echelon, single period case. In their model the authors also consider the cost for processing and obsolescence, and of disposing materials.

3.3.1.4.4 Sahyouni, Savaskan, Daskin (Transportation Science 2007)

In this paper the authors present 3 facility location models that include both collection and distribution of goods, considering both the forward and the reverse logistics. In these models both bidirectional and mono-directional facilities are considered. The authors solved the models tank to a lagrangean relaxation algorithm, relaxing the assignment constraints. This article does not treat stochastic problems, but include the reverse logistics.

3.3.1.4.5 Baron, Berman, Krass (Manufacturing & Service Operations Management 2008)

The authors study the facility location problem with stochastic demands and congestion. The congestion is expressed as a service process by using queueing theory. They decide the number, the location, and the capacity of the facilities. They consider a spatially distributed continuous demand and have a maximum travel distance constraint and limits on waiting times facilities. Customers are assumed to be served by the closest facility. The problem is decomposed in easier subproblems.

3.3.1.4.6 Balcik and Beamon (International Journal of Logistics 2008)

The authors consider the facility location in humanitarian relief. They locate the distribution centre and decide the inventory of relief supplies in each centre. Thus they solve a facility location with inventory. They consider multiple commodities (items). They present a maximum covering type of model that locates facilities to maximize the amount of covered demand subject to resource limitations. In the considered problem demands, costs, and times depend on scenarios. At the first stage they decide the location of the distribution centres and the units of the items to be stored in each distribution centre. At the second stage they decide the proportion of each item to be satisfied by each distribution centre in each scenario. They have a dataset of 167 points and 45 distribution centres. They solve the example by using GAMS-Cplex.

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3.3.1.4.7 Ozsen, Daskin, Coullard (Transportation Science 2009)

In this paper the authors solve the capacitated inventory problem that minimizes the location, transportation and inventory costs. They evaluate the risk pooling benefits of multisourcing. The problem is formulated as a non-linear integer programming problem. The supply chain is two-echelon, but the problem is only based on one, moreover the problem considers singe product, single plant, multiple locations. They also consider a safety stock. Demands follow a Poisson distribution approximated to a normal distribution and are independent. They solve the problem with lagrangean relaxation (they also include a heuristic to provide an upper bound).

3.3.1.4.8 Albareda-Sambola, Fernàndez, Saldanha-da-Gama (Omega 2011)

The authors consider the so-called facility location with Bernoulli demands. That has only one echelon. The problem is formulated as a 2-stage stochastic program where uncertainty is on the demands. The decision to be made is the location and assignment before the realization of the demands. If it is not possible to serve the customers they consider two types of recourse functions based on outsourcing.

3.3.1.4.9 Wang, Makond, Liu (Expert Systems with Applications 2011)

The authors address a two level, but 1-echelon, facility location and allocation problem with stochastic demands. They propose a 2-stage stochastic programming model and a generic algorithm to solve the problem.

3.3.1.4.10 Murali, Ordóñez, Dessouky (Socio-Economic Planning Sciences 2012)

The authors solve a facility location problem with uncertainty to respond to a large scale bioterror attack. They consider location and inventory; the problem is modelled as a chance constraint problem. They solve the problem as a locate-allocate heuristic with 1 echelon.

3.3.1.4.11 Fazel-Zarandi, Berman, Beck (IIE Transactions 2013)

The authors solve a stochastic facility location fleet management problem with one echelon. They must locate facilities, determine the fleet size for each facility, allocating customers to facilities and vehicles. The times are stochastic. They solve a 2-3 stage bender's decomposition model.

3.3.1.4.12 Mousavi, Niaki, Mahdizadeh, Tavarzoth (International Journal of Systems Science 2013)

The authors present a model for the capacitated multi-facility location-allocation problem with probabilistic customer locations and demands. They present an expected value model and a chance constraint programming model. They present among the others a genetic algorithm combined with simplex and stochastic simulation.

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3.3.2 Class 2: Routing problems: 2E-VRPs

3.3.2.1.1 Crainic, Ricciardi, Storchi. Models for evaluating and planning city logistics systems. (Tech. Rep. CIRRELT [then on Transportation Science] 2009): 3/T/T(DWCNSOBE)

The authors introduce city logistics systems reporting real world experiences and examples. They report some possible problems related to the two-echelon literature that can arise in city logistics systems. They firstly describe the two-tier city logistics systems including many possible features, such as multi period, multi commodity, time windows, cross-docking synchronization, etc. Afterwards they describe the day-before planning problem, where decisions are made the day before the operations take place. The main features of this problem are the followings: the logistic structure of the system is given (no location problem); the satellites and their characteristics have already been established; the customers have been assigned to one or more satellites (no allocation problem); the type, number and characteristics of the vehicles of the two tiers are known; the demand is given in volume, product type time window, and customer; the time horizon is divided in periods; the loading and unloading time is known for each vehicle; the travel time can vary with departure time; the possible vehicles can be defined for set of products that they can carry; special corridors for urban vehicles can be defined; direct shipment can be allowed if customers are close to the depot. The authors also recall three more possible versions of the problem: one version where vehicles can be used for multiple routes; one version where the fleet size is not known; one version where split delivery is allowed.

The authors propose a set partitioning formulation for the problem, but no information on how all the features are considered in the construction of the first and second echelon routes and no description on their synchronization is given. They propose to decompose the problem between the two echelons, but they do not provide any solution algorithm or computational results.

3.3.2.1.2 Gonzalez-Feliu (PhD Thesis 2008): 3/T/T

The author give a description of the city logistics systems, provides examples and good or bad applications. The author then presents two formulations for the two-echelon capacitated vehicle routing problem 2E-CVRP, a flow based formulation (suitable for directed and undirected costs) and a TSP based formulation (suitable just for undirected costs). For both formulations are presented some valid inequalities. Eventually, he also presents set partitioning and set covering formulations.

The problem that the author solved considers one depot and capacitated satellites, two capacitated homogenous fleets of vehicles, one for each echelon, and the fact that the satellite-customer link is not known in advance. The objective is to minimize the traveling costs and the handling costs (loading/unloading).

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The author also describes other versions of the problem for whose he does not provide solution methods: the version where each satellite is served by just one vehicle; the version where split delivery is allowed; the version where maximum distance constraints are included; the version where multiple depots are considered; the version where time windows are considered; the version where cross-docking synchronization is treated; the version where pickup and deliveries are considered; and the version where direct shipping is considered.

3.3.2.1.3 Jepsen, Spoorendonk, Ropke (Transportation Science 2011): 3/T/T

The authors solve the symmetric 2E-CVRP by means of a branch-and-cut algorithm based on a 3-index formulation and propose some results on separation procedures. They obtain a lower bound by relaxing the edge flow model and propose a specialized branching scheme to obtain feasible solutions.

3.3.2.1.4 Perboli, Tadei, Vigo (Transportation Science 2011): 3/T/T

The authors claim that this paper introduces for the first time the 2E-CVRP and present a classification of the related problems similar to the one presented by Gozalez-Feliu. They present a flow based model and valid inequalities. In addition the authors propose two math-heuristics based on the presented model.

3.3.2.1.5 Perboli, Masoero, Tadei (Electronic Notes in Discrete Mathematics 2010): 3/T/T

In this paper the authors present new classes of valid inequalities for the 2E-CVRP. The presented inequalities are based on the TSP, on the CVRP, on the network flow formulation, and on the connectivity of the transportation system graph. They test the valid inequalities by means of a branch-and-cut algorithm.

3.3.2.1.6 Crainic, Mancini, Perboli, Tadei (Technical Report CIRRELT 2008): 3/T/T

The authors present several metaheuristics for the 2E-CVRP based on separating the first and the second echelon routing problems, by solving them iteratively and adjusting the satellites workloads that link them. The two main metaheuristics presented use a clustering and a multi depot approach, respectively.

3.3.2.1.7 Crainic, Mancini, Perboli, Tadei (EvoCOP 2011): 3/T/T

The authors present a family of multi-start heuristics for the 2E-CVRP. The heuristics based on the separation of the two echelons, then the solution is adjusted to obtain a feasible one and local searches and a diversification procedure are applied.

3.3.2.1.8 Crainic, Mancini, Perboli, Tadei (Book Chapter in Advances in Metaheuristics 2011): 3/T/T

The authors a meta-heuristic based on GRASP combined with Path Relinking to address the 2E-CVRP. They treat the problem by separating the two echelon

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routing problem, and by iteratively solving the two resulting routing subproblems, while adjusting the satellite workloads that link them. The metaheuristic scheme consists of applying a GRASP followed by local search procedures. The resulting solution is linked to an elite solution by means of a Path Relinking procedure. To escape from infeasible solutions a feasibility search procedure is applied within Path Relinking.

3.3.2.1.9 Baldacci, Mingozzi, Roberti, Wolfler Calvo (Operation Research 2013): 3/T/T

The authors present an exact algorithm for the undirected 2E-CVRP. They include the setup costs for the satellites in the cost matrix. They propose a new formulation and present a new bounding procedure based on dynamic programming, a dual descent method, and an exact algorithm that decomposes the 2E-CVRP into a limited set of multi depot capacitated VRPs with side constraints.

3.3.2.1.10 Hemmelmayr, Cordeau, Crainic (Computers & Operations Research 2012): 3/T/T

The authors present an Adaptive Large Neighborhood Search for the 2E-CVRP and for the subproblem obtained when routing is considered just at the second level (3/R/T). They build an initial solution by assigning each customer to a satellite by means of a roulette wheel selection and then by using the Clarke and Wright algorithm for every satellite. Afterwards the first level routes are formed again with the Savings algorithm. Once a feasible solution is on hand they use destroy-and-repair procedures followed by some local search procedures. These procedures make advantage of the 2 level structure of the problem. They outperformed existing methods.

3.3.2.1.11 Santos, da Cunha, Mateus (Optimization Letters 2012); Santos, Mateus, da Cunha (Transportation Science 2014): 3/T/T

In the first paper, the authors present an integer programming formulation and branch-and-price algorithm for the 2E-CVRP (3/R/T) providing new upper bounds. They consider loading and unloading operations cost together with the travelling cost. In the second paper the authors provide a branch-and-cut-and-price algorithm for the same problem, by using a set of new valid inequalities and new upper bounds.

3.3.2.1.12 Soysal, Bloemhof-Ruwaard, Bektaş (International Journal of Production Economics 2014): 3/T/T(NS)

The author presents a time dependent 2E-CVRP with one depot, non-homogeneous vehicles at the first echelon and homogeneous vehicles at each satellite. They consider the travelled distance, the vehicle speed, the vehicle load, the emissions and the handling costs. The authors recognize 4 time zones in each of which a different speed is consider to evaluate the traffic; this depend on the departure time of each vehicle and on the moment in which the arcs are travelled be the vehicles: we can consider this problem to consider

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dynamicity. A formulation is proposed for the problem and some good inequalities are defined. The authors solve a case study and make use of different objective functions in order to provide some comparison; thanks to that they conclude that two echelon distribution systems provide environmentally friendly solutions, while single echelon ones provide the least costs solutions.

3.3.2.1.13 Ahmadizar, Zeynivand, Arkat (Applied Mathematical Modelling 2015): 3/T/T(CNIOEX)

The authors propose a 2E-CVRP with cross docking, where heterogeneous vehicles and multiple products are considered. AN inventory cost is imposed when the vehicles must wait for loading and a maximum time is imposed to complete the pickup, the crossing, and the delivery. The authors propose a MILP formulation and solve the problem with a genetic algorithm whose solution is improved by local search procedures.

3.3.2.1.14 Grangier, Gendreau, Lehuédé, Rousseau (European Journal of Operations Research 2016): 3/T/T(WCX)

The authors solve a 2E-CVRP with time windows and cross docking synchronization, which is needed because no storage capacity is allowed at satellites. Multiple trips are allowed on the second echelon and a maximum time is imposed for each route. The authors provide a MILP formulation and solve it with an Adaptive Large Neighborhood Search (ALNS) that includes a customized destroy and repair procedure and fast feasibility checks.

3.3.2.1.15 Song, Gu, Haung (Journal of Combinatorial Optimization 2016): 3/T/T(DE)

The authors propose to solve a 2E-CVRP where direct shipping is also allowed, for this reason they call the problem as adaptive 2E-CVRP. Multiple depots are also considered. They propose a formulation, a lower bound based on its lagrangean formulation, and an upper bound based on Baldacci et al. 2013.

3.3.2.1.16 Breunig, Schmid, Hartl, Vidal (Computer and Operations Research 2016): 3/T/T and 3/T/$\overline{T}$

In this paper two problems are addressed, the 2E-VRP and the 2E-LRP, in the first case the routing and handling costs are considered, while in the second case also the facility location is evaluated. For both problems they propose a hybrid metaheuristic that includes local search procedures, a destroy and repair principle, and tailored operators. Very high quality solutions are provided.

3.3.2.1.17 Liu, Tao, Hu, Xie (International Journal of Production Research 2016): 3/T/T(S)

The authors solve a 2E-CVRP with stochastic demands. They do not present a formulation; however, they solve the problem with a tabu search algorithm where the stochasticity is tackled by a Monte Carlo sampling.

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3.3.2.1.18 Dellaert, Saridarq, Van Woensel, Crainic (Technical Report CIRRELT 2016): 3/T/T(WE)

The authors present two path based formulations for the 2E-CVRP with time windows and multiple depots. They solve them with branch-and-price algorithms.

3.3.2.1.19 Butty, Stuber, Hanne, Dornberg (4th International Symposium on Computational and Business Intelligence 2016): 3/T/T

In this conference paper the authors propose a heuristic algorithm for the simple version of the 2E-CVRP. No formulation is reported. The algorithm is a GRASP with a learning process made of two heuristics and a VND with two neighborhoods. They also show a very simple visualization method for the output of the obtained solutions.

3.3.2.1.20 Li, Zhang, Lv, Chang (Transportation Research Part B 2016): 3/T/T(DWCNX)

The authors solve a 2E-CVRP with direct shipping allowance, non-homogeneous vehicles, time windows, a maximum time duration for each route, and crossdocking synchronization. H authors present a MILP formulation. The objective function includes travelling's costs, handling costs, and waiting costs. The problem is thus solved by means of a Clarke and Wright heuristic improved with local search procedures.

3.3.2.1.21 Li, Yuan, Lv; Chang (Transportation Research Part D 2016): 3/T/T(DWCNX)

This paper is very similar to the previous one for definition and used methodology; however the authors include CO2 emissions depending on ton and kilometers in the objective.

3.3.3 Class 3: Location-Routing Problems: 2E-LRPs

3.3.3.1 3/R/ $\overline{T}$

3.3.3.1.1 Nikbakhsh, Zegordi (Transaction E: Industrial Engineering 2010): 3/R/ $\overline{T}$ (WEX)

The authors consider a two-echelon location-routing problem where time windows and a maximum duration constraint for the vehicles are considered. The time windows are soft time windows and operate as follows: there is a first time windows where to deliver products is free and a second time windows that implies a fixed penalty cost. The authors propose a 4-index formulation and a 2-phase heuristic made of a constructive heuristic improved by local searches and a lower bound derived from the relaxation of the proposed model.

3.3.3.1.2 Dalfard, Kaveh, Nosratian (Neural Computer & Application 2012): 3/R/ $\overline{T}$ (EX)

The authors tackle a symmetric 2E-LRP version with maximum duration constraints for the routes and where the fleet size of two types of vehicles has to

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be determined. The authors propose a hybrid genetic algorithm and a simulated annealing to solve the problem.

3.3.3.1.3 Guerrero, Prodhon, Velasco, Amaya (International Journal of Production Economics 2013): $3/R/\overline{T}$ (IBE)

In this paper the authors consider a multi depot, multi period, and asymmetric version of the 2E-LRP where satellites have initial inventory, and obsolescence costs are included in the objective function together with routing costs, opening costs and the cost of using one vehicle at least once. The fleet is homogeneous, capacitated, and unlimited. They propose a MILP formulation for the problem. The second echelon routing part makes use of 4-index variables, while they use 5-index variables for the inventorying part. The formulation provides bounds on the solutions. The authors solve the problem by means of hybrid heuristic made of a randomized Clarke and Wright algorithm improved by local searches.

3.3.3.2 $3/\overline{T}/\overline{R}$

3.3.3.2.1 Vivodic, Ratkovic, Bjelic, Popovic (Expert Systems with Applications 2016): $3/\overline{T}/\overline{R}$

In this paper the authors consider a reverse logistics 2E-LRP. The scope is to collect waste from customers, consolidate it into satellites, and then carry it to the depots. In this case the direction is opposite with respect to the other papers: pickups are considered instead of deliveries. The objective of the presented problem is to maximize the profit for the collection of recyclables considering the opening costs, the idle time for vehicles and the traveling cost. The authors want to size and determine the number and location of facilities. They propose a MILP formulation where the routes are made with up to 4 vertices (one set of variable for 1-vertex routes, one set for 2-vertex routes, one set for 3-vertex routes, and one for 4-vertex routes). They also propose a heuristic approach based on the relaxation of the model.

3.3.3.3 $3/T/\overline{T}$

3.3.3.3.1 Jacobsen, Madsen (European Journal of Operations Research 1980): $3/T/\overline{T}$ (WX)

In this paper the authors study a two-echelon system for newspaper distribution. They impose a maximum capacity for the first echelon vehicles; they also consider a maximum duration constraint for the second echelon routes and last delivery time for the customers. The decision involves the location of the satellites with no opening costs and the definition of the routes at both echelons. The authors propose three heuristic algorithms to solve the problem.

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3.3.3.3.2 Madsen (European Journal of Operations Research 1983): 3/T/ $\overline{T}$ (WX)

In this paper the author presents some modifications to two of the three heuristic algorithm presented in Jacobsen, Madsen 1990.

3.3.3.3.3 Nguyen, Prins, Prodhon (European Journal of Operations Research 2012): 3/T/ $\overline{T}$ (D)

The authors propose a 2E-LRP with one depot, where the size of the fleet and the opening of the satellites are decision variable with a cost that has to be minimized together with the traveling costs. The direct shipping is allowed but performed by second echelon vehicles. No storage is allowed in the satellites. The authors present a 2-index MILP formulation and present 4 constructive heuristic algorithms and a metaheuristic one. This last one is a GRAPS complemented by a learning process and path relinking. The learning process involves three greedy randomized heuristics and two VNDs to improve the obtained solutions. The path relinking provides intensification and post optimization.

3.3.3.3.4 Nguyen, Prins, Prodhon (Engineering Application of Artificial Intelligence 2012): 3/T/ $\overline{T}$ (D)

The authors tackled the same problem as in the previous paper. They propose a 3-index formulation that is hard to be solved by the typical MILP solvers. Thus they also propose a multistart iterated local search where three randomized greedy heuristic are used to get initial solutions. Each ILS run alternates between two search spaces: the 2E-LRP and the TSP ones. The solutions are stored in a tabu list. The ILS is strengthened by path relinking procedures.

3.3.3.3.5 Rahmani, Cherif-Khettaf, Oulamara (International Federation of Automatic Control – Conference Paper 2015): 3/T/ $\overline{T}$

The authors claim that the problem they present is multi commodity and pickup and delivery, but it appears not to be a multi commodity nor pickup and delivery problem. This problem has one depot and only the satellites need to be located while minimizing opening cost for satellites and routing costs of the homogeneous vehicles. The authors present no models for the problem, but just two local search procedures.

3.3.3.3.6 Rahmani, Cherif-Khettaf, Oulamara (International Journal of Production Research 2015): 3/T/ $\overline{T}$ (POX)

The authors solve a two echelon location routing problem with multiple products and considering a maximum duration for each route. They present a MILP formulation and an extension for the problem of the nearest neighbor and insertion approach; moreover they present a clustering based approach.

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3.3.3.3.7 Breunig, Schmid, Hartl, Vidal (Computer and Operations Research 2016): 3/T/T and $3/T/\overline{T}$

As reported previously, the authors addressed both the 2E-VRP and the 2E-LRP with a hybrid metaheuristic that includes local search procedures, a destroy and repair principle, and tailored operators.

3.3.3.4 $3/\overline{T}/\overline{T}$

3.3.3.4.1 Boccia, Crainic, Sforza, Sterle (Technical Report CIRRELT 2011 and Experimental algorithms: lecture notes in computer science 2010): $3/\overline{T}/\overline{T}$ (E)

In this paper the authors proposed the notation from which we started for our classification. The propose 3, 2, and 1-index MILP formulations for a multi depot version of the 2E-LRP where the location of both depots and satellites is to be decided together with the allocation of both echelons and the fleet size and routing. They evaluate the formulations by solving a set of instances with XPRESS. They also provide an instance generator.

The authors also describe possible related problems such as multi commodity problems, multi period problems, constraints such as time windows and cross-dock synchronization, and the stochastic version derived from data uncertainty.

3.3.3.4.2 Crainic, Sforza, Sterle (Technical Report CIRRELT 2011): $3/\overline{T}/\overline{T}$ (E)

In this paper the authors solve the same version of 2E-LRP tackled in the previous paper. To do so they propose a Tabu Search metaheuristic based on the decomposition of the problem in two location-routing problems, one for each echelon. Then each subproblem is decomposed into a capacitated facility location problem and a multi depot vehicle routing problem. The TS uses an iterative-nested approach to combine the solutions of the four subproblems.

3.3.3.4.3 Contardo, Hemmelmayr, Crainic (Computers & Operations Research 2012): $3/\overline{T}/\overline{T}$ (E)

The authors solve the same problem as the one tackled in the previous paper. They propose a branch-and-cut algorithm based on a 2-index formulation and several families of valid inequalities. They also propose an ALNS metaheuristic that includes the Savings algorithm for gathering the initial solution, some destroy and repair procedures and local search procedures.

3.3.3.4.4 Schwengerer, Pirkwieser, Raidl (Evolutionary Computation in Combinatorial Optimization: Lecture Notes in Computer Science 2012): $3/\overline{T}/\overline{T}$ (E)

The authors solve a symmetric version of 2E-LRP and solve it by means of a Variable Neighborhood Search derived from a previously defined VNS for the

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LRP: They make use of 21 specific neighborhood structures while the intensification is provided by 2 local searches.

3.3.3.4.5 Govindan, Jafarian, Khodaverdi, Devika (International Journal of Production Economics 2014): 3/ $\overline{T}$ / $\overline{T}$ (WNIBEJX)

The 2E-LRP studied in this paper includes soft time windows, maximum duration constraints for the routes, heterogeneous vehicles while determining the number, location and routes at each echelon. The problem is a multi objective one, where in the first objective are considered the routing costs, the opening costs, and the holding/inventory costs, and in the second objective it is evaluated the environmental impact. They solved the problem by making use of hybrid approaches such as hybridation of particle swarm optimization methods.

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4 Urban Construction Logistics Supply Chain: the SUCCESS case

In this chapter we propose the sets of problems that can represent the supply chain considered in the SUCCESS Project.

We remark that the suppliers and the dump sites of the SUCCESS supply chain are called depots in the two-echelon literature, the Construction Consolidation Centers are called satellites, and the construction sites are called customers. We will stick with this notation in the following. The graphical representation of all the three types of vertices is recalled in Figure 2.

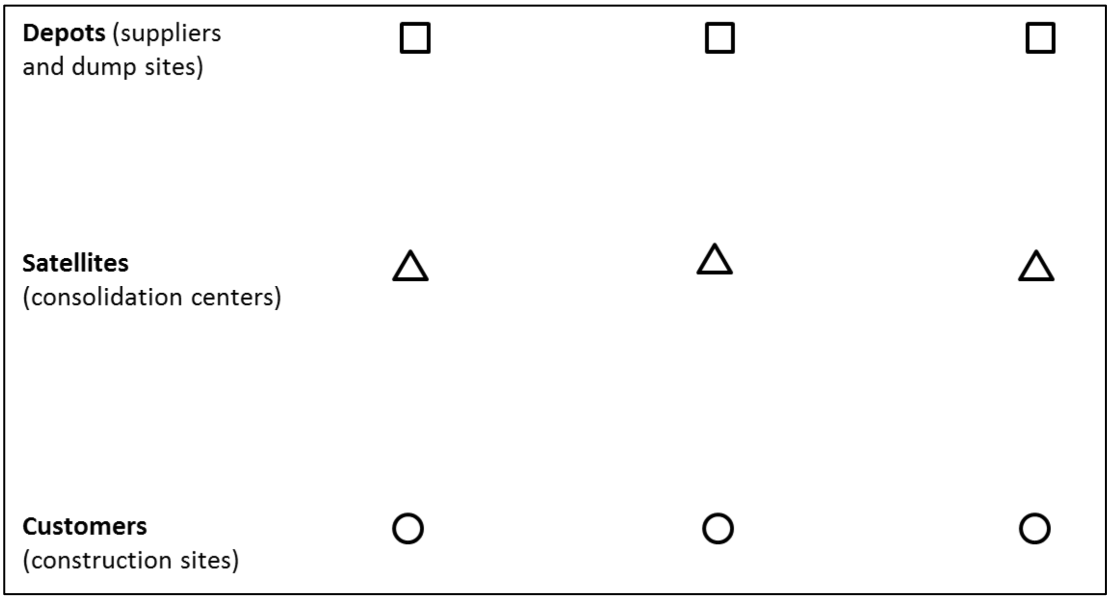

Figure 2 Subdivision and graphical representation of the three vertices of the supply chain

4.1 Typical characteristics for the SUCCESS two-echelon problems

The representation we provide of the urban construction supply chain in is based on the two-echelon structure and can include a set of many features that we list in the following.

- Multi depot problems: more than one supplier and/or dump site (E);
- Multi commodity problems: several materials are considered, because of the nature of the construction site (O);
- Multi period problem: more than one period considered (B)
- Different types of vehicles. This can be due to multiple commodities and to multiple actors involves (different suppliers, carriers, etc.) (N);
- Direct shipping for some materials: for example concrete that cannot be consolidated (D);
- Inventory: into the consolidation centers (I).

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Possible other features that can be considered in a two-echelon problem:

- Multi-routes: more than one route starting from one depot
- Stochastic information: on the location of CCCs (S).

4.2 Problems Proposal

To simulate the urban construction supply chain we propose a set of optimization problems. These problems are part of the wide class of two-echelon problems and can include the previously presented features. We present the optimization problems by following the notation previously presented; and thus the following features should be considered: **(DNIOBE)** or **(DNIOBES)**.

1) Two-echelon (stochastic) facility location problems: 3/R/ $\overline{R}$

One of the main problems we have to tackle represents a strategical decision, which is the location and possibly the sizing of the CCCs in our supply chain. In this case we must consider the class of *two-echelon facility location problem*, in particular the 3/R/ $\overline{R}$.

We will propose a set of multiple versions of the problem with many features in Chapter 5. One of the features that we will address is the use if stochastic demands: the material demands can be considered as stochastic variables depending on a set of scenarios, each one with a probability; in this case we can talk about the stochastic version of the problem.

In Figure 3, one can see the simplified representation two-echelon (stochastic) facility location network, where the CCCs must be located and the material flows represent the transportation costs.

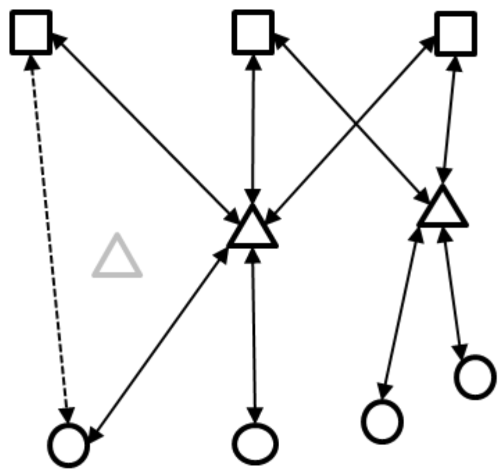

Figure 3 Two-echelon (stochastic) facility location schematic representation

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2) Two-echelon allocation problems

For some of the scenarios that we will consider, it will be required an intermediate optimization between the strategic decision (the location problem deciding the location of CCCs) and the operational problem (the routing problem deciding the material distribution). This is the case of a tactical problem that is the allocation problem, where the CCCs will be allocated to supplier and/or construction sites. This decision must be made because in many scenarios the suppliers or the construction sites will define and sign contracts with no more than one CCC.

The allocation decisions not necessarily require the use of optimization, indeed they can also derived from a human decision. For instance, the allocation can be a decision made during the contractualization.

In Figure 4 the two-echelon allocation scheme is reported: the CCCs to open have already been decided, and the decision maker must allocate the supplier and / or the construction sites to the CCCs. By making this, the resulting subnetworks can be considered separately in the following operational problems.

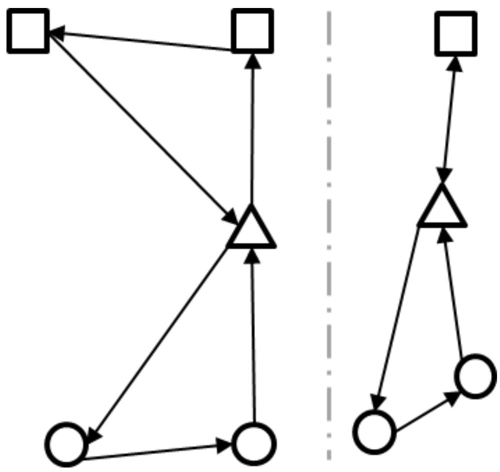

Figure 4 Two-echelon allocation schematic representation

3) Vehicle routing problems: 3/T/T

At the operational level, materials must be transported from their origin to their destination in the day by day operations. We thus intend to propose a set of methods to solve problems representing the 3/T/T. More specifically, the routing part can be considered as Capacitated Vehicle Routing Problems in both echelons, where the fleets of vehicles have a larger capacity in the firs echelon and a smaller one in the second echelon.

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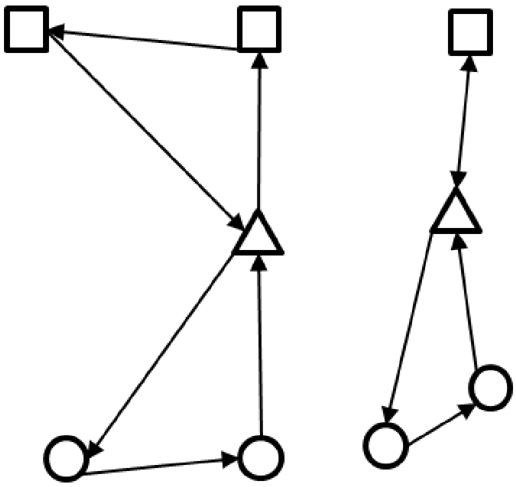

Figure 5 Vehicle routing problems schematic representations

In some of the considered scenarios the introduction of the CCCs is not performed, in this case we will also have to solve a Capacitated Vehicle Routing Problem.

4) Inventory vs Transport problems

In some evaluation scenarios, where the optimization is restricted to particular parts of the supply chain, we propose a problem that takes into account the cost of inventory, the cost of transport, and the minimization of the number of vehicles to transport materials.

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4.3 Correspondence with the simulation scenarios

In Figure 6 we report the set of scenarios detected in *WP4 Solution Design and Test*. The correspondence between the scenarios and the proposed problems is reported in Table 2.

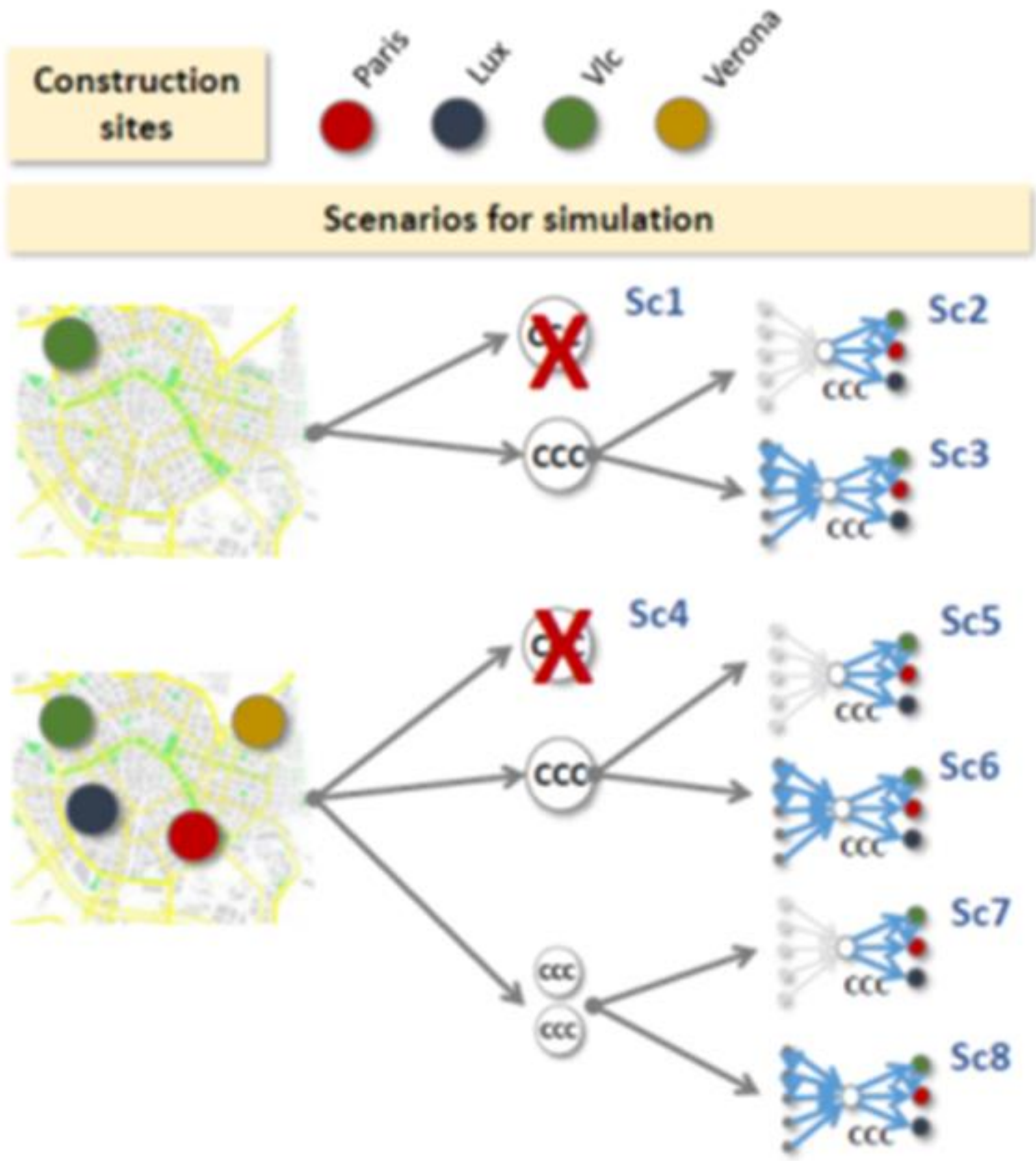

Figure 6 Simulation Scenarios Scheme

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Table 2 Correspondence between simulation scenarios and optimization problems

Scenario	Description			Problems	Solving methods
	Sites	CCCs	Echelons		
Sc1	1	0	-	CVRP • one for the deliveries • one for the reverse logistics	Heuristics algorithms
Sc2	1	1	2nd	Two-echelon (Stochastic) Facility Location	Mathematical models / L-shaped Method
				Inventory vs Transport	Mathematical models
Sc3	1	1	1st/2nd	Two-echelon (Stochastic) Facility Location	Mathematical models / L-shaped Method
				CVRP (1st echelon) • one for the deliveries • one for the reverse logistics	Heuristics algorithms
				Inventory vs Transport (2nd echelon)	Mathematical models
Sc4	multi	0	-	CVRP: • one for the deliveries • one for the reverse logistics	Heuristics algorithms
Sc5	multi	1	2nd	Two-echelon (Stochastic) Facility Location	Mathematical models / L-shaped Method
				CVRP • one for the deliveries • one for the reverse logistics	Heuristics algorithms
Sc6	multi	1	1st/2nd	Two-echelon (Stochastic) Facility Location	Mathematical models / L-shaped Method

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				CVRP • one for the collections in the 1st echelon • one for the deliveries in the 2nd echelon • one for the reverse logistics in the 2nd echelon • one for the reverse logistics in the 1st echelon	Heuristics algorithms
Sc7	multi	multi	2nd	Two-echelon (Stochastic) Facility Location	Mathematical models / L-shaped Method
				Allocation	Mathematical models
				CVRP • one for the collections in the 1st echelon • one for the deliveries in the 2nd echelon • one for the reverse logistics in the 2nd echelon • one for the reverse logistics in the 1st echelon	Heuristics algorithms
Sc8	multi	multi	1st/2nd	Two-echelon (Stochastic) Facility Location	Mathematical models / L-shaped Method
				Allocation	Mathematical models
				CVRP • one for the collections in the 1st echelon • one for the deliveries in the 2nd echelon • one for the reverse logistics in the 2nd echelon • one for the reverse logistics in the 1st echelon	Heuristics algorithms

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5 Two-echelon (Stochastic) Facility Location Problems

In this chapter we propose a set of mathematical models to solve the Facility Location Problem related to the introduction of Construction Consolidation Centers (CCC) to serve urban construction sites. The mathematical models are Mixed Integer Programming (MILP) Models and include different features, such as multiple materials, multiple periods, direct shipping, reverse logistics, and stochastic demands. This also represents a novelty, indeed these features have not been studied all together. The strenght of the Facility Location models is that they are normally not very hard to solve and thus very complex models can be addressed and better represent reality. The main benefit of these models is that good solutions can be provided accounting for many characteristics of the supply chain.

In the following, we firstly propose the mathamatical notation and thus the set of MILP models with an increasing difficulty.

5.1 Notation

The Notation is reported divided into sets, parameters, and variables.

Sets	
Symbol	**Meaning**
A	Set of arcs
P	Set of construction sites
D	Set of CCCs
F	Set of suppliers (and/or dumpsites)
V	Set of vertices, $V = P \cup D \cup F$
M'	Set of materials that cannot be directly shipped from suppliers to sites
M''	Set of materials that cannot be directly shipped from sites to suppliers / dumpsites
$\breve{M}$	Set of materials that can also be directly shipped from suppliers to sites
$\hat{M}$	Set of materials that can also be shipped from sites to suppliers / dumpsites
M	Set of materials, $M = M' \cup M'' \cup \breve{M} \cup \hat{M}$ (not for all the following models the subsets are specified or not null)
T	Set of periods

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T'	Set of periods plus one, $T' = T \cup \{\|T\|+1\}$
Ω	Set of scenarios

Parameters	
Symbol	**Meaning**
l_h	Setup cost for CCC $h \in D$
c_{ij}	Distance between i and j
q_{ij}	Request of material from supplier $i \in F$ to site $j \in P$
q_{ij}^m	Request of material $m \in M$ from supplier $i \in F$ to site $j \in P$
q_{ij}^t	Request of material from supplier $i \in F$ to site $j \in P$ in period $t \in T$
q_{ij}^{mt}	Request of material $m \in M$ from supplier $i \in F$ to site $j \in P$ in period $t \in T$
$\tilde{q}_{ij}^{\omega}$	Request of material from supplier $i \in F$ to site $j \in P$ in scenario $\omega \in \Omega$
$\tilde{q}_{ij}^{mt\omega}$	Request of material $m \in M$ from supplier $i \in F$ to site $j \in P$ in period $t \in T$, in scenario $\omega \in \Omega$
r_{ji}	Request of material from site $j \in P$ to supplier $i \in F$
$\tilde{r}_{ji}^{mt\omega}$	Request of material $m \in M$ from site $j \in P$ to supplier/dumpsite $i \in F$, in period $t \in T$, in scenario $\omega \in \Omega$
C_h	Capacity of the CCC $h \in D$
C_m	Capacity for material $m \in M$ of the CCCs
C_m^h	Capacity for material $m \in M$ of the CCC $h \in D$
B	Maximum number of CCCs
p_{ω}	Probability of scenario $\omega \in \Omega$
d_{ij}	Cost for directly shipping materials from suppliers to sites or from sites to suppliers/dumpsites
b^h	Cost of inventory in CCC $h \in D$

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$\breve{\kappa}_h$	Capacity for incoming materials operations at the CCC $h \in D$
$\hat{\kappa}_h$	Capacity for exiting materials operations at the CCC $h \in D$

Variables	
Symbol	**Meaning**
y_h	1 if CCC $h \in D$ is opened, 0 otherwise
g_{ij}^{h}	Flow of material from supplier $i \in F$ to site $j \in P$ passing through CCC $h \in D$
g_{ij}^{hm}	Flow of material $m \in M$ from supplier $i \in F$ to site $j \in P$ passing through CCC $h \in D$
g_{ij}^{ht}	Flow of material from supplier $i \in F$ to site $j \in P$ passing through CCC $h \in D$ in period $t \in T$
g_{ij}^{hmt}	Flow of material $m \in M$ from supplier $i \in F$ to site $j \in P$ passing through CCC $h \in D$ in period $t \in T$
$g_{ij}^{h\omega}$	Flow of material from supplier $i \in F$ to site $j \in P$ passing through CCC $h \in D$ in scenario $\omega \in \Omega$
f_{ji}^{h}	Flow of reverse material from site $j \in P$ to supplier $i \in F$ passing through CCC $h \in D$
f_{ij}^{hm}	Flow of reverse material $m \in M$ from site $j \in P$ to supplier $i \in F$ passing through CCC $h \in D$
f_{ij}^{ht}	Flow of reverse material from site $j \in P$ to supplier $i \in F$ passing through CCC $h \in D$ in period $t \in T$
f_{ij}^{hmt}	Flow of reverse material $m \in M$ from site $j \in P$ to supplier $i \in F$ passing through CCC $h \in D$ in period $t \in T$
x_{ij}	Direct flow of material from supplier $i \in F$ to site $j \in P$
w_{ji}	Direct flow of reverse material from site $j \in P$ to supplier/dumpsite $i \in F$
$x_{ij}^{mt\omega}$	Direct flow of material $m \in \breve{M}$ from supplier $i \in F$ to site $j \in P$, in period $t \in T$, in scenario $\omega \in \Omega$

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$w_{ji}^{mt\omega}$	Direct flow of reverse material $m \in \hat{M}$ from site $j \in P$ to supplier/dumpsite $i \in F$, in period $t \in T$, in scenario $\omega \in \Omega$
$\overline{g}_{ij}^{ht}$	Flow of material from supplier $i \in F$ to CCC $h \in D$ direct to site $j \in P$ in period $t \in T$
$\underline{g}_{ij}^{ht}$	Flow of material from CCC $h \in D$ to site $j \in P$ coming from supplier $i \in F$ in period $t \in T$
$\underline{f}_{ji}^{ht}$	Flow of material from site $j \in P$ to CCC $h \in D$ direct to dumpsite $i \in F$ in period $t \in T$
$\overline{f}_{ji}^{ht}$	Flow of material from CCC $h \in D$ to dumpsite $i \in F$ coming from site $j \in P$ in period $t \in T$
$\overline{g}_{ij}^{hmt}$	Flow of material $m \in M' \cup \breve{M}$ from supplier $i \in F$ to CCC $h \in D$ direct to site $j \in P$ in period $t \in T$
$\underline{g}_{ij}^{hmt}$	Flow of material $m \in M' \cup \breve{M}$ from CCC $h \in D$ to site $j \in P$ coming from supplier $i \in F$ in period $t \in T$
$\underline{f}_{ji}^{hmt}$	Flow of material $m \in M'' \cup \hat{M}$ from site $j \in P$ to CCC $h \in D$ direct to dumpsite $i \in F$ in period $t \in T$
$\overline{f}_{ji}^{hmt}$	Flow of material $m \in M'' \cup \hat{M}$ from CCC $h \in D$ to dumpsite $i \in F$ coming from site $j \in P$ in period $t \in T$
$\overline{g}_{ij}^{hmt\omega}$	Flow of material $m \in M' \cup \breve{M}$ from supplier $i \in F$ to CCC $h \in D$ direct to site $j \in P$ in period $t \in T$ for scenario $\omega \in \Omega$
$\underline{g}_{ij}^{hmt\omega}$	Flow of material $m \in M' \cup \breve{M}$ from CCC $h \in D$ to site $j \in P$ coming from supplier $i \in F$ in period $t \in T$ for scenario $\omega \in \Omega$
$\underline{f}_{ji}^{hmt\omega}$	Flow of material $m \in M'' \cup \hat{M}$ from site $j \in P$ to CCC $h \in D$ direct to dumpsite $i \in F$ in period $t \in T$ for scenario $\omega \in \Omega$
$\overline{f}_{ji}^{hmt\omega}$	Flow of material $m \in M'' \cup \hat{M}$ from CCC $h \in D$ to dumpsite $i \in F$ coming from site $j \in P$ in period $t \in T$ for scenario $\omega \in \Omega$
I_{ij}^{ht}	Inventory of material in CCC $h \in D$ coming from supplier $i \in F$ to site $j \in P$ in period $t \in T$
J_{ji}^{ht}	inventory of reverse logistics material in CCC $h \in D$ coming from site $j \in P$ to supplier/dumpsite $i \in F$ to site in period $t \in T$

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I_{ij}^{hmt}	Inventory of material $m \in M' \cup \breve{M}$ in CCC $h \in D$ coming from supplier $i \in F$ to site $j \in P$ in period $t \in T$
J_{ji}^{hmt}	Inventory of reverse logistics material $m \in M'' \cup \hat{M}$ l in CCC $h \in D$ coming from site $j \in P$ to supplier/dumpsite $i \in F$ to site in period $t \in T$
$I_{ij}^{hmt\omega}$	Inventory of material $m \in M' \cup \breve{M}$ in CCC $h \in D$ coming from supplier $i \in F$ to site $j \in P$ in period $t \in T$ in scenario $\omega \in \Omega$
$J_{ji}^{hmt\omega}$	Inventory of reverse logistics material $m \in M'' \cup \hat{M}$ in CCC $h \in D$ coming from site $j \in P$ to supplier/dumpsite $i \in F$ to site in period $t \in T$ in scenario $\omega \in \Omega$

5.2 Mathematical Models

In the following we propose the MILP models starting from a Basic Model that includes a selected number of features and then more and more complex models including more features.

5.2.1 Basic Model

The *Basic Problem* represents the Facility Location Problem related to the introduction of CCCs in its simplest form. The model decides where to locate one or more CCCs selected from the input list of possible CCCs minimizing the opening costs and a representation of the transportation costs. The decision is bounded by the CCCs' capacity and by the maximum number of CCC allowed to open.

In the following the *Basic Model* is reported.

$$\min \sum_{h \in D} l_h y_h + \sum_{i \in F} \sum_{j \in P} \sum_{h \in D} (c_{ih} + c_{hj}) g_{ij}^h \tag{5.1}$$

$$\sum_{h \in D} g_{ij}^h = q_{ij} \qquad i \in F, j \in P \tag{5.2}$$

$$\sum_{i \in F} \sum_{j \in P} g_{ij}^h \le C_h y_h \qquad h \in D \tag{5.3}$$

$$\sum_{h \in D} y_h \le B \tag{5.4}$$

$$g_{ij}^h \ge 0 \qquad i \in F, j \in P, h \in D \tag{5.5}$$

$$y_h \in \{0,1\} \qquad h \in D \tag{5.6}$$

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The objective function (5.1) is made of two components: the first component minimizes the cost of opening the CCCs, while the second component minimizes the amount of material multiplied by the cost of transportation from the suppliers to the CCCs and from the CCCs to the clients. Constraint (5.2) states that the quantity of materials starting from a supplier $i \in F$, passing by a CCC $h \in D$, and headed to a construction site $j \in P$ must satisfy exactly the request q_{ij} of material between the two points, $i \in F, j \in P$. Constraint (5.3) imposes a maximum capacity to each CCC, if opened. In constraint (5.4) we impose the number of opened CCCs to be less than a maximum quantity. The domain of the variables is defined in (5.5) and (5.6).

5.2.2 Multi Period and Multi Material Models

In this section we include multiple materials and multiple periods into the models. The benefit of this is that so we can reproduce better the reality, by imposing different capacities for different materials and providing a better representation of the material requests with respect of the time horizon. Another benefit of considering these feature is that a better representation of costs is provided.

5.2.2.1 Multi Material Model

The second model we present, the *Multi Material Model*, is based on the basic one with the introduction of the set of different materials. Indeed, the location of CCCs is still the main output based on opening costs and on the evaluation of transportation costs. However, the transportation variables take now into account the several materials managed in the considered network. The decision are conbstrainde by the CCCs' total capacity, by the CCCs' material capacity and by the maximum number of CCCs allowed to open.

$$\min \sum_{h \in D} l_h y_h + \sum_{m \in M} \sum_{i \in F} \sum_{j \in P} \sum_{h \in D} (c_{ih} + c_{hj}) g_{ij}^{hm} \tag{5.7}$$

$$\sum_{h \in D} g_{ij}^{hm} = q_{ij}^{m} \qquad i \in F, j \in P, m \in M \tag{5.8}$$

$$\sum_{i \in F} \sum_{j \in P} g_{ij}^{hm} \le C_h^m y_h \qquad h \in D, m \in M \tag{5.9}$$

$$\sum_{m \in M} \sum_{i \in F} \sum_{j \in P} g_{ij}^{hm} \le C_h y_h \qquad h \in D \tag{5.10}$$

$$\sum_{h \in D} y_h \le B \tag{5.11}$$

$$g_{ij}^{hm} \ge 0 \qquad i \in F, j \in P, h \in D, m \in M \tag{5.12}$$

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$$y_h \in \{0,1\} \qquad h \in D \tag{5.13}$$

The objective function (5.7) and the constraints (5.8), (5.10)-(5.13) are very similar to their correspective in the previous model. The novel constrain (5.9), instead, considers a capacity for each material $m \in M$ in each CCC $h \in D$. This representsthe fact that inside the CCCs different materials can have dedicated and capacitated areas.

5.2.2.2 *Multi Period Model*

The *Multi Period Model* is based on the Basic Mode where the material flows and requests are considered by periods $t \in T$. The CCCs capacities must be not exceeded for each period $t \in T$, as imposed by (5.16). Both the objective function (5.14) and the constraints (5.15)-(5.19) are very similar to the ones in the Basic Model.

$$\min \sum_{h \in D} l_h y_h + \sum_{t \in T} \sum_{i \in F} \sum_{j \in P} \sum_{h \in D} (c_{ih} + c_{hj}) g_{ij}^{ht} \tag{5.14}$$

$$\sum_{h \in D} g_{ij}^{ht} = q_{ij}^{t} \qquad i \in F, j \in P, t \in T \tag{5.15}$$

$$\sum_{i \in F} \sum_{j \in P} g_{ij}^{ht} \leq C_h y_h \qquad h \in D, t \in T \tag{5.16}$$

$$\sum_{h \in D} y_h \leq B \tag{5.17}$$

$$g_{ij}^{ht} \geq 0 \qquad i \in F, j \in P, h \in D, t \in T \tag{5.18}$$

$$y_h \in \{0,1\} \qquad h \in D \tag{5.19}$$

5.2.2.3 *Multi Material Multi Period Model*

The *Multi Material Multi Period Model* considers both the multi material and the multi period features presented in the previous models. Thus, the flows variables take into account these features, the request are separated by period and material, the CCCs capacities and the capacities for each material must be respected in each period.

$$\min \sum_{h \in D} l_h y_h + \sum_{m \in M} \sum_{t \in T} \sum_{i \in F} \sum_{j \in P} \sum_{h \in D} (c_{ih} + c_{hj}) g_{ij}^{hmt} \tag{5.20}$$

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$$\sum_{h\in D} g_{ij}^{hmt} = q_{ij}^{mt} \qquad i\in F, j\in P, m\in M, t\in T \qquad (5.21)$$

$$\sum_{i\in F}\sum_{j\in P} g_{ij}^{hmt} \le C_h^m y_h \qquad h\in D, m\in M, t\in T \qquad (5.22)$$

$$\sum_{m\in M}\sum_{i\in F}\sum_{j\in P} g_{ij}^{hmt} \le C_h y_h \qquad h\in D, t\in T \qquad (5.23)$$

$$\sum_{h\in D} y_h \le B \qquad (5.24)$$

$$g_{ij}^{hmt} \ge 0 \qquad i\in F, j\in P, h\in D, m\in M, t\in T \qquad (5.25)$$

$$y_h \in \{0,1\} \qquad h\in D \qquad (5.26)$$

5.2.3 Reverse Models

In this section we add a new feature to the previous models: the reverse logistics, that is expressed by involving a new set of variables f. This set of variables considers the amount of materials traveling from the construction site $j\in P$ to the dumpsites/suppliers $i\in F$ passing by a CCC. Considering the reverse logistics is innovative per se, indeed many precedent works do not account for it. The benefit of inlcuding reverse logistics is that we can decide the location and the size of the CCCs taking into account materials, capacities, and costs that will be included in the real-life use of a CCC.

5.2.3.1 Basic Reverse Model

In the *Basic Reverse Model* we include the reverse logistics into the basic model. The main changes are related to the objective function (5.27), in which the reverse logistics costs are taken into account. While the costraints that include the main changes can be described as follows: constraint (5.29) states that the reverse logistic request $r_{ji}, j\in P, i\in F$ has to be satisfied. Constraint (5.30) considers both forward and reverse flows when imposing that the capacity of CCCs must not be exceeded. The remaining constraints can be re-conducted to the previously presented models.

$$\min \sum_{h\in D} l_h y_h + \sum_{i\in F}\sum_{j\in P}\sum_{h\in D} (c_{ih}+c_{hj}) g_{ij}^h + \sum_{j\in F}\sum_{i\in P}\sum_{h\in D} (c_{jh}+c_{hi}) f_{ji}^h \qquad (5.27)$$

$$\sum_{h\in D} g_{ij}^h = q_{ij} \qquad i\in F, j\in P \qquad (5.28)$$

$$\sum_{h\in D} f_{ji}^h = r_{ji} \qquad i\in F, j\in P \qquad (5.29)$$

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$$\sum_{i\in F}\sum_{j\in P}(g_{ij}^h + f_{ji}^h) \le C_h y_h \qquad h\in D \tag{5.30}$$

$$\sum_{h\in D} y_h \le B \tag{5.31}$$

$$g_{ij}^h, f_{ji}^h \ge 0 \qquad i\in F, j\in P, h\in D \tag{5.32}$$

$$y_h \in \{0,1\} \qquad h\in D \tag{5.33}$$

5.2.3.2 Reverse Multi Material Model

The *Reverse Multi Material Model* includes the multi material features into the Reverse Model.

$$\begin{aligned} \min \sum_{h\in D} l_h y_h + \sum_{m\in M}\sum_{i\in F}\sum_{j\in P}\sum_{h\in D}(c_{ih}+c_{hj})g_{ij}^{hm} + \\ \sum_{m\in M}\sum_{j\in F}\sum_{i\in P}\sum_{h\in D}(c_{jh}+c_{hi}) f_{ji}^{hm} \end{aligned} \tag{5.34}$$

$$\sum_{h\in D} g_{ij}^{hm} = q_{ij}^m \qquad i\in F, j\in P, m\in M \tag{5.35}$$

$$\sum_{h\in D} f_{ji}^{hm} = r_{ji}^m \qquad i\in F, j\in P, m\in M \tag{5.36}$$

$$\sum_{i\in F}\sum_{j\in P}(g_{ij}^{hm} + f_{ji}^{hm}) \le C_h^m y_h \qquad h\in D, m\in M \tag{5.37}$$

$$\sum_{m\in M}\sum_{i\in F}\sum_{j\in P}(g_{ij}^{hm} + f_{ji}^{hm}) \le C_h y_h \qquad h\in D \tag{5.38}$$

$$\sum_{h\in D} y_h \le B \tag{5.39}$$

$$g_{ij}^{hm}, f_{ji}^{hm} \ge 0 \qquad i\in F, j\in P, h\in D, m\in M \tag{5.40}$$

$$y_h \in \{0,1\} \qquad h\in D \tag{5.41}$$

In this model the variables, the requests and the capacities depend also on the materials. The constraint that is different from the previous model is constraint (5.37), in which a capacity for each material is imposed to forward and revers material flows interesting each CCC.

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5.2.3.3 *Reverse Multi Period Model*

The *Reverse Multi Period Model* is similar to the Reverse Logistic Model where multiple periods are considered. Thus, variables and flows depend also on the period $t \in T$.

$$\begin{aligned} \min \sum_{h\in D} l_h y_h + \sum_{t\in T}\sum_{i\in F}\sum_{j\in P}\sum_{h\in D}(c_{ih}+c_{hj}) g_{ij}^{ht} + \\ \sum_{t\in T}\sum_{j\in F}\sum_{i\in P}\sum_{h\in D}(c_{jh}+c_{hi}) f_{ji}^{ht} \end{aligned} \tag{5.42}$$

$$\sum_{h\in D} g_{ij}^{ht} = q_{ij}^{t} \qquad i \in F, j \in P, t \in T \tag{5.43}$$

$$\sum_{h\in D} f_{ji}^{ht} = r_{ji}^{t} \qquad i \in F, j \in P, t \in T \tag{5.44}$$

$$\sum_{i\in F}\sum_{j\in P}(g_{ij}^{ht} + f_{ji}^{ht}) \le C_h y_h \qquad h \in D, t \in T \tag{5.45}$$

$$\sum_{h\in D} y_h \le B \tag{5.46}$$

$$g_{ij}^{ht}, f_{ji}^{ht} \ge 0 \qquad i \in F, j \in P, h \in D, t \in T \tag{5.47}$$

$$y_h \in \{0,1\} \qquad h \in D \tag{5.48}$$

5.2.3.4 *Reverse Multi Period Multi Material Model*

The *Reverse Multi Period Multi Material Model* is obtained by including both multiple materials and multiple periods into the Reverse Logistic Model. In this model we consider both forward and reverse material flows, for each material and for each considered period. The forward and reverse requests of all materials must be satisfied in each period. The total capacity and the material wise capacity must be respected in each CCC. The number of CCCs to open is limited.

$$\begin{aligned} \min \sum_{h\in D} l_h y_h + \sum_{m\in M}\sum_{t\in T}\sum_{i\in F}\sum_{j\in P}\sum_{h\in D}(c_{ih}+c_{hj}) g_{ij}^{hmt} \\ + \sum_{m\in M}\sum_{t\in T}\sum_{j\in F}\sum_{i\in P}\sum_{h\in D}(c_{jh}+c_{hi}) f_{ji}^{hmt} \end{aligned} \tag{5.49}$$

$$\sum_{h\in D} g_{ij}^{hmt} = q_{ij}^{mt} \qquad i \in F, j \in P, t \in T, m \in M \tag{5.50}$$

$$\sum_{h\in D} f_{ji}^{hmt} = r_{ji}^{mt} \qquad i \in F, j \in P, t \in T, m \in M \tag{5.51}$$

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$$\sum_{i\in F}\sum_{j\in P}(g_{ij}^{hmt}+f_{ji}^{hmt})\leq C_h^m y_h \qquad h\in D, t\in T, m\in M \tag{5.52}$$

$$\sum_{m\in M}\sum_{i\in F}\sum_{j\in P}(g_{ij}^{hmt}+f_{ji}^{hmt})\leq C_h y_h \qquad h\in D, t\in T \tag{5.53}$$

$$\sum_{h\in D} y_h \leq B \tag{5.54}$$

$$g_{ij}^{hmt}, f_{ji}^{hmt}\geq 0 \qquad i\in F, j\in P, h\in D, m\in M, t\in T \tag{5.55}$$

$$y_h \in \{0,1\} \qquad h\in D \tag{5.56}$$

5.2.4 Direct Shipping

In this section we consider the possibility of accounting direct shipping from suppliers to construction sites and from construction site to dumpsites for some materials. Direct shipping has a different cost with respect to material shipped via CCC, thus a benefit is that a better representation of reality and of costs is given. Moreover, the allowance of direct shipping can decrease infeasibility problems related to the CCCs capacities.

5.2.4.1 Basic Reverse and Direct Model

In the *Basic Reverse and Direct Model* we consider the possibility of carring material from the supplier to the construction site directly (direct shipping) or through a CCC. This is valid in both the forward and the reverse case. The cost of direct shipping is $d_{ij}, i\in F, j\in P$ or vice versa, in case of reverse direct shipping. In some solutions the use of direct shipping can be important when the capacity of the CCC has been reached. To include the new feature two new sets of variables are needed: the variable $x_{ij}, i\in F, j\in P$ represents the amount of material directly shipped from supplier i to construction site j; the variable $w_{ji}, j\in P, i\in F$ represents the amount of materials directly shipped from the construction site i to the supplier/dumpsite j. The new cost of transporting material directly are included int the objective function (5.57). Constraints (5.58) and (5.59) state that the material must be delivered either by making use of a CCC or by direct shipping, in the forward or reverse case, respectively. We also defined the new variables as non negatives in (5.63). The other constraints are similar to those presented in the previous models.

$$\min \sum_{h\in D} l_h y_h + \sum_{i\in F}\sum_{j\in P}\sum_{h\in D}(c_{ih}+c_{hj})g_{ij}^h + \sum_{j\in F}\sum_{i\in P}\sum_{h\in D}(c_{jh}+c_{hi})f_{ji}^h + \sum_{j\in F}\sum_{i\in P}(d_{ij}x_{ij}+d_{ji}w_{ji}) \tag{5.57}$$

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$$x_{ij} + \sum_{h \in D} g_{ij}^h = q_{ij} \qquad i \in F, j \in P \tag{5.58}$$

$$w_{ji} + \sum_{h \in D} f_{ji}^h = r_{ji} \qquad i \in F, j \in P \tag{5.59}$$

$$\sum_{i \in F} \sum_{j \in P} (g_{ij}^h + f_{ji}^h) \leq C_h y_h \qquad h \in D \tag{5.60}$$

$$\sum_{h \in D} y_h \leq B \tag{5.61}$$

$$g_{ij}^h, f_{ji}^h \geq 0 \qquad i \in F, j \in P, h \in D \tag{5.62}$$

$$x_{ij}, w_{ji} \geq 0 \qquad i \in F, j \in P \tag{5.63}$$

$$y_h \in \{0,1\} \qquad h \in D \tag{5.64}$$

5.2.5 Stochastic Models

In this section we introduce the stochasticity to our models. In particular, we will consider the material demands as non-deterministic. They depend on different scenarios $\omega \in \Omega$, where each scenario ω is given with a probability p_ω, $\sum_{\omega \in \Omega} p_\omega = 1$.

Stochastic information can provide a better representation of reality, and improved evaluation of costs, and overcome infeasibilities.

5.2.5.1 Stochastic Basic Model

The first stochastic model we present is the *Stochastic Basic Model*. The demand $\tilde{q}_{ij}^{\omega}$ depends on the scenario ω, and so do the material flows $g_{ij}^{h\omega}$. In the objective function we consider the cost of the flows of each scenario multiplied by its probability (see, e.g., (5.65)).

In the following we consider the same problem in its *Deterministic Equivalent* form and in its *Two-Stage Formulation* form. In the first case all the scenarios are considered into the same model, while in the second case we consider the decisions linked to variables y_h to be made before the realization of the stochastic variables ($\tilde{q}_{ij}^{\omega}$) in the first stage model, and the decision linked to variables $g_{ij}^{h\omega}$ to be made after the realization of the stochastic variables in the second stage models, that is a set of models, one for each scenario. These models can be decomposed because they rely on independent scenarios. The second case is typically solved by using the L-shaped Method, that solves the first stage model, inserts the current values of the first stage variables into the

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two stage models and solves them. If at least one of the subproblems of the second stage is infeasible then we need to introduce an equation called *feasibility cut* into the first stage model and solve again. Otherwise, if all the subproblems are feasible, we can define another equation called *optimality cut* to make the first stage model pay for the recourse function derived from the second stage, if needed. The recourse function is, in this case, the $\sum_{\omega\in\Omega} p_\omega \theta^\omega$, where $\theta^\omega = \min \sum_{i\in F}\sum_{j\in P}\sum_{h\in D}(c_{ih}+c_{hj})g_{ij}^{h\omega}, \omega \in \Omega$. If all the subproblems are feasible and the recourse function has been paid by the first stage model, thus the first stage model solution is also the optimal solution, that is the same as the one found by the deterministic equivalent. The advantages of making use of the two stage formulation and the L-shaped method is that it normally makes the stochastic models easier to be solved thanks to the decomposition.

5.2.5.1.1 Stochastic Basic Model: Deterministic Equivalent

$$\min \sum_{h\in D} l_h y_h + \sum_{\omega\in\Omega}\sum_{i\in F}\sum_{j\in P}\sum_{h\in D} p_\omega (c_{ih}+c_{hj}) g_{ij}^{h\omega} \tag{5.65}$$

$$\sum_{h\in D} g_{ij}^{h\omega} = \tilde{q}_{ij}^{\omega} \qquad i\in F, j\in P, \omega\in\Omega \tag{5.66}$$

$$\sum_{i\in F}\sum_{j\in P} g_{ij}^{h\omega} \le C_h y_h \qquad h\in D, \omega\in\Omega \tag{5.67}$$

$$\sum_{h\in D} y_h \le B \tag{5.68}$$

$$g_{ij}^{h\omega} \ge 0 \qquad i\in F, j\in P, h\in D, \omega\in\Omega \tag{5.69}$$

$$y_h \in \{0,1\} \qquad h\in D \tag{5.70}$$

5.2.5.1.2 Stochastic Basic Model: Two-Stage Formulation

5.2.5.1.2.1 I stage Model

$$\min \sum_{h\in D} l_h y_h + \sum_{\omega\in\Omega} p_\omega \theta^\omega \tag{5.71}$$

$$\sum_{h\in D} y_h \le B \tag{5.72}$$

$$y_h \in \{0,1\} \qquad h\in D \tag{5.73}$$

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5.2.5.1.2.2 II stage Model

$$\theta^{\omega} = \min \sum_{i \in F} \sum_{j \in P} \sum_{h \in D} (c_{ih} + c_{hj}) g_{ij}^{h\omega} \tag{5.74}$$

$$\sum_{h \in D} g_{ij}^{h\omega} = \tilde{q}_{ij}^{\omega} \qquad i \in F, j \in P \tag{5.75}$$

$$\sum_{i \in F} \sum_{j \in P} g_{ij}^{h\omega} \le C_h y_h \qquad h \in D \tag{5.76}$$

$$g_{ij}^{h\omega} \ge 0 \qquad i \in F, j \in P, h \in D \tag{5.77}$$

5.2.5.2 Stochastic Multi Period Multi Material Reverse Direct with different set of materials Model

We believe that the reader is now familiar with the features we included step by step in the previous models, and thus we decided to move directly to a more complicated model, where we included: multiple periods, multiple materials, forward and reverse logistics, and the possibility of direct shipping in both directions based on different set of materials. We present in the following the Deterministic equivalent of the problem and its two-stage formulation.

5.2.5.2.1 Stochastic Multi Period Multi Material Reverse Direct with different set of materials Model: Deterministic Equivalent

$$\begin{aligned} \min \sum_{h \in D} l_h y_h &+ \\ \sum_{\omega \in \Omega} \sum_{m \in M' \cup \breve{M}} \sum_{t \in T} \sum_{i \in F} \sum_{j \in P} \sum_{h \in D} p_{\omega} (c_{ih} + c_{hj}) g_{ij}^{hmt\omega} &+ \\ \sum_{\omega \in \Omega} \sum_{m \in M'' \cup \hat{M}} \sum_{t \in T} \sum_{i \in F} \sum_{j \in P} \sum_{h \in D} p_{\omega} (c_{jh} + c_{hi}) f_{ji}^{hmt\omega} &+ \\ \sum_{\omega \in \Omega} \sum_{m \in \breve{M}} \sum_{t \in T} \sum_{i \in F} \sum_{j \in P} p_{\omega} d_{ij} x_{ij}^{mt\omega} &+ \\ \sum_{\omega \in \Omega} \sum_{m \in \hat{M}} \sum_{t \in T} \sum_{i \in F} \sum_{j \in P} p_{\omega} d_{ji} w_{ji}^{mt\omega} & \end{aligned} \tag{5.78}$$

$$\sum_{h \in D} g_{ij}^{hmt\omega} = \tilde{q}_{ij}^{mt\omega} \qquad i \in F, j \in P, t \in T, \omega \in \Omega, m \in M' \tag{5.79}$$

$$\sum_{h \in D} f_{ji}^{hmt\omega} = \tilde{r}_{ji}^{mt\omega} \qquad i \in F, j \in P, t \in T, \omega \in \Omega, m \in M'' \tag{5.80}$$

$$x_{ij}^{mt\omega} + \sum_{h \in D} g_{ij}^{hmt\omega} = \tilde{q}_{ij}^{mt\omega} \qquad i \in F, j \in P, t \in T, \omega \in \Omega, m \in \breve{M} \tag{5.81}$$

$$w_{ji}^{mt\omega} + \sum_{h \in D} f_{ji}^{hmt\omega} = \tilde{r}_{ji}^{mt\omega} \qquad i \in F, j \in P, t \in T, \omega \in \Omega, m \in \hat{M} \tag{5.82}$$

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$$\sum_{i\in F}\sum_{j\in P} g_{ij}^{hmt\omega} \le C_h^m y_h \qquad h\in D, t\in T, \omega\in\Omega, m\in M'\cup\breve{M} \tag{5.83}$$

$$\sum_{i\in F}\sum_{j\in P} f_{ji}^{hmt\omega} \le C_h^m y_h \qquad h\in D, t\in T, \omega\in\Omega, m\in M''\cup\hat{M} \tag{5.84}$$

$$\sum_{m\in M'\cup\breve{M}}\sum_{i\in F}\sum_{j\in P} g_{ij}^{hmt\omega} + \sum_{m\in M''\cup\hat{M}}\sum_{i\in F}\sum_{j\in P} f_{ji}^{hmt\omega} \le C_h y_h \qquad h\in D, t\in T, \omega\in\Omega \tag{5.85}$$

$$\sum_{h\in D} y_h \le B \tag{5.86}$$

$$g_{ij}^{hmt\omega}, f_{ji}^{hmt\omega} \ge 0 \qquad i\in F, j\in P, h\in D, t\in T, \omega\in\Omega, m\in M \tag{5.87}$$

$$x_{ij}^{mt\omega} \ge 0 \qquad i\in F, j\in P, t\in T, \omega\in\Omega, m\in\breve{M} \tag{5.88}$$

$$w_{ji}^{mt\omega} \ge 0 \qquad i\in F, j\in P, t\in T, \omega\in\Omega, m\in\hat{M} \tag{5.89}$$

$$y_h \in \{0,1\} \qquad h\in D \tag{5.90}$$

The objective function (5.78) is made of five components: the first component is the only deterministic and considers the costs of opening the CCCs, the remaining components are part of the new recourse function that is the summation of the cost of the many scenarios multiplied by their probability. In particular, the second and the third components represent the cost of transporting material through the CCCs in the forward and reverse directions. The fourth and the fifth components consider the transportation costs for the forward and reverse direct shipping.

In this model we separate the materials in several sets, in particular we recall: M' is the set of materials to be delivered to construction sites that must pass through a CCC; M'' is the set of materials of the reverse logistics that must pass through a CCC; $\breve{M}$ is the set of materials of forward logistics that can be delivered by a CCC or directly; $\hat{M}$ is the set of materials of reverse logistics that can be dumped passing by a CCC or directly. To observe that $M = M'\cup M''\cup\breve{M}\cup\hat{M}$, and that the mutual intersection of these subsets is an empty set. Constraint (5.79) states that the demand of the forward logistics $\tilde{q}_{ij}^{mt\omega}$ that is required to pass through the CCCs has to be satisfied for each supplier $i\in F$, for each construction site $j\in P$, in each period $t\in T$, for each material interested $m\in M'$, for each scenario $\omega\in\Omega$. Constraint (5.80) states that the demand of the reverse logistics $\tilde{r}_{ji}^{mt\omega}$ that is required to pass through the CCCs has to be satisfied for each construction site $j\in P$, for each supplier $i\in F$, in each period $t\in T$, for each material interested $m\in M''$, for each scenario $\omega\in\Omega$. Constraint (5.81) states that the demand of the forward logistics $\tilde{q}_{ij}^{mt\omega}$

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that can be delivered via CCC or directly has to be satisfied for each supplier $i \in F$, for each construction site $j \in P$, in each period $t \in T$, for each material interested $m \in \breve{M}$, for each scenario $\omega \in \Omega$. Constraint (5.82) states that the demand of the reverse logistics $\tilde{r}_{ji}^{mt\omega}$ that can be delivered via CCC or directly has to be satisfied for each construction site $j \in P$, for each supplier $i \in F$, in each period $t \in T$, for each material interested $m \in \hat{M}$, for each scenario $\omega \in \Omega$. Constraint (5.83) and (5.84) guarantee that the capacity of each material in both forward and reverse direction is not exceeded in each CCC. Constraint (5.85) guarantees that the total capacity of each CCC is respected. Constraint (5.86) imposes a maximum number of CCCs to be opened. The domain of the variables is defined into (5.87)-(5.90).

5.2.5.2.2 Stochastic Multi Period Multi Material Reverse Direct with different set of materials Model: Two-stage formulation

5.2.5.2.2.1 I stage Model

The first stage model reports only the variables that are linked to the decision to be made before the realization of the stochastic variables, the $y_h, h \in D$. In the objective function one can find the cost of opening the CCCs and the recourse function, made of the weighted costs of the scenarios.

$$\min \sum_{h \in D} l_h y_h + \sum_{\omega \in \Omega} p_\omega \theta^\omega \tag{5.91}$$

$$\sum_{h \in D} y_h \leq B \tag{5.92}$$

$$y_h \in \{0,1\} \qquad h \in D \tag{5.93}$$

5.2.5.2.2.2 II stage Model

In the second stage one can find all the components of the model that depend on the scenarios. As for the first presented stochastic model, also this can produce optimality and feasibility cuts to be passed to the first stage in order to determine the optimal solution.

$$\begin{aligned} \theta^\omega = \min & \sum_{m \in M' \cup \breve{M}} \sum_{t \in T} \sum_{i \in F} \sum_{j \in P} \sum_{h \in D} (c_{ih} + c_{hj}) g_{ij}^{hmt\omega} + \\ & \sum_{m \in M'' \cup \hat{M}} \sum_{t \in T} \sum_{i \in F} \sum_{j \in P} \sum_{h \in D} (c_{jh} + c_{hi}) f_{ji}^{hmt\omega} + \\ & \sum_{m \in \breve{M}} \sum_{t \in T} \sum_{i \in F} \sum_{j \in P} d_{ij} x_{ij}^{mt\omega} + \sum_{m \in \hat{M}} \sum_{t \in T} \sum_{i \in F} \sum_{j \in P} d_{ji} w_{ji}^{mt\omega} \end{aligned} \tag{5.94}$$

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$$\sum_{h\in D} g_{ij}^{hmt\omega} = \tilde{q}_{ij}^{mt\omega} \qquad i\in F, j\in P, t\in T, m\in M' \tag{5.95}$$

$$\sum_{h\in D} f_{ji}^{hmt\omega} = \tilde{r}_{ji}^{mt\omega} \qquad i\in F, j\in P, t\in T, m\in M'' \tag{5.96}$$

$$x_{ij}^{mt\omega} + \sum_{h\in D} g_{ij}^{hmt\omega} = \tilde{q}_{ij}^{mt\omega} \qquad i\in F, j\in P, t\in T, m\in \breve{M} \tag{5.97}$$

$$w_{ji}^{mt\omega} + \sum_{h\in D} f_{ji}^{hmt\omega} = \tilde{r}_{ji}^{mt\omega} \qquad i\in F, j\in P, t\in T, m\in \hat{M} \tag{5.98}$$

$$\sum_{i\in F}\sum_{j\in P} g_{ij}^{hmt\omega} \le C_h^m y_h \qquad h\in D, t\in T, m\in M'\cup\breve{M} \tag{5.99}$$

$$\sum_{i\in F}\sum_{j\in P} f_{ji}^{hmt\omega} \le C_h^m y_h \qquad h\in D, t\in T, m\in M''\cup\hat{M} \tag{5.100}$$

$$\sum_{m\in M'\cup\breve{M}}\sum_{i\in F}\sum_{j\in P} g_{ij}^{hmt\omega} + \sum_{m\in M''\cup\hat{M}}\sum_{i\in F}\sum_{j\in P} f_{ji}^{hmt\omega} \le C_h y_h \qquad h\in D, t\in T \tag{5.101}$$

$$g_{ij}^{hmt\omega}, f_{ji}^{hmt\omega} \ge 0 \qquad i\in F, j\in P, h\in D, t\in T, m\in M \tag{5.102}$$

$$x_{ij}^{mt\omega} \ge 0 \qquad i\in F, j\in P, t\in T, m\in \breve{M} \tag{5.103}$$

$$w_{ji}^{mt\omega} \ge 0 \qquad i\in F, j\in P, t\in T, m\in \hat{M} \tag{5.104}$$

5.2.6 Inventory

In this section we define mathematical models that include Inventory of materials inseide the CCCs as a feature, and in particualr as a variable, I. In order to inlcude inventory, the following models are built on the multi period model.

Inventory is a benefit because increases flexibility of the models and makes easier to consider the inventory costs so to represent better reality.

5.2.6.1 Multi Period with Inventory Model

The *Multi Period with Inventory Model* includes the inventory variables I, that definnes the amount of material that can be stored into the CCCs. This amount has a relative cost that must be minimized.

$$\min \sum_{h\in D} l_h y_h + \sum_{t\in T}\sum_{i\in F}\sum_{j\in P}\sum_{h\in D}\left(c_{ih}\overline{g}_{ij}^{ht} + c_{hj}\underline{g}_{ij}^{ht}\right) + \sum_{t\in T'}\sum_{i\in F}\sum_{j\in P}\sum_{h\in D} b^h I_{ij}^{ht} \tag{5.105}$$

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$$\bar{g}_{ij}^{ht} + I_{ij}^{ht} = \underline{g}_{ij}^{ht} + I_{ij}^{ht+1}, i \in F, j \in P, h \in D, t \in T \qquad (5.106)$$

$$\sum_{h \in D} \underline{g}_{ij}^{ht} = q_{ij}^{t}, i \in F, j \in P, t \in T \qquad (5.107)$$

$$\sum_{i \in F} \sum_{j \in P} I_{ij}^{ht} \leq C_h y_h, h \in D, t \in T' \qquad (5.108)$$

$$\sum_{i \in F} \sum_{j \in P} \bar{g}_{ij}^{ht} \leq \breve{\kappa}_h y_h, h \in D, t \in T \qquad (5.109)$$

$$\sum_{i \in F} \sum_{j \in P} \underline{g}_{ij}^{ht} \leq \widehat{\kappa}_h y_h, h \in D, t \in T \qquad (5.110)$$

$$I_{ij}^{h0} = 0, i \in F, j \in P, h \in D \qquad (5.111)$$

$$\sum_{h \in D} y_h \leq B \qquad (5.112)$$

$$\bar{g}_{ij}^{ht}, \underline{g}_{ij}^{ht} \geq 0, i \in F, j \in P, h \in D, t \in T \qquad (5.113)$$

$$I_{ij}^{ht} \geq 0, i \in F, j \in P, h \in D, t \in T' \qquad (5.114)$$

$$y_h \in \{0,1\}, h \in D \qquad (5.115)$$

The objective function (5.105) is made of three components, the cost of openinf the CCCs, the material flows represnting the cost of transportation, and the cost of invnetoring material for each period.

In constraint (5.106) the flow consorveation of each CCC is guaranteed. Constraint (5.107) guarantees the material requests satisfaction. Constraint (5.108) states that if we open a certaain CCC than the amount of inventory sotored must respect the CCC capacity. Constraints (5.108) and (5.109) impose handling capacities on the entering and exiting flows in CCCs. Constraint (5.111) imposes a null amount of material stored into the CCC at the beginning of the period. In (5.112) we impose a maximum number of CCCs to be opened. In (5.113)-(5.115) the variables' domains are defined.

5.2.6.2 Multi Period with Inventory and Reverse logistics Model

The followign model is similar to the previous one, but includes the reverse logistics, and the inventory for reverse logistic materails, that are defined by the variable J. As for the other, the cost of the reverse logistics inventory must be minimized.

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$$
\begin{aligned}
\min & \sum_{h\in D} l_h y_h + \sum_{t\in T}\sum_{i\in F}\sum_{j\in P}\sum_{h\in D}(c_{ih}\bar{g}_{ij}^{ht} + c_{hj}\underline{g}_{ij}^{ht}) + \\
& \sum_{t\in T}\sum_{i\in F}\sum_{j\in P}\sum_{h\in D}(c_{jh}\underline{f}_{ji}^{ht} + c_{hi}\bar{f}_{ji}^{ht}) + \\
& \sum_{t\in T'}\sum_{i\in F}\sum_{j\in P}\sum_{h\in D}(b^h I_{ij}^{ht} + b^h J_{ji}^{ht})
\end{aligned}
\tag{5.116}
$$

$$\bar{g}_{ij}^{ht} + I_{ij}^{ht} = \underline{g}_{ij}^{ht} + I_{ij}^{ht+1}, i\in F, j\in P, h\in D, t\in T \tag{5.117}$$

$$\sum_{h\in D}\underline{g}_{ij}^{ht} = q_{ij}^{t}, i\in F, j\in P, t\in T \tag{5.118}$$

$$\underline{f}_{ji}^{ht} + J_{ji}^{ht} = \bar{f}_{ji}^{ht} + J_{ji}^{ht+1}, i\in F, j\in P, h\in D, t\in T \tag{5.119}$$

$$\sum_{h\in D}\bar{f}_{ji}^{ht} = r_{ji}^{t}, i\in F, j\in P, t\in T \tag{5.120}$$

$$\sum_{i\in F}\sum_{j\in P}(I_{ij}^{ht} + J_{ji}^{ht}) \le C_h y_h, h\in D, t\in T' \tag{5.121}$$

$$I_{ij}^{h0} = 0, i\in F, j\in P, h\in D \tag{5.122}$$

$$J_{ji}^{h0} = 0, i\in F, j\in P, h\in D \tag{5.123}$$

$$\sum_{i\in F}\sum_{j\in P}(\bar{g}_{ij}^{ht} + \underline{f}_{ji}^{ht}) \le \breve{\kappa}_h y_h, h\in D, t\in T \tag{5.124}$$

$$\sum_{i\in F}\sum_{j\in P}(\underline{g}_{ij}^{ht} + \bar{f}_{ji}^{ht}) \le \widehat{\kappa}_h y_h, h\in D, t\in T \tag{5.125}$$

$$\sum_{h\in D} y_h \le B \tag{5.126}$$

$$\bar{g}_{ij}^{ht}, \underline{g}_{ij}^{ht}, \bar{f}_{ji}^{ht}, \underline{f}_{ji}^{ht} \ge 0, i\in F, j\in P, h\in D, t\in T \tag{5.127}$$

$$I_{ij}^{ht}, J_{ji}^{ht} \ge 0, i\in F, j\in P, h\in D, t\in T' \tag{5.128}$$

$$y_h \in \{0,1\}, h\in D \tag{5.129}$$

The objective funtion (5.116) includes the cost of opening the CCCs, the material flows cost representing the transportation costs to be minimized, and the invenory for all kind of materials, whose cost must be minimized. In constraints (5.117) and (5.119) the flow conservation in the CCCs is guaranteed for the supplies and the reverse logistics materials. The constraint (5.118) and (5.120) guarantees the respect of the supply and reverse logistics demands. The initial inventories are set to zero in (5.122) and (5.123). Constraint (5.121) imposes that the amount af all materials into a CCC mus be lower than its capacity in

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case the CCC is opened. Constriants (5.124) and (5.125) impose a handling capacity in entrance and exit for the opened CCCs. Then a maximum number of CCCs is imposed.

5.2.6.3 Multi Period Multi Material with Inventory, Reverse logistics and Direct shipping Model

The following models includes also the possibility of deliver and dispose materials by making use odf direct shipping. This is guaranteed by the use of the variables x and w.

$$\begin{aligned}
&\min \sum_{h\in D} l_h y_h + \\
&\sum_{t\in T}\sum_{i\in F}\sum_{j\in P}\sum_{h\in D}\sum_{m\in M'\cup\breve{M}} (c_{ih}\overline{g}_{ij}^{hmt} + c_{hj}\underline{g}_{ij}^{hmt}) + \sum_{t\in T}\sum_{i\in F}\sum_{j\in P}\sum_{h\in D}\sum_{m\in M''\cup\hat{M}} (c_{jh}\underline{f}_{ji}^{hmt} + c_{hi}\overline{f}_{ji}^{hmt}) + \\
&\sum_{t\in T}\sum_{i\in F}\sum_{j\in P}\left(\sum_{m\in M'\cup\breve{M}} d_{ij}x_{ij}^{mt} + \sum_{m\in M''\cup\hat{M}} d_{ji}w_{ji}^{mt}\right) + \\
&\sum_{t\in T'}\sum_{i\in F}\sum_{j\in P}\sum_{h\in D}\left(\sum_{m\in M'\cup\breve{M}} b^h I_{ij}^{hmt} + \sum_{m\in M''\cup\hat{M}} b^h J_{ji}^{hmt}\right)
\end{aligned} \tag{5.130}$$

$$\overline{g}_{ij}^{hmt} + I_{ij}^{hmt} = \underline{g}_{ij}^{hmt} + I_{ij}^{hmt+1}, i\in F, j\in P, h\in D, t\in T, m\in M'\cup\breve{M} \tag{5.131}$$

$$\sum_{h\in D}\underline{g}_{ij}^{hmt} = q_{ij}^{mt}, i\in F, j\in P, t\in T, m\in M' \tag{5.132}$$

$$\sum_{h\in D}\underline{g}_{ij}^{hmt} + x_{ij}^{mt} = q_{ij}^{mt}, i\in F, j\in P, t\in T, m\in \breve{M} \tag{5.133}$$

$$\underline{f}_{ji}^{hmt} + J_{ji}^{hmt} = \overline{f}_{ji}^{hmt} + J_{ji}^{hmt+1}, i\in F, j\in P, h\in Dt\in T, m\in M''\cup\hat{M} \tag{5.134}$$

$$\sum_{h\in D}\overline{f}_{ji}^{hmt} = r_{ji}^{mt}, i\in F, j\in P, t\in T, m\in M'' \tag{5.135}$$

$$\sum_{h\in D}\overline{f}_{ji}^{hmt} + w_{ji}^{mt} = r_{ji}^{mt}, i\in F, j\in P, t\in T, m\in \hat{M} \tag{5.136}$$

$$\sum_{i\in F}\sum_{j\in P} I_{ij}^{hmt} \le C_h^m y_h, h\in D, t\in T', m\in M'\cup\breve{M} \tag{5.137}$$

$$\sum_{i\in F}\sum_{j\in P} J_{ji}^{hmt} \le C_h^m y_h, h\in D, t\in T', m\in M''\cup\hat{M} \tag{5.138}$$

$$\sum_{i\in F}\sum_{j\in P}\left(\sum_{m\in M'\cup\breve{M}} I_{ij}^{hmt} + \sum_{m\in M''\cup\hat{M}} J_{ji}^{hmt}\right) \le C_h y_h, h\in D, t\in T' \tag{5.139}$$

$$\sum_{i\in F}\sum_{j\in P}\left(\sum_{m\in M'\cup\breve{M}} \overline{g}_{ij}^{hmt} + \sum_{m\in M''\cup\hat{M}} \underline{f}_{ji}^{hmt}\right) \le \breve{\kappa}_h y_h, h\in D, t\in T \tag{5.140}$$

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$$\sum_{i\in F}\sum_{j\in P}\left(\sum_{m\in M'\cup\breve{M}}\underline{g}_{ij}^{hmt}+\sum_{m\in M''\cup\hat{M}}\overline{f}_{ji}^{hmt}\right)\leq\widehat{\kappa}_h y_h, h\in D, t\in T \qquad (5.141)$$

$$I_{ij}^{hm0}=0, i\in F, j\in P, h\in D, m\in M'\cup\breve{M} \qquad (5.142)$$

$$J_{ji}^{hm0}=0, i\in F, j\in P, h\in D, m\in M''\cup\hat{M} \qquad (5.143)$$

$$\sum_{h\in D}y_h\leq B \qquad (5.144)$$

$$\overline{g}_{ij}^{hmt}, \underline{g}_{ij}^{hmt}\geq 0, i\in F, j\in P, h\in D, t\in T, m\in M'\cup\breve{M} \qquad (5.145)$$

$$\overline{f}_{ji}^{hmt}, \underline{f}_{ji}^{hmt}\geq 0, i\in F, j\in P, h\in D, t\in T, m\in M''\cup\hat{M} \qquad (5.146)$$

$$x_{ij}^{mt}\geq 0, i\in F, j\in P, t\in T, m\in\breve{M} \qquad (5.147)$$

$$w_{ji}^{mt}\geq 0, i\in F, j\in P, t\in T, m\in\hat{M} \qquad (5.148)$$

$$I_{ij}^{hmt}\geq 0, i\in F, j\in P, h\in D, t\in T', m\in M'\cup\breve{M} \qquad (5.149)$$

$$J_{ji}^{hmt}\geq 0, i\in F, j\in P, h\in D, t\in T', m\in M''\cup\hat{M} \qquad (5.150)$$

$$y_h\in\{0,1\}, h\in D \qquad (5.151)$$

We describe here only the changes with respect to the previous model. The objective funtion includes a cost for direct shipping materials. Constraitns (5.133) and (5.136) allow the direct shipping for deliveries and reverse logistics.

5.2.6.4 Stochastic Multi Period Multi Material with Inventory, Reverse logistics and Direct shipping Model

The following model is similar to the *Multi Period Multi Material with Inventory, Reverse logistics and Direct shipping Model* where the stochastic component has been included.

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$$
\begin{aligned}
\min \quad & \sum_{h\in D} l_h y_h + \\
& \sum_{\omega\in\Omega} p_\omega \sum_{t\in T}\sum_{i\in F}\sum_{j\in P}\sum_{h\in D}\sum_{m\in M'\cup \breve{M}} \left(c_{ih}\overline{g}_{ij}^{hmt\omega} + c_{hj}\underline{g}_{ij}^{hmt\omega}\right) + \\
& \sum_{\omega\in\Omega} p_\omega \sum_{t\in T}\sum_{i\in F}\sum_{j\in P}\sum_{h\in D}\sum_{m\in M''\cup \hat{M}} \left(c_{jh}\underline{f}_{ji}^{hmt\omega} + c_{hi}\overline{f}_{ji}^{hmt\omega}\right) + \\
& \sum_{\omega\in\Omega} p_\omega \sum_{t\in T}\sum_{i\in F}\sum_{j\in P}\left(\sum_{m\in M'\cup \breve{M}} d_{ij}x_{ij}^{mt\omega} + \sum_{m\in M''\cup \hat{M}} d_{ji}w_{ji}^{mt\omega}\right) + \\
& \sum_{\omega\in\Omega} p_\omega \sum_{t\in T'}\sum_{i\in F}\sum_{j\in P}\sum_{h\in D}\left(\sum_{m\in M'\cup \breve{M}} b^h I_{ij}^{hmt\omega} + \sum_{m\in M''\cup \hat{M}} b^h J_{ji}^{hmt\omega}\right)
\end{aligned}
\tag{5.152}
$$

$$\overline{g}_{ij}^{hmt\omega} + I_{ij}^{hmt\omega} = \underline{g}_{ij}^{hmt\omega} + I_{ij}^{hmt+1\omega}, i\in F, j\in P, h\in D, t\in T, m\in M'\cup \breve{M}, \omega\in\Omega \tag{5.153}$$

$$\sum_{h\in D}\underline{g}_{ij}^{hmt\omega} = q_{ij}^{mt\omega}, i\in F, j\in P, t\in T, m\in M', \omega\in\Omega \tag{5.154}$$

$$\sum_{h\in D}\underline{g}_{ij}^{hmt\omega} + x_{ij}^{mt\omega} = q_{ij}^{mt\omega}, i\in F, j\in P, t\in T, m\in \breve{M}, \omega\in\Omega \tag{5.155}$$

$$\underline{f}_{ji}^{hmt\omega} + J_{ji}^{hmt\omega} = \overline{f}_{ji}^{hmt\omega} + J_{ji}^{hmt+1\omega}, i\in F, j\in P, h\in D, t\in T, m\in M''\cup \hat{M}, \omega\in\Omega \tag{5.156}$$

$$\sum_{h\in D}\overline{f}_{ji}^{hmt\omega} = r_{ji}^{mt\omega}, i\in F, j\in P, t\in T, m\in M'', \omega\in\Omega \tag{5.157}$$

$$\sum_{h\in D}\overline{f}_{ji}^{hmt\omega} + w_{ji}^{mt\omega} = r_{ji}^{mt\omega}, i\in F, j\in P, t\in T, m\in \hat{M}, \omega\in\Omega \tag{5.158}$$

$$\sum_{i\in F}\sum_{j\in P} I_{ij}^{hmt\omega} \le C_h^m y_h, h\in D, t\in T', m\in M'\cup \breve{M}, \omega\in\Omega \tag{5.159}$$

$$\sum_{i\in F}\sum_{j\in P} J_{ji}^{hmt\omega} \le C_h^m y_h, h\in D, t\in T', m\in M''\cup \hat{M}, \omega\in\Omega \tag{5.160}$$

$$\sum_{i\in F}\sum_{j\in P}\left(\sum_{m\in M'\cup \breve{M}} I_{ij}^{hmt\omega} + \sum_{m\in M''\cup \hat{M}} J_{ji}^{hmt\omega}\right) \le C_h y_h, h\in D, t\in T', \omega\in\Omega \tag{5.161}$$

$$\sum_{i\in F}\sum_{j\in P}\left(\sum_{m\in M'\cup \breve{M}} \overline{g}_{ij}^{hmt\omega} + \sum_{m\in M''\cup \hat{M}} \underline{f}_{ji}^{hmt\omega}\right) \le \breve{\kappa}_h y_h, h\in D, t\in T, \omega\in\Omega \tag{5.162}$$

$$\sum_{i\in F}\sum_{j\in P}\left(\sum_{m\in M'\cup \breve{M}} \underline{g}_{ij}^{hmt\omega} + \sum_{m\in M''\cup \hat{M}} \overline{f}_{ji}^{hmt\omega}\right) \le \widehat{\kappa}_h y_h, h\in D, t\in T, \omega\in\Omega \tag{5.163}$$

$$I_{ij}^{hm0\omega} = 0, i\in F, j\in P, h\in D, m\in M'\cup \breve{M}, \omega\in\Omega \tag{5.164}$$

$$J_{ji}^{hm0\omega} = 0, i\in F, j\in P, h\in D, m\in M''\cup \hat{M}, \omega\in\Omega \tag{5.165}$$

$$\sum_{h\in D} y_h \le B \qquad (5.166)$$

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$$\overline{g}_{ij}^{hmt\omega}, \underline{g}_{ij}^{hmt\omega} \geq 0, i \in F, j \in P, h \in D, t \in T, m \in M' \cup \breve{M}, \omega \in \Omega \qquad (5.167)$$

$$\overline{f}_{ji}^{hmt\omega}, \underline{f}_{ji}^{hmt\omega} \geq 0, i \in F, j \in P, h \in D, t \in T, m \in M'' \cup \hat{M}, \omega \in \Omega \qquad (5.168)$$

$$x_{ij}^{mt\omega} \geq 0, i \in F, j \in P, t \in T, m \in \breve{M}, \omega \in \Omega \qquad (5.169)$$

$$w_{ji}^{mt\omega} \geq 0, i \in F, j \in P, t \in T, m \in \hat{M}, \omega \in \Omega \qquad (5.170)$$

$$I_{ij}^{hmt\omega} \geq 0, i \in F, j \in P, h \in D, t \in T', m \in M' \cup \breve{M}, \omega \in \Omega \qquad (5.171)$$

$$J_{ji}^{hmt\omega} \geq 0, i \in F, j \in P, h \in D, t \in T', m \in M'' \cup \hat{M}, \omega \in \Omega \qquad (5.172)$$

$$y_h \in \{0,1\}, h \in D \qquad (5.173)$$

5.2.7 CCC Sizing

In order to define the CCCs' szing, we can operate in two ways.

5.2.7.1 From the Inventory variables

We can consider the summation of all the optimal inventory variables in the two following ways:

$$CAP_1 = max_{t \in T', \omega \in \Omega} \left\{ \sum_{i \in F} \sum_{j \in P} \sum_{m \in M' \cup \breve{M}} I_{ij}^{*hmt\omega} + \sum_{i \in F} \sum_{j \in P} \sum_{m \in M'' \cup \hat{M}} J_{ji}^{*hmt\omega} \right\} \qquad (5.171)$$

$$CAP_2 = \sum_{\omega \in \Omega} p_\omega \cdot \max_{t \in T'} \left\{ \sum_{i \in F} \sum_{j \in P} \sum_{m \in M' \cup \breve{M}} I_{ij}^{*hmt\omega} + \sum_{i \in F} \sum_{j \in P} \sum_{m \in M'' \cup \hat{M}} J_{ji}^{*hmt\omega} \right\} \qquad (5.172)$$

5.2.7.2 Defining Capacity variables

We can consider the capacity of all the CCCs as a decision variable $\mathrm{C}_h, h \in D$, and insert the following constraints:

$$\sum_{i \in F} \sum_{j \in P} \left(\sum_{m \in M' \cup \breve{M}} I_{ij}^{hmt\omega} + \sum_{m \in M'' \cup \hat{M}} J_{ji}^{hmt\omega} \right) \leq \mathrm{C}_h, h \in D, t \in T', \omega \in \Omega \qquad (5.173)$$

$$\mathrm{C}_h \leq C_h y_h, h \in D \qquad (5.174)$$

The capacity can depend also on the scenario, if it is the case.

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6 Two-echelon Allocation Problems

Once the location and the size of the CCC/CCCs have been decided, a shorter time horizon can be considered. The realization of the scenario has already happened so we can treat the problem for only one scenario that includes only the construction sites that are opened during the selected period. The decisions to be made at this point are of tactical type, i.e. the allocation of the construction sites to the CCC/CCCs or the allocation of the suppliers to the CCC/CCCs.

In the following, we firstly propose the mathamatical notaion and thus the set of MILP models.

6.1 Notation

The Notation is reported divided into sets, parameters, and variables.

Sets	
Symbol	**Meaning**
A	Set of arcs
P	Set of construction sites
D	Set of CCCs
F	Set of suppliers (and/or dumpsites)
V	Set of vertices $(V = P \cup D \cup F)$
M'	Set of materials that cannot be directly shipped from suppliers to sites
M''	Set of materials that cannot be directly shipped from sites to suppliers / dumpsites
$\breve{M}$	Set of materials that can also be directly shipped from suppliers to sites
$\hat{M}$	Set of materials that can also be shipped from sites to suppliers / dumpsites
M	Set of materials, $M = M' \cup M'' \cup \breve{M} \cup \hat{M}$ (not for all the following models the subsets are specified or not null)
T	Set of periods
T'	Set of periods plus one, $T' = T \cup \{\|T\|+1\}$
M	Set of materials $(M = M' \cup M'' \cup \breve{M} \cup \widehat{M})$

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Parameters	
Symbol	**Meaning**
l_{hj}	Cost of serving the site $j \in P$ from CCC $h \in D$
l_{ih}	Cost of serving the supplier $i \in F$ from CCC $h \in D$
c_{ij}^{k}	Cost of traveling between i and j with vehicle k
d_{ij}	Cost of direct shipping between i and j
b^{h}	Cost of inventory in CCC $h \in D$
q_{ij}^{mt}	Request of material $m \in M$ at period $t \in T$ in site $j \in P$ from vertex $i \in F$
r_{ji}^{mt}	Request of material $m \in M$ at period $t \in T$ from site $j \in P$ to vertex $i \in F$
C_{h}	Total capacity of CCC $h \in D$
C_{h}^{m}	Capacity for material $m \in M$ at the CCC $h \in D$
$\breve{\kappa}_{h}$	Capacity for incoming materials operations at the CCC $h \in D$
$\hat{\kappa}_{h}$	Capacity for exiting materials operations at the CCC $h \in D$

Variables	
Symbol	**Meaning**
y_{hj}	Equals1 if serving the site $j \in P$ from CCC $h \in D$, 0 otherwise
y_{ih}	Equals1 if serving the supplier $i \in F$ from CCC $h \in D$, 0 otherwise
x_{ij}^{mt}	Flow of material directly shipped from supplier $i \in F$ to site $j \in P$ of material $m \in M$ during period $t \in T$
w_{ji}^{mt}	Flow of material directly shipped from site $j \in P$ to supplier $i \in F$ of material $m \in M$ during period $t \in T$
$\overline{g}_{ij}^{hmt}$	Flow of material $m \in M' \cup \breve{M}$ from supplier $i \in F$ to CCC $h \in D$ direct to site $j \in P$ in period $t \in T$

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$\underline{g}_{ij}^{hmt}$	Flow of material $m \in M' \cup \breve{M}$ from CCC $h \in D$ to site $j \in P$ coming from supplier $i \in F$ in period $t \in T$
$\underline{f}_{ji}^{hmt}$	Flow of material $m \in M'' \cup \hat{M}$ from site $j \in P$ to CCC $h \in D$ direct to dumpsite $i \in F$ in period $t \in T$
$\overline{f}_{ji}^{hmt}$	Flow of material $m \in M'' \cup \hat{M}$ from CCC $h \in D$ to dumpsite $i \in F$ coming from site $j \in P$ in period $t \in T$
I_{ij}^{hmt}	Inventory of material $m \in M' \cup \breve{M}$ in CCC $h \in D$ coming from supplier $i \in F$ to site $j \in P$ in period $t \in T$
J_{ji}^{hmt}	Inventory of reverse logistics material $m \in M'' \cup \hat{M}$ in CCC $h \in D$ coming from site $j \in P$ to supplier/dumpsite $i \in F$ to site in period $t \in T$

6.2 Mathematical Models

The following models intend to allocate the CCC to construction site, in the first case, and to the suppliers, in the second case. This is a tactical decision and it is realistic that a contract is signed just with one CCC.

In both versions we want to minimize the allocation cost, and some another cost components such as transportation and inventory costs. This guarantees the response to material requests and the capacities of the supply chain.

6.2.1 Allocation to construction sites

In this first model we decide to allocate the construction site to a consolidation centre.

$$
\begin{aligned}
\min \quad & \sum_{h \in D} \sum_{j \in P} l_{hj} y_{hj} \\
& \sum_{t \in T} \sum_{i \in F} \sum_{j \in P} \sum_{h \in D} \sum_{m \in M' \cup \breve{M}} \left(c_{ih} \overline{g}_{ij}^{hmt} + c_{hj} \underline{g}_{ij}^{hmt}\right) + \\
& \sum_{t \in T} \sum_{i \in F} \sum_{j \in P} \sum_{h \in D} \sum_{m \in M'' \cup \hat{M}} \left(c_{jh} \underline{f}_{ji}^{hmt} + c_{hi} \overline{f}_{ji}^{hmt}\right) + \\
& \sum_{t \in T} \sum_{i \in F} \sum_{j \in P} \left(\sum_{m \in M' \cup \breve{M}} d_{ij} x_{ij}^{mt} + \sum_{m \in M'' \cup \hat{M}} d_{ji} w_{ji}^{mt} \right) + \\
& \sum_{t \in T'} \sum_{i \in F} \sum_{j \in P} \sum_{h \in D} \left(\sum_{m \in M' \cup \breve{M}} b^h I_{ij}^{hmt} + \sum_{m \in M'' \cup \hat{M}} b^h J_{ji}^{hmt} \right)
\end{aligned} \tag{6.1}
$$

$$
\overline{g}_{ij}^{hmt} + I_{ij}^{hmt} = \underline{g}_{ij}^{hmt} + I_{ij}^{hmt+1}, i \in F, j \in P, h \in D, t \in T, m \in M' \cup \breve{M} \tag{6.2}
$$

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$$\underline{g}_{ij}^{hmt} = q_{ij}^{mt} y_{hj}, i \in F, j \in P, t \in T, m \in M', h \in D \tag{6.3}$$

$$\sum_{h \in D} \underline{g}_{ij}^{hmt} + x_{ij}^{mt} = q_{ij}^{mt}, i \in F, j \in P, t \in T, m \in \breve{M} \tag{6.4}$$

$$\underline{g}_{ij}^{hmt} \leq \left(\sum_{i \in F} \sum_{j \in P} \sum_{t \in T} \sum_{m \in M' \cup \breve{M}} q_{ij}^{mt} + 1 \right) y_{hj}, i \in F, j \in P, t \in T, m \in \breve{M}, h \in D \tag{6.5}$$

$$\underline{f}_{ji}^{hmt} + J_{ji}^{hmt} = \overline{f}_{ji}^{hmt} + J_{ji}^{hmt+1}, i \in F, j \in P, h \in D, t \in T, m \in M'' \cup \hat{M} \tag{6.6}$$

$$\overline{f}_{ji}^{hmt} = r_{ji}^{mt} y_{hj}, i \in F, j \in P, t \in T, m \in M'', h \in D \tag{6.7}$$

$$\sum_{h \in D} \overline{f}_{ji}^{hmt} + w_{ji}^{mt} = r_{ji}^{mt}, i \in F, j \in P, t \in T, m \in \hat{M}, h \in D \tag{6.8}$$

$$\overline{f}_{ji}^{hmt} \leq \left(\sum_{i \in F} \sum_{j \in P} \sum_{t \in T} \sum_{m \in M'' \cup \hat{M}} r_{ji}^{mt} + 1 \right) y_{hj}, i \in F, j \in P, t \in T, m \in \hat{M}, h \in D \tag{6.9}$$

$$\sum_{i \in F} I_{ij}^{hmt} \leq C_h^m y_{hj}, j \in P, h \in D, t \in T', m \in M' \cup \breve{M} \tag{6.10}$$

$$\sum_{i \in F} J_{ji}^{hmt} \leq C_h^m y_{hj}, j \in P, h \in D, t \in T', m \in M'' \cup \hat{M} \tag{6.11}$$

$$\sum_{i \in F} \sum_{j \in P} I_{ij}^{hmt} \leq C_h^m, h \in D, t \in T', m \in M' \cup \breve{M} \tag{6.12}$$

$$\sum_{i \in F} \sum_{j \in P} J_{ji}^{hmt} \leq C_h^m, h \in D, t \in T', m \in M'' \cup \hat{M} \tag{6.13}$$

$$\sum_{i \in F} \sum_{j \in P} \left(\sum_{m \in M' \cup \breve{M}} I_{ij}^{hmt} + \sum_{m \in M'' \cup \hat{M}} J_{ji}^{hmt} \right) \leq C_h, h \in D, t \in T' \tag{6.14}$$

$$\sum_{i \in F} \sum_{j \in P} \left(\sum_{m \in M' \cup \breve{M}} \overline{g}_{ij}^{hmt} + \sum_{m \in M'' \cup \hat{M}} \underline{f}_{ji}^{hmt} \right) \leq \breve{\kappa}_h, h \in D, t \in T \tag{6.15}$$

$$\sum_{i \in F} \sum_{j \in P} \left(\sum_{m \in M' \cup \breve{M}} \underline{g}_{ij}^{hmt} + \sum_{m \in M'' \cup \hat{M}} \overline{f}_{ji}^{hmt} \right) \leq \hat{\kappa}_h, h \in D, t \in T \tag{6.16}$$

$$I_{ij}^{hm0} = 0, i \in F, j \in P, h \in D, m \in M' \cup \breve{M} \tag{6.17}$$

$$J_{ji}^{hm0} = 0, i \in F, j \in P, h \in D, m \in M'' \cup \hat{M} \tag{6.18}$$

$$\sum_{h \in D} y_{hj} = 1, j \in P \tag{6.19}$$

$$\overline{g}_{ij}^{hmt}, \underline{g}_{ij}^{hmt} \geq 0, i \in F, j \in P, h \in D, t \in T, m \in M' \cup \breve{M} \tag{6.20}$$

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$$\overline{f}_{ji}^{hmt}, \underline{f}_{ji}^{hmt} \geq 0, i \in F, j \in P, h \in D, t \in T, m \in M'' \cup \hat{M} \quad (6.21)$$

$$I_{ij}^{hmt} \geq 0, i \in F, j \in P, h \in D, t \in T', m \in M' \cup \breve{M} \quad (6.22)$$

$$J_{ji}^{hmt} \geq 0, i \in F, j \in P, h \in D, t \in T', m \in M'' \cup \hat{M} \quad (6.23)$$

$$y_{hj} \in \{0,1\}, h \in D, j \in P \quad (6.24)$$

The objective function is made of five components: the cost of allocating the construction sites to the CCCs; the cost of material supply and reverse logistics; the cost of direct shipping; the cost of inventory. Constraints (6.2) and (6.6) guarantee the flow conservation inside the CCCs. Constraint (6.3) defines the supply of material is performed when needed from the allocated CCC. Constraint (6.4) guarantees the supply for those materials that can be directly shipped. Constraint (6.5) defines a limit for the materials that can be shipped directly or via CCC, if a part of the material is shipped via CCC this can be provided only via the allocated CCC. Similarly to the previous constraints, (6.7), (6.8), (6.9), impose the same for the reverse logistics flows. Constraints (6.10)-(6.13) set a material capacity for the materials inventory inside the CCC for those goods that must be supplied or collected at the allocated sites. In constraint (6.14) is imposed a total inventory capacity for each of the CCCs. Constraint (6.15) and (6.16) impose an inbound and outbound capacities for operations in the CCCs. Constraints (6.17) and (6.18) impose a null quantity soterd into the CCC at the beginning of the time horizon. Constraint (6.19) imposes that one construction site is allocated to one and only one CCC. Constraints (6.20)-(6.24) define the variables.

6.2.2 Allocation to suppliers

In this model, similar to the previous one, we consider to allocate the suppliers to a consolidation center.

$$\begin{aligned}
\min \quad & \sum_{i \in F} \sum_{h \in D} l_i^h y_{ih} \\
& \sum_{t \in T} \sum_{i \in F} \sum_{j \in P} \sum_{h \in D} \sum_{m \in M' \cup \breve{M}} \left(c_{ih} \overline{g}_{ij}^{hmt} + c_{hj} \underline{g}_{ij}^{hmt}\right) + \\
& \sum_{t \in T} \sum_{i \in F} \sum_{j \in P} \sum_{h \in D} \sum_{m \in M'' \cup \hat{M}} \left(c_{jh} \underline{f}_{ji}^{hmt} + c_{hi} \overline{f}_{ji}^{hmt}\right) + \\
& \sum_{t \in T} \sum_{i \in F} \sum_{j \in P} \left(\sum_{m \in M' \cup \breve{M}} d_{ij} x_{ij}^{mt} + \sum_{m \in M'' \cup \hat{M}} d_{ji} w_{ji}^{mt} \right) + \\
& \sum_{t \in T'} \sum_{i \in F} \sum_{j \in P} \sum_{h \in D} \left(\sum_{m \in M' \cup \breve{M}} b^h I_{ij}^{hmt} + \sum_{m \in M'' \cup \hat{M}} b^h J_{ji}^{hmt} \right)
\end{aligned} \quad (6.23)$$

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$$\overline{g}_{ij}^{hmt} + I_{ij}^{hmt} = \underline{g}_{ij}^{hmt} + I_{ij}^{hmt+1}, i \in F, j \in P, h \in D, t \in T, m \in M' \cup \breve{M} \tag{6.24}$$

$$\underline{g}_{ij}^{hmt} = q_{ij}^{mt} y_{hi}, i \in F, j \in P, t \in T, m \in M', h \in D \tag{6.25}$$

$$\sum_{h \in D} \underline{g}_{ij}^{hmt} + x_{ij}^{mt} = q_{ij}^{mt}, i \in F, j \in P, t \in T, m \in \breve{M} \tag{6.26}$$

$$\underline{g}_{ij}^{hmt} \leq \left(\sum_{i \in F} \sum_{j \in P} \sum_{t \in T} \sum_{m \in M' \cup \breve{M}} q_{ij}^{mt} + 1 \right) y_{hi}, i \in F, j \in P, t \in T, m \in \breve{M}, h \in D \tag{6.27}$$

$$\underline{f}_{ji}^{hmt} + J_{ji}^{hmt} = \overline{f}_{ji}^{hmt} + J_{ji}^{hmt+1}, i \in F, j \in P, h \in D, t \in T, m \in M'' \cup \hat{M} \tag{6.28}$$

$$\overline{f}_{ji}^{hmt} = r_{ji}^{mt} y_{ih}, i \in F, j \in P, t \in T, m \in M'', h \in D \tag{6.29}$$

$$\sum_{h \in D} \overline{f}_{ji}^{hmt} + w_{ji}^{mt} = r_{ji}^{mt}, i \in F, j \in P, t \in T, m \in \hat{M}, h \in D \tag{6.30}$$

$$\overline{f}_{ji}^{hmt} \leq \left(\sum_{i \in F} \sum_{j \in P} \sum_{t \in T} \sum_{m \in M'' \cup \hat{M}} r_{ji}^{mt} + 1 \right) y_{ih}, i \in F, j \in P, t \in T, m \in \hat{M}, h \in D \tag{6.31}$$

$$\sum_{j \in P} I_{ij}^{hmt} \leq C_h^m y_{ih}, i \in F, h \in D, t \in T', m \in M' \cup \breve{M} \tag{6.32}$$

$$\sum_{j \in P} J_{ji}^{hmt} \leq C_h^m y_{ih}, i \in F, h \in D, t \in T', m \in M'' \cup M \tag{6.33}$$

$$\sum_{i \in F} \sum_{j \in P} I_{ij}^{hmt} \leq C_h^m, h \in D, t \in T', m \in M' \cup \breve{M} \tag{6.34}$$

$$\sum_{i \in F} \sum_{j \in P} J_{ji}^{hmt} \leq C_h^m, h \in D, t \in T', m \in M'' \cup M \tag{6.35}$$

$$\sum_{i \in F} \sum_{j \in P} \left(\sum_{m \in M' \cup \breve{M}} I_{ij}^{hmt} + \sum_{m \in M'' \cup \hat{M}} J_{ji}^{hmt} \right) \leq C_h, h \in D, t \in T' \tag{6.36}$$

$$\sum_{i \in F} \sum_{j \in P} \left(\sum_{m \in M' \cup \breve{M}} \overline{g}_{ij}^{hmt} + \sum_{m \in M'' \cup \hat{M}} \underline{f}_{ji}^{hmt} \right) \leq \breve{\kappa}_h, h \in D, t \in T \tag{6.37}$$

$$\sum_{i \in F} \sum_{j \in P} \left(\sum_{m \in M' \cup \breve{M}} \underline{g}_{ij}^{hmt} + \sum_{m \in M'' \cup \hat{M}} \overline{f}_{ji}^{hmt} \right) \leq \hat{\kappa}_h, h \in D, t \in T \tag{6.38}$$

$$I_{ij}^{hm0} = 0, i \in F, j \in P, h \in D, m \in M' \cup \breve{M} \tag{6.39}$$

$$J_{ji}^{hm0} = 0, i \in F, j \in P, h \in D, m \in M'' \cup \hat{M} \tag{6.40}$$

$$\sum_{h \in D} y_{ih} = 1, j \in F \tag{6.41}$$

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$$\overline{g}_{ij}^{hmt}, \underline{g}_{ij}^{hmt} \geq 0, i \in F, j \in P, h \in D, t \in T, m \in M' \cup \breve{M} \quad (6.42)$$

$$\overline{f}_{ji}^{hmt}, \underline{f}_{ji}^{hmt} \geq 0, i \in F, j \in P, h \in D, t \in T, m \in M'' \cup \hat{M} \quad (6.43)$$

$$I_{ij}^{hmt} \geq 0, i \in F, j \in P, h \in D, t \in T', m \in M' \cup \breve{M} \quad (6.44)$$

$$J_{ji}^{hmt} \geq 0, i \in F, j \in P, h \in D, t \in T', m \in M'' \cup \hat{M} \quad (6.45)$$

$$y_{ih} \in \{0,1\}, h \in D, i \in F \quad (6.46)$$

This model is very similar to the previous one and the meaning of the constraints reflects the previous ones. Let us focus on the objective function, where the cost of allocation depends on the allocation of suppliers to the CCCs. Moreover, constraint (6.39) imposes that each supplier is allocated to one and only one CCCs.

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7 Capacitated Vehicle Routing Problem

Once the allocation of suppliers or construction sites to each CCC has been done, the focus can be moved to a more operational activity, which is the supply and collection of materials from their starting to their ending point.

In the following, we firstly propose the mathamatical notaion and thus the set of MILP models.

7.1 Notation

The Notation is reported divided into sets, parameters, and variables.

Sets	
Symbol	**Meaning**
V	Set of vertices, where 0 is the CCC
A	Set of arcs
K	Set of vehicles
M	Set of materials $(M = M' \cup M'')$.

Parameters	
Symbol	**Meaning**
c_{ij}^k	Cost of traveling between i and j with vehicle k
l^k	Cost of using a vehicle $k \in K$
q_i^m	Request of material $m \in M$ from vertex $i \in V \setminus \{0\}$
Q^k	Capacity of the vehicle $k \in K$

Variables	
Symbol	**Meaning**
x_{ij}^k	Equals 1 if the arc $(i, j) \in A$ is used by vehicle $k \in K$, 0 otherwise
f_{ij}^{mk}	Flow of material $m \in M$ from $i \in V$ to $j \in V$ on vehicle $k \in K$
y_{im}^k	Equals 1 if the request of vertex $i \in V$ of material $m \in M$ is delivered by vehicle $k \in K$, 0 otherwise

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7.2 Mathematical Model

This model is made to take the operational day-by-day routing decision in order to minimize the traveling and vehicle costs, responding to the material requests and respecting vehicles' capacity. Having to take into account the day-by-day activities the multi period feature is not involved into this model. The model is defined for material supply in the second echelon, but we can apply it to the material collection in the first echelon, to the reverse logistic in both the first and second echelons, by changing the meaning of q_i^m.

$$\min \sum_{i\in V}\sum_{j\in V}\sum_{k\in K} c_{ij}^k x_{ij}^k + \sum_{j\in V}\sum_{k\in K} l^k x_{0j}^k \tag{7.1}$$

$$\sum_{i\in V} x_{ij}^k = \sum_{i\in V} x_{ji}^k,\ j\in V, k\in K \tag{7.2}$$

$$\sum_{k\in K}\sum_{i\in V} x_{ij}^k \le 1,\ j\in V\setminus\{0\} \tag{7.3}$$

$$\sum_{j\in V} f_{ji}^{mk} - \sum_{j\in V} f_{ij}^{mk} = q_i^m y_{im}^k, i\in V\setminus\{0\}, m\in M, k\in K \tag{7.4}$$

$$\sum_{k\in K} y_{im}^k = 1, i\in V\setminus\{0\}, m\in M \mid q_i^m > 0 \tag{7.5}$$

$$\sum_{m\in M} f_{ij}^{mk} \le Q^k x_{ij}^k, (i,j)\in A, k\in K \tag{7.6}$$

$$x_{ij}^k \in \{0,1\}, i\in V, j\in V, k\in K \tag{7.7}$$

$$y_{im}^k \in \{0,1\}, i\in V, m\in M, k\in K \tag{7.8}$$

$$f_{ij}^{mk} \ge 0, i, j\in V, m\in M, k\in K \tag{7.9}$$

The objective function (7.1) minimizes the traveling costs (as in the first component) and the number of used vehicles (as in the second component). Constraint (7.2) states that if a vehicle enters a customer it must also leave the customer. For the depot (0) the constraint means that the vehicles must return to the depot if they leave it. Constraint (7.3) states that only one vehicle can enter a vertex and maximum once. Constraint (7.4) assures the delivery of each required material on one vehicle. Constraint (7.5) imposes that one and only one vehicle responds to one request q_i^m. Constraints (7.6) impose a maximum capacity on each vehicle.

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8 Inventory vs Transport Problems

The following models take into account the delivery of material from suppliers to construction site via CCC. The decision is to find the best trade-off between the inventory costs and the transportation costs. These models are considered for those scenarios that include just one CCC and one site.

8.1 Notation

Sets	
Symbol	**Meaning**
A	Set of arcs
P	Set of construction sites
F	Set of suppliers (and/or dumpsites)
V	Set of vertices, $V = P \cup F$
K	Set of vehicles
M	Set of materials
$M(k)$	Set of materials that can be carried on vehicle $k \in K$
T	Set of periods

Parameters	
Symbol	**Meaning**
c_j^k	Cost of traveling between CCC and $j \in P$ with vehicle $k \in K$
b	Cost of inventory
γ	Cost of storage on site before request time
q_{ij}^{mt}	Request of material $m \in M$ at period $t \in T$ in site $j \in P$ from vertex $i \in F$
r_{ji}^{mt}	Request to dispose material $m \in M$ at period $t \in T$ from site $j \in P$ to vertex $i \in F$
Q^k	Capacity of the vehicle $k \in K$
C^m	Capacity for material $m \in M$ at the CCC

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$\bar{x}_{ij}^{mt}$	Fixed flow of material coming from supplier $i \in F$ to CCC for site $j \in P$ of material $m \in M$ during period $t \in T$

Variables	
Symbol	**Meaning**
y_j^{kt}	Number of vehicles $k \in K$, leaving the CCC to site $j \in P$ during period $t \in T$
g_{ij}^{mtk}	Flow of material $m \in M$ from CCC coming from supplier $i \in F$ to $j \in P$ during period $t \in T$ on vehicle of type $k \in K$
f_{ji}^{mtk}	Flow of material $m \in M$ to CCC coming from site $j \in P$ to $i \in F$ during period $t \in T$ on vehicle of type $k \in K$
I_{ij}^{mt}	Inventory of material $m \in M$ in CCC coming from supplier $i \in F$ to site $j \in P$ in period $t \in T$
z_{ij}^{mt}	Material $m \in M$ coming from supplier $i \in F$ to $j \in P$ during period $t \in T$ stored at the construction site

8.2 Mathematical Models

8.2.1 Basic Model

In this model we choose the correct number and type of vehicles to minimize the transportation and inventory costs responding to the material requests and respecting the given capacities. The inventory into the CCC is considered but the related decision is very limited.

$$\min \sum_{j\in P}\sum_{t\in T}\left(\sum_{k\in K} 2c_j^k y_j^{kt} + \sum_{i\in F}\sum_{m\in M} bI_{ij}^{mt}\right) \quad (8.6)$$

$$\bar{x}_{ij}^{mt} + I_{ij}^{mt} = I_{ij}^{mt+1} + \sum_{k\in K|m\in M(k)} g_{ij}^{mtk}, i\in F, j\in P, m\in M, t\in T \quad (8.7)$$

$$\sum_{i\in F}\sum_{m\in M(k)} g_{ij}^{mtk} \le Q^k y_j^{kt}, j\in P, k\in K, t\in T \quad (8.8)$$

$$\sum_{k\in K|m\in M(k)} g_{ij}^{mtk} = q_{ij}^{mt}, i\in F, j\in P, t\in T, m\in M \quad (8.9)$$

$$\sum_{i\in F}\sum_{j\in P} I_{ij}^{mt} \le C^m, m\in M, t\in T \quad (8.10)$$

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$$g_{ij}^{mtk} \geq 0, i \in F, j \in P, m \in M, k \in K, t \in T \tag{8.11}$$

$$I_{ij}^{mt} \geq 0, i \in F, j \in P, m \in M, t \in T \tag{8.12}$$

$$y_j^{kt} \in N, j \in P, k \in K, t \in T \tag{8.13}$$

In the objective function (8.6) we consider two components: the cost of transportation between the CCC and the construction site (in both directions) and the cost of inventory. Constraint (8.7) guarantees the flow conservation into the CCC. Constraint (8.8) sets the number and type of required vehicles to transport the material to the construction site. Constraint (8.9) ensures the correct amount of material is delivered to the construction sites. In (8.10) the inventory is constrained by a capacity. In (8.11)-(8.13) we define the variables.

8.2.2 Model with possible anticipation

In this model we add a novel feature that considers the fact that we can decide when to supply materials to the construction site. We can anticipate the suypply, maybe in order to increase the vehicles' load rate, but by paying the fact that the material must be storaged into the cnstruction site.

$$\min \sum_{j \in P} \sum_{t \in T} \left(\sum_{k \in K} 2 c_j^k y_j^{kt} + \sum_{i \in F} \sum_{m \in M} \left(b I_{ij}^{mt} + \gamma z_{ij}^{mt} \right) \right) \tag{8.14}$$

$$\bar{x}_{ij}^{mt} + I_{ij}^{mt} = I_{ij}^{mt+1} + \sum_{k \in K | m \in M(k)} g_{ij}^{mtk}, i \in F, j \in P, m \in M, t \in T \tag{8.15}$$

$$\sum_{i \in F} \sum_{m \in M(k)} g_{ij}^{mtk} \leq Q^k y_j^{kt}, j \in P, k \in K, t \in T \tag{8.16}$$

$$\sum_{k \in K | m \in M(k)} \sum_{\tau=0}^{t} g_{ij}^{m\tau k} \geq q_{ij}^{mt}, i \in F, j \in P, m \in M, t \in T \tag{8.17}$$

$$\sum_{\tau=0}^{t} \left(\sum_{k \in K | m \in M(k)} g_{ij}^{m\tau k} - q_{ij}^{m\tau} \right) = z_{ij}^{mt}, i \in F, j \in P, m \in M, t \in T \tag{8.18}$$

$$\sum_{i \in F} \sum_{j \in P} I_{ij}^{mt} \leq C^m, m \in M, t \in T \tag{8.19}$$

$$g_{ij}^{mtk} \geq 0, i \in F, j \in P, m \in M, t \in T, k \in K \tag{8.20}$$

$$I_{ij}^{mt} \geq 0, i \in F, j \in P, m \in M, t \in T \tag{8.21}$$

$$z_{ij}^{mt} \geq 0, i \in F, j \in P, m \in M, t \in T \tag{8.23}$$

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$$y_j^{kt} \in N, j \in P, k \in K, t \in T \quad (8.24)$$

In the objective function (8.14) we consider three components: the cost of transportation between the CCC and the construction site (in both directions), the cost of inventory, and the cost of anticipating material deliveries. Constraint (8.15) guarantees the flow conservation into the CCC. Constraint (8.16) sets the number and type of required vehicles to transport the material to the construction site. Constraint (8.17) ensures the correct amount of material is delivered to the construction sites. Constriant (8.18) is used to determin the amount of material that arrives early at the construction site. In (8.19) the inventory is constrained by a capacity. In (8.20)-(8.24) we define the variables.

8.2.3 Model with possible anticipation and reverse logistics

In this model we consider the same components as before and the fact that the reverse logistics materials must be brought to the dumpsites.

$$\min \sum_{j \in P} \sum_{t \in T} \left(\sum_{k \in K} 2 c_j^k y_j^{kt} + \sum_{i \in F} \sum_{m \in M} \left(b I_{ij}^{mt} + \gamma z_{ij}^{mt} \right) \right) \quad (8.25)$$

$$\bar{x}_{ij}^{mt} + I_{ij}^{mt} = I_{ij}^{mt+1} + \sum_{k \in K | m \in M(k)} g_{ij}^{mtk}, i \in F, j \in P, m \in M, t \in T \quad (8.26)$$

$$\sum_{i \in F} \sum_{m \in M(k)} g_{ij}^{mtk} \leq Q^k y_j^{kt}, j \in P, k \in K, t \in T \quad (8.27)$$

$$\sum_{k \in K | m \in M(k)} \sum_{\tau = 0}^{t} g_{ij}^{m\tau k} \geq q_{ij}^{mt}, i \in F, j \in P, m \in M, t \in T \quad (8.28)$$

$$\sum_{\tau = 0}^{t} \left(\sum_{k \in K | m \in M(k)} g_{ij}^{m\tau k} - q_{ij}^{m\tau} \right) = z_{ij}^{mt}, i \in F, j \in P, m \in M, t \in T \quad (8.29)$$

$$\sum_{i \in F} \sum_{m \in M(k)} f_{ji}^{mtk} \leq Q^k y_j^{kt}, j \in P, k \in K, t \in T \quad (8.30)$$

$$\sum_{k \in K | m \in M(k)} f_{ji}^{mtk} = r_{ji}^{mt}, i \in F, j \in P, t \in T, m \in M \quad (8.31)$$

$$\sum_{i \in F} \sum_{j \in P} I_{ij}^{mt} \leq C^m, m \in M, t \in T \quad (8.32)$$

$$g_{ij}^{mtk} \geq 0, i \in F, j \in P, m \in M, t \in T, k \in K \quad (8.33)$$

$$f_{ji}^{mtk} \geq 0, i \in F, j \in P, m \in M, t \in T, k \in K \quad (8.34)$$

$$I_{ij}^{mt} \geq 0, i \in F, j \in P, m \in M, t \in T \quad (8.35)$$

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$$z_{ij}^{mt} \geq 0, i \in F, j \in P, m \in M, t \in T \tag{8.36}$$

$$y_j^{kt} \in N, j \in P, k \in K, t \in T \tag{8.37}$$

In the objective function (8.25) we consider three components: the cost of transportation between the CCC and the construction site (in both directions), the cost of inventory, and the cost of anticipating material deliveries. Constraint (8.26) guarantees the flow conservation into the CCC. Constraint (8.27) sets the number and type of required vehicles to transport the material to the construction site. Constraint (8.28) ensures the correct amount of material is delivered to the construction sites. Constriant (8.29) is used to determin the amount of material that arrives early at the construction site. Constraint (8.31) ensures that the correct amount of reverse logistics material is collecte, while (8.30) explores the possibility of making use of the correct returning vehicle and making its capacity respected. In (8.19) the inventory is constrained by a capacity. In (8.33)-(8.37) we define the variables.

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9 Optimization Algorithms and Tools

In this chapter we explain the algorithms that we developed and used to solve the problems proposed and modelled in the previous chapters. In the following, we will describe the used algorithms, the data input required, and the outputs proposed.

9.1 Solving algorithms

The presented models for the *Two-echelon Facility Location Problems*, the *Two-echelon Allocation Problems,* and the *Inventory vs Transport Problems* will be solved directly with the use of optimization solvers (such as FICO Xpress[1], and IBM Cplex[2]), that make use of embedded *Exact Algorithms*. The *Vehicle Routing Problem* will be solved with the use of a *Heuristic Algorithm*. The models containing the stochastic variables, the *Two-echelon Stochastic Facility Location Problems,* will be solved by making use of solvers (used directly when for the Deterministic Equivalent form) and by using the *L-shaped method,* the Benders' decomposition dedicated to the stochastic programming models, when solving the decomposed models; both are exact algorithms.

9.1.1 Exact algorithms vs Heuristic algorithms

Exact Algorithms and Heuristic Algorithms are both optimization algorithms that intend to solve optimization problems. The optimization problems that we have modelled in this Deliverable are Mixed Integer Linear Programming models and these models can be solved by both Exact and Heuristics Algorithms. Roughly speaking, Exact algorithms (such as branch-and-bound, branch-and-cut, etc.) are algorithms that guarantee to find the problems' optimal solution at the end of the algorithms' run; however, the computing time to solve a real size problem to optimality can be extremely long in time and make the algorithm unusable. On the other hand, the Heuristic algorithms can normally provide solutions with objective values close to the optimal one, and sometimes also the optimal one, in a very short computing time; however, they do not provide any guarantee on the optimality of the obtained solution. Deciding when to use one or another mainly depends on the hardness and the size of the tackled problem, on the availability of time, and on the number of times the solution must be re-optimized and thus the algorithm rerun. The class of Vehicle Routing Problem (VRP) is a very well-known class of hard problems, and VRP problems are problems to be solved in an operational horizon, and this is why we decided to use a heuristic algorithms. On the other hand, Facility Location, Allocation, and Transport-type problems are well known to be more easily solved with the use of Exact Algorithms and represent more strategic and tactical problems, this is

[1] http://www.fico.com/en/products/fico-xpress-optimization-suite
[2] https://www-01.ibm.com/software/commerce/optimization/cplex-optimizer/

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why we decided to use directly optimization solvers, that apply an embedded branch-and-bound algorithm. This is also the reason why it was possible to provide such complicated models for those problems.

As we said, to solve the VRP we applied a heuristic algorithm. We firstly provide an initial solution by making use of two constructive methods: a cluster first route second algorithm and a simple greedy algorithm.

- In the first algorithm we firstly separate the vertices in cluster depending on the vehicles capacities and materials requests; once a cluster is defined, a route among the selected vertices is defined in a greedy way.
- The second algorithm simply uses a closest first algorithm with some further checks to prevent infeasible solutions. Closest first means that we build routes starting from the depot (the CCC) by choosing the closest non-visited customer (construction site) that can be served by the current type of vehicles, until the vehicle's capacity is respected. Otherwise a new vehicle is used. The algorithms finishes when all off the requests have been fulfilled.

The heuristic algorithms take the best of the solutions provided by the two algorithms, and thus applies to the obtained solutions the most used local searches (2-opt, or-opt, etc.) to improve the obtained solution. The local search procedures take in input a given feasible solution and perform movements of parts of the solution (e.g., exchange customer one with customer two on one route) to improve the current objective function value. When the local search procedure have been applied the algorithms terminates.

9.1.2 The L-Shaped Method

For stochastic optimization problems, the direct use of solvers to the models can be done in two ways: by solving the entire Equivalent Deterministic Formulation of the problem or by including the use of solvers into a decomposing method. Both are exact algorithms.

The decomposition is applied to the model that is thus divided into two stages. The first stage represents the part of the model that includes only the decisions to be made before the realization of the stochastic variables, the so-called here-and-now decisions. While the second stage is represented by a set of submodels, one for each stochastic scenario, that depend on the decisions to be made after the realization of the stochastic variables. The subdivision into two stages reflects the so-called Bender's decomposition; moreover, the submodels are independent to each other, thus they can be solved separately. This is called L-shaped Method.

In the L-shaped Method the first stage model is firstly solved. The decisions non-depending on the stochastic scenarios are made and are represented by the

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first stage variables. The current value of these variables after the first iteration is plugged into the second stage submodels as if they were a constant. At this point, the second stage models are solved: if at least one scenario submodel provides a non-feasible solution, thus a new constraint depending on the infeasible submodel, called feasibility cut, must be included into the first stage model to provide feasibility in the next iteration. Then the first stage model with the new constraint is solved and the iteration continues. In case that all the second stage submodels are feasible with the given first stage solution, an adjustment of the first stage model can be required. Indeed, the submodels can require charging some costs into the first stage objective function: the so-called recursive function. To do so a new constraint is added to the first stage model, the so-called Optimality cut. Then the first stage model with the new constraint is solved and the iteration continues until no feasibility or optimality cuts are required. In that case the obtained solution is optimal.

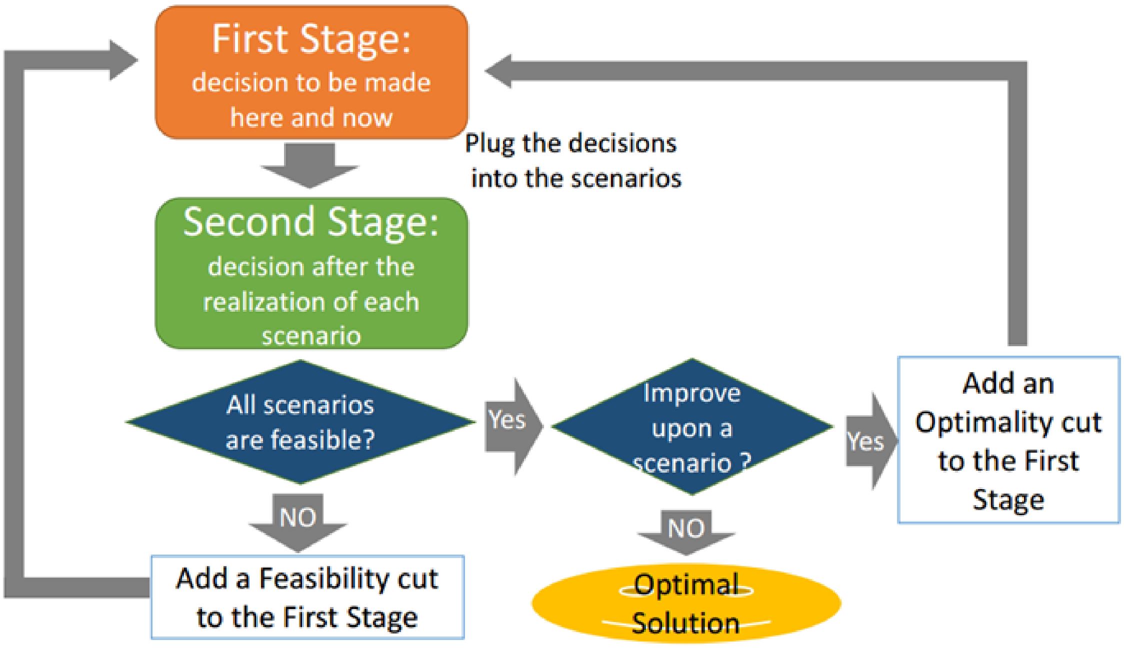

Figure 7 L-shaped method scheme

9.2 Data input: Required data and information

Once the algorithms to solve the defined problems are available, we need to define the input data. Before explaining the data format needed by the algorithms, we describe the data and information needed to model and solve a problem of the one describe in the previous chapters, together with their origin.

The data origin can be:

- A known information
- The excel file designed for data collection in collaboration with WP4

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- A decision made or derived from the proposed Business models on T3.3
- A direct computation derived from collected data
- An information got thanks to a brief interview with the direct stakeholders
- Estimation obtain from the current available data

In the Table 3 Data list and their origin we depicted the origin of the required input data.

Table 3 Data list and their origin

Data	Origin of data
Locations and distances	
Location of construction sites	Known information
Location of suppliers	Data collection (excel file WP4)
Location of dump sites	Data collection (excel file WP4)
Possible location of CCC	Data collection (excel file WP4) Decision made or derived from the proposed Business models Interview with the direct stakeholders
Travel distance / time between vertices	Direct computation from other information (QGis, Google)
Vehicles	
Type of vehicles	Data collection (excel file WP4) Decision made or derived from the proposed Business models
Vehicle capacity	Data collection (excel file WP4) Decision made or derived from the proposed Business models
Materials that can be carried by one type of vehicle	Data collection (excel file WP4) Decision made or derived from the proposed Business models
Cost of using a vehicle	Decision made or derived from the proposed Business models Interview with the direct stakeholders

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Material requests	
Materials requests: type of material, required quantity (volume and weight), period of delivery	Data collection (excel file WP4)
Reverse logistics material requests: type of material, quantity (volume and weight), period of needed collection	Data collection (excel file WP4)
Information of requests: e.g. if materials can be directly shipped to the construction site	Decision made or derived from the proposed Business models Interview with the direct stakeholders
CCCs	
Possible dimensions (capacity)	Decision made or derived from the proposed Business models Derived from other simulation models results
CCC opening costs	Decision made or derived from the proposed Business models
Inventory costs	Decision made or derived from the proposed Business models
Maximum number of CCCs	Decision made or derived from the proposed Business models
Cost of serving sites and suppliers from CCCs	Decision made or derived from the proposed Business models
Capacity for incoming and exiting materials	Decision made or derived from the proposed Business models Derived from other simulation models results
Others	
Travel cost (it can coincide with distance and time)	Decision made or derived from the proposed Business models A direct computation derived from collected data

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Cost of storage on site	Decision made or derived from the proposed Business models Interview with the direct stakeholders
Material flows	Derived from other simulation models results
Stochastic information	Interview with the direct stakeholders Estimations

In the following we describe all the data needed as input by the proposed mathematical models. We provide information on both the format of the input file and on the required datatype.

9.2.1 Two-echelon (Stochastic) Facility Location Problems

9.2.1.1 *Basic Model*

The input of the Basic Model must be provided in two .txt files:

- **Main data**: a .txt file that includes the main required input data. The meaning and the format are described and explained in Table 4;
- **Travelling costs**: a .txt file including the travelling costs: its description is provided in Table 5.

Table 4 FL Basic Model Main Data

Name	meaning	size	type
coorx	x coordinates of the vertices	Array of vertices	double
coory	y coordinates of the vertices	Array of vertices	double
s_supp	The vertices are ordered starting from suppliers, then CCCs, and terminating with the construction sites. *s_supp* identifies the starting index of the suppliers (it is supposed to be 0) into the vertex array	Number	integer
s_ccc	Starting index of the CCC into the vertex array	Number	integer
s_sites	Starting index of the sites into the vertex array	Number	integer

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q	Matrix with the size of the number of suppliers multiplied by the number of construction sites, reporting the material requests in quantity, defined by origin (supplier) and destination (construction site)	Matrix (suppliers, construction sites)	double
cap_ccc	Capacity of each CCC	Array of CCCs	double
cost_ccc:	Costs of opening each CCC	Array of CCCs	double
max_ccc	Maximum number of CCCs that can be opened	Number	double

In Figure 8 one can find the format as it written to be used by the solver.

```
coorx: [(0) 0 (1) 40 (2) 0 (3) 70 (4) 60 (5) 27 (6) 10 (7) 30 (8) 15 (9) 35 (10) 50 (11) 43]
coory: [(0) 0 (1)  0 (2) 50(3) 70 (4) 6  (5) 60 (6) 20 (7) 40 (8) 52 (9) 35 (10) 30 (11) 23]
s_supp: 0
s_ccc: 4
s_sites: 7
q: [(0,7)   2 (1,7)  4 (2,7)  5 (3,7)  3
        (0,8)   2 (1,8)  4 (2,8)  5 (3,8)  3
        (0,9)   2 (1,9)  4 (2,9)  5 (3,9)  3
        (0,10)  2 (1,10) 4 (2,10) 5 (3,10) 3
        (0,11)  2 (1,11) 4 (2,11) 5 (3,11) 3]
cap_ccc: [(4) 100 (5) 100 (6) 100]
cost_ccc: [(4) 10 (5) 10 (6) 10]
max_ccc: 3
```

Figure 8 Example of the Main Data input file for the Facility Location Basic Model

For each datum, the name of the input datum is required followed by a column (:), and thus, depending on the datatype:

- If it is a case of a **single number datum**, thus the single number can be inserted.

  E.g.: s_supp: 0

- In case of an **array**, the data must be set into square brackets, and the index of each element of the array must be indicated into brackets before the datum. The array must be as long as the defined size (see, e.g., <u>coorx</u> in Figure 8).

  E.g.: coorx: [(0) 0 (1) 40 (3) 70 (4) 60 (7) 30 (8) 15 (9) 35 (10) 50 (11) 43]

- In case of a **matrix**, the data must be set into square brackets. Inside the square brackets, two or more indices must be indicated in brackets, depending on the dimension of the matrix, for each datum. The indices must be separated by a comma. Then the datum can be inserted (see, e.g., <u>q</u> in Figure 8).

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E.g.: q: *[(0,7) 2 (1,7) 4 (2,7) 5 (3,7) 3*

(0,8) 2 (1,8) 4 (2,8) 5 (3,8) 3

(0,9) 2 (1,9) 4 (2,9) 5 (3,9) 3

(0,10) 2 (1,10) 4 (2,10) 5 (3,10) 3]

9.2.1.1.1 Travelling Cost / Distance /Time computation

An additional input .txt file is required for the travelling costs / distance. We compute the road distance by making use of the coordinates of the selected vertices and use the Google API[3]. We provide an .html file that, once the correct coordinates are inserted as input, can be opened with a browser and produce a map with the inserted points, a distance matrix between each couple of vertices in meters and also the time matrix in seconds. These values can be used to feed the models, taking care of changing the 0 values of the matrix main diagonal into an arbitrary large number.

Table 5 FL Basic Model Travelling Cost Data

Name	meaning	size	type
cost	Matrix of costs /distance among the vertices of the network. The cost between the same vertex is set to a high value to avoid that trip into the model.	Vertex by vertex matrix	Double

[3] https://developers.google.com/maps/

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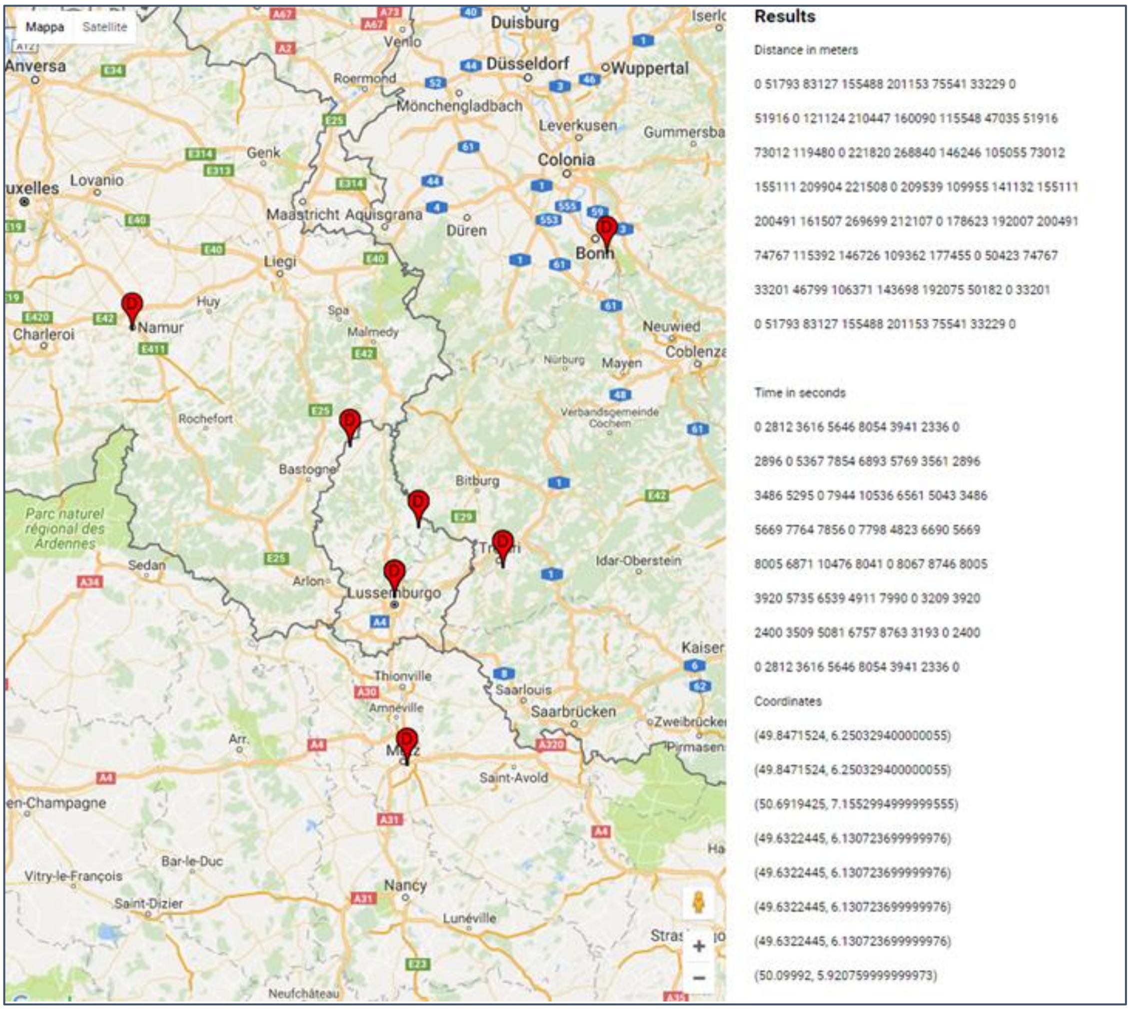

Figure 9 Html file using the google api to compute distances and times

For some of the following models not all the distances between the vertices are needed, for example the distance between a supplier and a construction site when the direct shipping is not allowed. In this case these values are not required into the input file. In other cases the cost of direct shipping is not necessarily linked to the distance: however, this value can be inserted into the cost matrix.

In Figure 10 one can find the cost matrix input file for the Xpress models.

```
cost: [ (0,0) 99999 (0,1) 20 (0,2) 10 (0,3) 10
        (1,0) 19 (1,1) 99999 (1,2) 15 (1,3) 15
        (2,0) 11 (2,1) 16 (2,2) 99999 (2,3) 9
        (3,0) 10 (3,1) 15 (3,2) 10 (3,3) 99999
]
```

Figure 10 Example of cost matrix of the Travelling Costs input file

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9.2.1.2 *Multi Material Model*

The first input file for the *Multi Material Model* is a .txt file similar to the one for the *Basic Model*, the **Main Data** input file. The changes are represented by: the request q, and the capacity cap_ccc_m. See the Table 6 for the complete list of data, the changes with respect to the previous models are highlighted in all the following tables in grey). The second .txt input file is the **Travelling costs** one, and includes the distance / cost matrix, as in Table 6.

Table 6 FL Multi Material Model Data

Name	meaning	size	type
	First input file: Main Data		
coorx	x coordinates of the vertices	Array of vertices	double
coory	y coordinates of the vertices	Array of vertices	double
s_supp	The vertices are ordered starting from suppliers, then CCCs, and terminating with the construction sites. s_supp identifies the starting index of the suppliers (it is supposed to be 0) into the vertex array	Number	integer
s_ccc	Starting index of the CCC into the vertex array	Number	integer
s_sites	Starting index of the sites into the vertex array	Number	integer
q	Material requests quantity defined by origin (supplier), destination (construction site), and material	Three dimensional Matrix (suppliers, construction sites, materials)	double
cap_ccc	Capacity of each CCC	Array of CCCs	double
cap_ccc_m	Capacity for each material inside the CCCs	Matrix (CCCs, materials)	double
cost_ccc:	Costs of opening each CCC	Array of CCCs	double
max_ccc	defines the maximum number of CCCs that can be opened	Number	double

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

Second input file: Travelling Costs			
cost	Matrix of costs /distance among the vertices of the network. The cost between the same vertex is set to a high value to avoid that trip into the model.	Vertex by vertex matrix	Double

```
coorx: [(0) 0 (1) 40 (2) 0 (3) 70 (4) 60 (5) 27 (6) 10 (7) 30 (8) 15 (9) 35 (10) 50 (11) 43]
coory: [(0) 0 (1)  0 (2) 50(3) 70 (4) 6  (5) 60 (6) 20 (7) 40 (8) 52 (9) 35 (10) 30 (11) 23]
s_supp: 0
s_ccc: 4
s_sites: 7
q: [(0,7,0)   10 (1,7,0)  4 (2,7,0)  8 (3,7,0)  9
        (0,8,0)   10 (1,8,0)  4 (2,8,0)  8 (3,8,0)  9
        (0,9,0)   10 (1,9,0)  4 (2,9,0)  8 (3,9,0)  9
        (0,10,0)  10 (1,10,0) 4 (2,10,0) 8 (3,10,0) 9
        (0,11,0)  10 (1,11,0) 4 (2,11,0) 8 (3,11,0) 9
        (0,7,1)   1 (1,7,1)  2 (2,7,1)  9 (3,7,1)  3
        (0,8,1)   1 (1,8,1)  2 (2,8,1)  9 (3,8,1)  3
        (0,9,1)   1 (1,9,1)  2 (2,9,1)  9 (3,9,1)  3
        (0,10,1)  1 (1,10,1) 2 (2,10,1) 9 (3,10,1) 3
        (0,11,1)  1 (1,11,1) 2 (2,11,1) 9 (3,11,1) 3
        (0,7,2)   5 (1,7,2)  6 (2,7,2)  4 (3,7,2)  7
        (0,8,2)   5 (1,8,2)  6 (2,8,2)  4 (3,8,2)  7
        (0,9,2)   5 (1,9,2)  6 (2,9,2)  4 (3,9,2)  7
        (0,10,2)  5 (1,10,2) 6 (2,10,2) 4 (3,10,2) 7
        (0,11,2)  5 (1,11,2) 6 (2,11,2) 4 (3,11,2) 7
        ]
cap_ccc: [(4) 200 (5) 200 (6) 200]
cap_ccc_m: [(0,4) 200 (1,4) 200 (2,4) 200
        (0,5) 200 (1,5) 200 (2,5) 200
        (0,6) 200 (1,6) 200 (2,6) 200
]
cost_ccc: [(4) 10 (5) 10 (6) 10]
max_ccc: 3
```

Figure 11 Example of the *Main Data* input file for the *Multi Material Model*

9.2.1.3 *Multi Period Model*

The *Multi Period Model* also requires two .txt file: the **Main Data** file and **Travelling Costs** file. In the *Multi Period Model* only the first one changes with respect to the *Basic Model*. This change is registered only for request q, as reported in Table 7.

Table 7 FL Multi Period Model Data

Name	meaning	size	type
First input file: Main Data			
coorx	x coordinates of the vertices	Array of vertices	double
coory	y coordinates of the vertices	Array of vertices	double

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s_supp	The vertices are ordered starting from suppliers, then CCCs, and terminating with the construction sites. s_supp identifies the starting index of the suppliers (it is supposed to be 0) into the vertex array	Number	integer
s_ccc	Starting index of the CCC into the vertex array	Number	integer
s_sites	Starting index of the sites into the vertex array	Number	integer
q	Material requests quantity, defined by origin (supplier), destination (construction site), and period [double].	Three dimensional Matrix (suppliers, construction sites, periods)	double
cap_ccc	Capacity of each CCC	Array of CCCs	double
cost_ccc:	Costs of opening each CCC	Array of CCCs	double
max_ccc	Maximum number of CCCs that can be opened	Number	double
Second input file: Travelling Costs			
cost	Matrix of costs /distance among the vertices of the network. The cost between the same vertex is set to a high value to avoid that trip into the model.	Vertex by vertex matrix	Double

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

```
coorx: [(0) 0 (1) 40 (2) 0 (3) 70 (4) 60 (5) 27 (6) 10 (7) 30 (8) 15 (9) 35 (10) 50 (11) 43]
coory: [(0) 0 (1)  0 (2) 50(3) 70 (4) 6  (5) 60 (6) 20 (7) 40 (8) 52 (9) 35 (10) 30 (11) 23]
s_supp: 0
s_ccc: 4
s_sites: 7
q: [(0,7,0)   10 (1,7,0)  4 (2,7,0)  8 (3,7,0)  9
        (0,8,0)   10 (1,8,0)  4 (2,8,0)  8 (3,8,0)  9
        (0,9,0)   10 (1,9,0)  4 (2,9,0)  8 (3,9,0)  9
        (0,10,0)  10 (1,10,0) 4 (2,10,0) 8 (3,10,0) 9
        (0,11,0)  10 (1,11,0) 4 (2,11,0) 8 (3,11,0) 9
        (0,7,1)   1 (1,7,1)  2 (2,7,1)  9 (3,7,1)  3
        (0,8,1)   1 (1,8,1)  2 (2,8,1)  9 (3,8,1)  3
        (0,9,1)   1 (1,9,1)  2 (2,9,1)  9 (3,9,1)  3
        (0,10,1)  1 (1,10,1) 2 (2,10,1) 9 (3,10,1) 3
        (0,11,1)  1 (1,11,1) 2 (2,11,1) 9 (3,11,1) 3
        (0,7,2)   5 (1,7,2)  6 (2,7,2)  4 (3,7,2)  7
        (0,8,2)   5 (1,8,2)  6 (2,8,2)  4 (3,8,2)  7
        (0,9,2)   5 (1,9,2)  6 (2,9,2)  4 (3,9,2)  7
        (0,10,2)  5 (1,10,2) 6 (2,10,2) 4 (3,10,2) 7
        (0,11,2)  5 (1,11,2) 6 (2,11,2) 4 (3,11,2) 7
        ]
cap_ccc: [(4) 200 (5) 200 (6) 200]
cost_ccc: [(4) 10 (5) 10 (6) 10]
max_ccc: 3
```

Figure 12 Example of a Main Data input file for the Multi Period Model

9.2.1.4 *Multi Material Multi Period Model*

The input files for the *Multi Material Multi Period Model* are two .txt files similar to those required by the *Multi Material Model*: the **Main Data** file and **Travelling Costs** file. In the current model the request q depends on its origin, its destination, the material, and the period, and a maximum capacity material-dependent is given for each CCC. For the details see Table 8. For a graphical example see Figure 13.

Table 8 FL Multi Material Multi Period Model Data

Name	meaning	size	type
	First input file: Main Data		
coorx	x coordinates of the vertices	Array of vertices	double
coory	y coordinates of the vertices	Array of vertices	double
s_supp	The vertices are ordered starting from suppliers, then CCCs, and terminating with the construction sites. s_supp identifies the starting index of the suppliers (it is supposed to be 0) into the vertex array	Number	integer
s_ccc	Starting index of the CCC into the vertex array	Number	integer

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s_sites	Starting index of the sites into the vertex array	Number	integer
q	Material requests quantity, defined by origin (supplier), destination (construction site), material, and period	Four dimensional matrix (suppliers, construction sites, materials, periods).	double
cap_ccc	Capacity of each CCC	Array of CCCs	double
cap_ccc_m	Capacity for each material inside the CCCs	Matrix (CCCs, materials)	double
cost_ccc:	Costs of opening each CCC	Array of CCCs	double
max_ccc	Maximum number of CCCs that can be opened	Number	double
	Second input file: Travelling Costs		
cost	Matrix of costs /distance among the vertices of the network. The cost between the same vertex is set to a high value to avoid that trip into the model.	Vertex by vertex matrix	Double

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

```
coorx: [(0) 0 (1) 40 (2) 0 (3) 70 (4) 60 (5) 27 (6) 10 (7) 30 (8) 15 (9) 35 (10) 50 (11) 43]
coory: [(0) 0 (1)  0 (2) 50(3) 70 (4) 6  (5) 60 (6) 20 (7) 40 (8) 52 (9) 35 (10) 30 (11) 23]
s_supp: 0
s_ccc: 4
s_sites: 7
q: [(0,7,0,0)  10 (0,7,0,1)  9
        (1,7,0,0)  4  (1,7,0,1)  3
        (2,7,0,0)  8  (2,7,0,1)  7
        (3,7,0,0)  9  (3,7,0,1)  8
        (0,8,0,0)  10 (0,8,0,1)  9
        (1,8,0,0)  4  (1,8,0,1)  3
        (2,8,0,0)  8  (2,8,0,1)  7
        (3,8,0,0)  9  (3,8,0,1)  8
        (0,9,0,0)  10 (0,9,0,1)  9
        (1,9,0,0)  4  (1,9,0,1)  3
        (2,9,0,0)  8  (2,9,0,1)  7
        (3,9,0,0)  9  (3,9,0,1)  8
        (0,10,0,0) 10 (0,10,0,1) 9
        (1,10,0,0) 4  (1,10,0,1) 3
        (2,10,0,0) 8  (2,10,0,1) 7
        (3,10,0,0) 9  (3,10,0,1) 8
        (0,11,0,0) 10 (0,11,0,1) 9
        (1,11,0,0) 4  (1,11,0,1) 3
        (2,11,0,0) 8  (2,11,0,1) 7
        (3,11,0,0) 9  (3,11,0,1) 8
        (0,7,1,0)  1  (0,7,1,1)  2
        (1,7,1,0)  2  (1,7,1,1)  3
        (2,7,1,0)  9  (2,7,1,1)  10
        (3,7,1,0)  3  (3,7,1,1)  4
        (0,8,1,0)  1  (0,8,1,1)  2
        (1,8,1,0)  2  (1,8,1,1)  3
        (2,8,1,0)  9  (2,8,1,1)  10
        (3,8,1,0)  3  (3,8,1,1)  4
        (0,9,1,0)  1  (0,9,1,1)  2
        (1,9,1,0)  2  (1,9,1,1)  3
        (2,9,1,0)  9  (2,9,1,1)  10
        (3,9,1,0)  3  (3,9,1,1)  4
        (0,10,1,0) 1  (0,10,1,1) 2
        (1,10,1,0) 2  (1,10,1,1) 3
        (2,10,1,0) 9  (2,10,1,1) 10
        (3,10,1,0) 3  (3,10,1,1) 4
        (0,11,1,0) 1  (0,11,1,1) 2
        (1,11,1,0) 2  (1,11,1,1) 3
        (2,11,1,0) 9  (2,11,1,1) 10
        (3,11,1,0) 3  (3,11,1,1) 4
        (0,7,2,0)  5  (0,7,2,1)  4
        (1,7,2,0)  6  (1,7,2,1)  5
        (2,7,2,0)  4  (2,7,2,1)  3
        (3,7,2,0)  7  (3,7,2,1)  6
        (0,8,2,0)  5  (0,8,2,1)  4
        (1,8,2,0)  6  (1,8,2,1)  5
        (2,8,2,0)  4  (2,8,2,1)  3
        (3,8,2,0)  7  (3,8,2,1)  6
        (0,9,2,0)  5  (0,9,2,1)  4
        (1,9,2,0)  6  (1,9,2,1)  5
        (2,9,2,0)  4  (2,9,2,1)  3
        (3,9,2,0)  7  (3,9,2,1)  6
        (0,10,2,0) 5  (0,10,2,1) 4
        (1,10,2,0) 6  (1,10,2,1) 5
        (2,10,2,0) 4  (2,10,2,1) 3
        (3,10,2,0) 7  (3,10,2,1) 6
        (0,11,2,0) 5  (0,11,2,1) 4
        (1,11,2,0) 6  (1,11,2,1) 5
        (2,11,2,0) 4  (2,11,2,1) 3
        (3,11,2,0) 7  (3,11,2,1) 6
        ]
cap_ccc:  [(4) 200 (5) 200 (6) 200]
cap_ccc_m: [(0) 200 (1) 200 (2) 200]
cost_ccc: [(4) 10 (5) 10 (6) 10]
max_ccc: 3
```

Figure 13 Example of a Main Data input file for the Multi Material Multi Period Model

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

9.2.1.5 *Basic Reverse Model*

The input files for the *Basic Reverse Model* are very similar to the *Basic Model*: the **Main Data** file and **Travelling Costs** file. In the first file a new input is required: the reverse logistic material request r. Details are given in Table 9 and an example is provided in Figure 14.

Table 9 FL Basic Reverse Model

Name	meaning	size	type
	First input file: Main Data		
coorx	x coordinates of the vertices	Array of vertices	double
coory	y coordinates of the vertices	Array of vertices	double
s_supp	The vertices are ordered starting from suppliers, then CCCs, and terminating with the construction sites. s_supp identifies the starting index of the suppliers (it is supposed to be 0) into the vertex array	Number	integer
s_ccc	Starting index of the CCC into the vertex array	Number	integer
s_sites	Starting index of the sites into the vertex array	Number	integer
q	Material requests quantity defined by origin (supplier), destination (construction site)	Matrix (suppliers, construction sites)	double
r	Request for reverse logistics that is a quantity defined by its origin (a construction site) and its destination (supplier / dumpsite)	Matrix (construction site, suppliers)	double
cap_ccc	Capacity of each CCC	Array of CCCs	double
cost_ccc:	Costs of opening each CCC	Array of CCCs	double
max_ccc	Maximum number of CCCs that can be opened	Number	double

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

	Second input file: Travelling Costs		
cost	Matrix of costs /distance among the vertices of the network. The cost between the same vertex is set to a high value to avoid that trip into the model.	Vertex by vertex matrix	Double

```
coorx: [(0) 0 (1) 40 (2) 0 (3) 70 (4) 60 (5) 27 (6) 10 (7) 30 (8) 15 (9) 35 (10) 50 (11) 43]
coory: [(0) 0 (1)  0 (2) 50(3) 70 (4) 6  (5) 60 (6) 20 (7) 40 (8) 52 (9) 35 (10) 30 (11) 23]
s_supp: 0
s_ccc: 4
s_sites: 7
q: [(0,7)   2 (1,7)  4 (2,7)  5 (3,7)  3
        (0,8)   2 (1,8)  4 (2,8)  5 (3,8)  3
        (0,9)   2 (1,9)  4 (2,9)  5 (3,9)  3
        (0,10)  2 (1,10) 4 (2,10) 5 (3,10) 3
        (0,11)  2 (1,11) 4 (2,11) 5 (3,11) 3
        ]
r: [(7,0)   2 (7,1)  4 (7,2)  5 (7,3)  3
        (8,0)   2 (8,0)  4 (8,2)  5 (8,3)  3
        (9,0)   2 (9,1)  4 (9,2)  5 (9,3)  3
        (10,0)  2 (10,1) 4 (10,2) 5 (10,3) 3
        (11,0)  2 (11,1) 4 (11,2) 5 (11,3) 3
        ]
cap_ccc: [(4) 200 (5) 200 (6) 200]
cost_ccc: [(4) 10 (5) 10 (6) 10]
max_ccc: 3
```

Figure 14 Example of a Main Data input file for the Basic Reverse Model

9.2.1.6 *Reverse Multi Material Model*

The input file required for the *Reverse Multi Material Model* is made of two .txt files similar to those required by the *Basic Reverse Model*: the **Main Data** file and **Travelling Costs** file. The first file changes with respect to the material request, the reverse logistic request, and the capacity at CCCs: these data also depend on the material.

Table 10 FL Reverse Multi Material Model Data

Name	meaning	size	type
	First input file: Main Data		
coorx	x coordinates of the vertices	Array of vertices	double
coory	y coordinates of the vertices	Array of vertices	double
s_supp	The vertices are ordered starting from suppliers, then CCCs, and terminating with the construction sites. s_supp identifies the starting index of the suppliers (it is supposed to be 0) into the vertex array	Number	integer

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

s_ccc	Starting index of the CCC into the vertex array	Number	integer
s_sites	Starting index of the sites into the vertex array	Number	integer
q	Quantity of material requests defined by origin (supplier), destination (construction site), and material	Three dimension Matrix (suppliers, construction sites, materials)	double
r	Request for reverse logistics that is a quantity defined by its origin (a construction site), its destination (supplier/dumpsite) and the material	Three dimension Matrix (construction site, suppliers, materials)	double
cap_ccc	Capacity of each CCC	Array of CCCs	double
cap_ccc_m	Capacity of different materials in each CCC	Matrix of (CCCs, materials)	double
cost_ccc	Costs of opening each CCC	Array of CCCs	double
max_ccc	Maximum number of CCCs that can be opened	Number	double
	Second input file: Travelling Costs		
cost	Matrix of costs /distance among the vertices of the network. The cost between the same vertex is set to a high value to avoid that trip into the model.	Vertex by vertex matrix	Double

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

```
coorx: [(0) 0 (1) 40 (2) 0 (3) 70 (4) 60 (5) 27 (6) 10 (7) 30 (8) 15 (9) 35 (10) 50 (11) 43]
coory: [(0) 0 (1)  0 (2) 50(3) 70 (4) 6  (5) 60 (6) 20 (7) 40 (8) 52 (9) 35 (10) 30 (11) 23]
s_supp: 0
s_ccc: 4
s_sites: 7
q: [     (0,7,0)   10 (1,7,0)  4 (2,7,0)  8 (3,7,0)  9
         (0,8,0)   10 (1,8,0)  4 (2,8,0)  8 (3,8,0)  9
         (0,9,0)   10 (1,9,0)  4 (2,9,0)  8 (3,9,0)  9
         (0,10,0)  10 (1,10,0) 4 (2,10,0) 8 (3,10,0) 9
         (0,11,0)  10 (1,11,0) 4 (2,11,0) 8 (3,11,0) 9
         (0,7,1)   1 (1,7,1)  2 (2,7,1)  9 (3,7,1)  3
         (0,8,1)   1 (1,8,1)  2 (2,8,1)  9 (3,8,1)  3
         (0,9,1)   1 (1,9,1)  2 (2,9,1)  9 (3,9,1)  3
         (0,10,1)  1 (1,10,1) 2 (2,10,1) 9 (3,10,1) 3
         (0,11,1)  1 (1,11,1) 2 (2,11,1) 9 (3,11,1) 3
         (0,7,2)   5 (1,7,2)  6 (2,7,2)  4 (3,7,2)  7
         (0,8,2)   5 (1,8,2)  6 (2,8,2)  4 (3,8,2)  7
         (0,9,2)   5 (1,9,2)  6 (2,9,2)  4 (3,9,2)  7
         (0,10,2)  5 (1,10,2) 6 (2,10,2) 4 (3,10,2) 7
         (0,11,2)  5 (1,11,2) 6 (2,11,2) 4 (3,11,2) 7
         ]

r: [     (7,0,0)   2 (7,1,0)  4 (7,2,0)  5 (7,3,0)  3
         (8,0,0)   2 (8,1,0)  4 (8,2,0)  5 (8,3,0)  3
         (9,0,0)   2 (9,1,0)  4 (9,2,0)  5 (9,3,0)  3
         (10,0,0)  2 (10,1,0) 4 (10,2,0) 5 (10,3,0) 3
         (11,0,0)  2 (11,1,0) 4 (11,2,0) 5 (11,3,0) 3
         (7,0,1)   2 (7,1,1)  4 (7,2,1)  5 (7,3,1)  3
         (8,0,1)   2 (8,0,1)  4 (8,2,1)  5 (8,3,1)  3
         (9,0,1)   2 (9,1,1)  4 (9,2,1)  5 (9,3,1)  3
         (10,0,1)  2 (10,1,1) 4 (10,2,1) 5 (10,3,1) 3
         (11,0,1)  2 (11,1,1) 4 (11,2,1) 5 (11,3,1) 3
         (7,0,2)   2 (7,1,2)  4 (7,2,2)  5 (7,3,2)  3
         (8,0,2)   2 (8,1,2)  4 (8,2,2)  5 (8,3,2)  3
         (9,0,2)   2 (9,1,2)  4 (9,2,2)  5 (9,3,2)  3
         (10,0,2)  2 (10,1,2) 4 (10,2,2) 5 (10,3,2) 3
         (11,0,2)  2 (11,1,2) 4 (11,2,2) 5 (11,3,2) 3
         ]
cap_ccc: [(4) 200 (5) 200 (6) 200]
cap_ccc_m: [     (0,4) 200 (1,4) 200 (2,4) 200
                 (0,5) 200 (1,5) 200 (2,5) 200
                 (0,6) 200 (1,6) 200 (2,6) 200
]
cost_ccc: [(4) 10 (5) 10 (6) 10]
max_ccc: 3
```

Figure 15 Example of a Main Data input file for the Reverse Multi Material Model

9.2.1.7 *Reverse Multi Period Model*

The input files required for the *Reverse Multi Period Model* are two: the **Main Data** file and **Travelling Costs** file. They are similar to the *Basic Reverse Model* ones, where the main difference is that the material requests and the reverse logistic requests also depend on the periods. Details are given in Table 11 and an example is provided in Figure 16.

Table 11 FL Reverse Multi Period Model Data

Name	meaning	size	type
	First input file: Main Data		
coorx	x coordinates of the vertices	Array of vertices	double
coory	y coordinates of the vertices	Array of vertices	double

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

s_supp	The vertices are ordered starting from suppliers, then CCCs, and terminating with the construction sites. s_supp identifies the starting index of the suppliers (it is supposed to be 0) into the vertex array	Number	integer
s_ccc	Starting index of the CCC into the vertex array	Number	integer
s_sites	Starting index of the sites into the vertex array	Number	integer
q	Material requests quantity defined by origin (supplier), destination (construction site), and period	Three dimensional Matrix (suppliers, construction sites, periods)	double
r	Request for reverse logistics that is a quantity defined by its origin (a construction site) and its destination (supplier/dumpsite), and period	Three dimensional Matrix (construction site, suppliers, periods)	double
cap_ccc	capacity of each CCC	Array of CCCs	double
cost_ccc:	costs of opening CCCs	Array of CCCs	double
max_ccc	Maximum number of CCCs that can be opened	number	double
Second input file: Travelling Costs			
cost	Matrix of costs /distance among the vertices of the network. The cost between the same vertex is set to a high value to avoid that trip into the model.	Vertex by vertex matrix	Double

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

```
coorx: [(0) 0 (1) 40 (2) 0 (3) 70 (4) 60 (5) 27 (6) 10 (7) 30 (8) 15 (9) 35 (10) 50 (11) 43]
coory: [(0) 0 (1)  0 (2) 50(3) 70 (4) 6  (5) 60 (6) 20 (7) 40 (8) 52 (9) 35 (10) 30 (11) 23]
s_supp: 0
s_ccc: 4
s_sites: 7
q: [    (0,7,0)   10 (1,7,0)  4 (2,7,0)  8 (3,7,0)  9
        (0,8,0)   10 (1,8,0)  4 (2,8,0)  8 (3,8,0)  9
        (0,9,0)   10 (1,9,0)  4 (2,9,0)  8 (3,9,0)  9
        (0,10,0)  10 (1,10,0) 4 (2,10,0) 8 (3,10,0) 9
        (0,11,0)  10 (1,11,0) 4 (2,11,0) 8 (3,11,0) 9
        (0,7,1)   1 (1,7,1)  2 (2,7,1)  9 (3,7,1)  3
        (0,8,1)   1 (1,8,1)  2 (2,8,1)  9 (3,8,1)  3
        (0,9,1)   1 (1,9,1)  2 (2,9,1)  9 (3,9,1)  3
        (0,10,1)  1 (1,10,1) 2 (2,10,1) 9 (3,10,1) 3
        (0,11,1)  1 (1,11,1) 2 (2,11,1) 9 (3,11,1) 3
        (0,7,2)   5 (1,7,2)  6 (2,7,2)  4 (3,7,2)  7
        (0,8,2)   5 (1,8,2)  6 (2,8,2)  4 (3,8,2)  7
        (0,9,2)   5 (1,9,2)  6 (2,9,2)  4 (3,9,2)  7
        (0,10,2)  5 (1,10,2) 6 (2,10,2) 4 (3,10,2) 7
        (0,11,2)  5 (1,11,2) 6 (2,11,2) 4 (3,11,2) 7
        ]
r: [    (7,0,0)   2 (7,1,0)  4 (7,2,0)  5 (7,3,0)  3
        (8,0,0)   2 (8,0,0)  4 (8,2,0)  5 (8,3,0)  3
        (9,0,0)   2 (9,1,0)  4 (9,2,0)  5 (9,3,0)  3
        (10,0,0)  2 (10,1,0) 4 (10,2,0) 5 (10,3,0) 3
        (11,0,0)  2 (11,1,0) 4 (11,2,0) 5 (11,3,0) 3
        (7,0,1)   2 (7,1,1)  4 (7,2,1)  5 (7,3,1)  3
        (8,0,1)   2 (8,0,1)  4 (8,2,1)  5 (8,3,1)  3
        (9,0,1)   2 (9,1,1)  4 (9,2,1)  5 (9,3,1)  3
        (10,0,1)  2 (10,1,1) 4 (10,2,1) 5 (10,3,1) 3
        (11,0,1)  2 (11,1,1) 4 (11,2,1) 5 (11,3,1) 3
        (7,0,2)   2 (7,1,2)  4 (7,2,2)  5 (7,3,2)  3
        (8,0,2)   2 (8,0,2)  4 (8,2,2)  5 (8,3,2)  3
        (9,0,2)   2 (9,1,2)  4 (9,2,2)  5 (9,3,2)  3
        (10,0,2)  2 (10,1,2) 4 (10,2,2) 5 (10,3,2) 3
        (11,0,2)  2 (11,1,2) 4 (11,2,2) 5 (11,3,2) 3
        ]
cap_ccc: [(4) 200 (5) 200 (6) 200]|
cost_ccc: [(4) 10 (5) 10 (6) 10]
max_ccc: 3
```

Figure 16 Example of a Main Data input file for the Reverse Multi Period Model

9.2.1.8 *Reverse Multi Period Multi Material Model*

The input data for the *Reverse Multi Period Multi Material Model* are inserted into two .txt files similar to those required to the previous models: the **Main Data** file and **Travelling Costs** file. In this case, the material requests and the revers logistic requests depend on both the materials and the periods in addition to the origin and destination. Moreover, a maximum capacity is set on each CCC for different materials. See Table 12 for details and Figure 17 for an example.

Table 12 FL Reverse Multi Period Multi Material Model Data

Name	meaning	size	type
	First input file: Main Data		
coorx	x coordinates of the vertices	Array of vertices	double
coory	y coordinates of the vertices	Array of vertices	double

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

s_supp	The vertices are ordered starting from suppliers, then CCCs, and terminating with the construction sites. s_supp identifies the starting index of the suppliers (it is supposed to be 0) into the vertex array	Number	integer
s_ccc	Starting index of the CCC into the vertex array	Number	integer
s_sites	Starting index of the sites into the vertex array	Number	integer
q	Material requests quantity defined by origin (supplier), destination (construction site), material, and period.	Three dimensional Matrix (suppliers, construction sites, materials, periods)	double
r	Request for reverse logistics that is a quantity defined by its origin (a construction site) and its destination (supplier/dumpsite), material, and period	Three dimensional Matrix (construction site, suppliers, materials, periods)	double
cap_ccc	Capacity of each CCC	Array of CCCs	double
cap_ccc_m	Capacity of different materials in each CCC	Matrix of (CCCs, materials)	double
cost_ccc:	Costs of opening CCCs	Array of CCCs	double
max_ccc	Maximum number of CCCs that can be opened	Number	double
Second input file: Travelling Costs			
cost	Matrix of costs /distance among the vertices of the network. The cost between the same vertex is set to a high value to avoid that trip into the model.	Vertex by vertex matrix	Double

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

```
coorx: [(0) 0 (1) 40 (2) 0 (3) 70 (4) 60 (5) 27 (6) 10 (7) 30 (8) 15 (9) 35 (10) 50 (11) 43]
coory: [(0) 0 (1)  0 (2) 50(3) 70 (4) 6  (5) 60 (6) 20 (7) 40 (8) 52 (9) 35 (10) 30 (11) 23]
s_supp: 0
s_ccc: 4
s_sites: 7
q: [    (0,7,0,0)  10 (0,7,0,1)  9 (1,7,0,0)  4  (1,7,0,1)  3 (2,7,0,0)  8  (2,7,0,1)  7 (3,7,0,0)  9  (3,7,0,1)  8
        (0,8,0,0)  10 (0,8,0,1)  9 (1,8,0,0)  4  (1,8,0,1)  3 (2,8,0,0)  8  (2,8,0,1)  7 (3,8,0,0)  9  (3,8,0,1)  8
        (0,9,0,0)  10 (0,9,0,1)  9 (1,9,0,0)  4  (1,9,0,1)  3 (2,9,0,0)  8  (2,9,0,1)  7 (3,9,0,0)  9  (3,9,0,1)  8
        (0,10,0,0) 10 (0,10,0,1) 9 (1,10,0,0) 4  (1,10,0,1) 3 (2,10,0,0) 8  (2,10,0,1) 7 (3,10,0,0) 9  (3,10,0,1) 8
        (0,11,0,0) 10 (0,11,0,1) 9 (1,11,0,0) 4  (1,11,0,1) 3 (2,11,0,0) 8  (2,11,0,1) 7 (3,11,0,0) 9  (3,11,0,1) 8
        (0,7,1,0)  1  (0,7,1,1)  2 (1,7,1,0)  2  (1,7,1,1)  3 (2,7,1,0)  9  (2,7,1,1)  10 (3,7,1,0)  3  (3,7,1,1)  4
        (0,8,1,0)  1  (0,8,1,1)  2 (1,8,1,0)  2  (1,8,1,1)  3 (2,8,1,0)  9  (2,8,1,1)  10 (3,8,1,0)  3  (3,8,1,1)  4
        (0,9,1,0)  1  (0,9,1,1)  2 (1,9,1,0)  2  (1,9,1,1)  3 (2,9,1,0)  9  (2,9,1,1)  10 (3,9,1,0)  3  (3,9,1,1)  4
        (0,10,1,0) 1  (0,10,1,1) 2 (1,10,1,0) 2  (1,10,1,1) 3 (2,10,1,0) 9  (2,10,1,1) 10 (3,10,1,0) 3  (3,10,1,1) 4
        (0,11,1,0) 1  (0,11,1,1) 2 (1,11,1,0) 2  (1,11,1,1) 3 (2,11,1,0) 9  (2,11,1,1) 10 (3,11,1,0) 3  (3,11,1,1) 4
        (0,7,2,0)  5  (0,7,2,1)  4 (1,7,2,0)  6  (1,7,2,1)  5 (2,7,2,0)  4  (2,7,2,1)  3 (3,7,2,0)  7  (3,7,2,1)  6
        (0,8,2,0)  5  (0,8,2,1)  4 (1,8,2,0)  6  (1,8,2,1)  5 (2,8,2,0)  4  (2,8,2,1)  3 (3,8,2,0)  7  (3,8,2,1)  6
        (0,9,2,0)  5  (0,9,2,1)  4 (1,9,2,0)  6  (1,9,2,1)  5 (2,9,2,0)  4  (2,9,2,1)  3 (3,9,2,0)  7  (3,9,2,1)  6
        (0,10,2,0) 5  (0,10,2,1) 4 (1,10,2,0) 6  (1,10,2,1) 5 (2,10,2,0) 4  (2,10,2,1) 3 (3,10,2,0) 7  (3,10,2,1) 6
        (0,11,2,0) 5  (0,11,2,1) 4 (1,11,2,0) 6  (1,11,2,1) 5 (2,11,2,0) 4  (2,11,2,1) 3 (3,11,2,0) 7  (3,11,2,1) 6
        ]
r: [    (7,0,0,0)   2 (7,1,0,0)  4 (7,2,0,0)  5 (7,3,0,0)  3 (7,0,0,1)   2 (7,1,0,1)  4 (7,2,0,1)  5 (7,3,0,1)  3
        (8,0,0,0)   2 (8,1,0,0)  4 (8,2,0,0)  5 (8,3,0,0)  3 (8,0,0,1)   2 (8,0,0,1)  4 (8,2,0,1)  5 (8,3,0,1)  3
        (9,0,0,0)   2 (9,1,0,0)  4 (9,2,0,0)  5 (9,3,0,0)  3 (9,0,0,1)   2 (9,1,0,1)  4 (9,2,0,1)  5 (9,3,0,1)  3
        (10,0,0,0)  2 (10,1,0,0) 4 (10,2,0,0) 5 (10,3,0,0) 3 (10,0,0,1)  2 (10,1,0,1) 4 (10,2,0,1) 5 (10,3,0,1) 3
        (11,0,0,0)  2 (11,1,0,0) 4 (11,2,0,0) 5 (11,3,0,0) 3 (11,0,0,1)  2 (11,1,0,1) 4 (11,2,0,1) 5 (11,3,0,1) 3
        (7,0,1,0)   2 (7,1,1,0)  4 (7,2,1,0)  5 (7,3,1,0)  3 (7,0,1,1)   2 (7,1,1,1)  4 (7,2,1,1)  5 (7,3,1,1)  3
        (8,0,1,0)   2 (8,0,1,0)  4 (8,2,1,0)  5 (8,3,1,0)  3 (8,0,1,1)   2 (8,0,1,1)  4 (8,2,1,1)  5 (8,3,1,1)  3
        (9,0,1,0)   2 (9,1,1,0)  4 (9,2,1,0)  5 (9,3,1,0)  3 (9,0,1,1)   2 (9,1,1,1)  4 (9,2,1,1)  5 (9,3,1,1)  3
        (10,0,1,0)  2 (10,1,1,0) 4 (10,2,1,0) 5 (10,3,1,0) 3 (10,0,1,1)  2 (10,1,1,1) 4 (10,2,1,1) 5 (10,3,1,1) 3
        (11,0,1,0)  2 (11,1,1,0) 4 (11,2,1,0) 5 (11,3,1,0) 3 (11,0,1,1)  2 (11,1,1,1) 4 (11,2,1,1) 5 (11,3,1,1) 3
        (7,0,2,0)   2 (7,1,2,0)  4 (7,2,2,0)  5 (7,3,2,0)  3 (7,0,2,1)   2 (7,1,2,1)  4 (7,2,2,1)  5 (7,3,2,1)  3
        (8,0,2,0)   2 (8,0,2,0)  4 (8,2,2,0)  5 (8,3,2,0)  3 (8,0,2,1)   2 (8,0,2,1)  4 (8,2,2,1)  5 (8,3,2,1)  3
        (9,0,2,0)   2 (9,1,2,0)  4 (9,2,2,0)  5 (9,3,2,0)  3 (9,0,2,1)   2 (9,1,2,1)  4 (9,2,2,1)  5 (9,3,2,1)  3
        (10,0,2,0)  2 (10,1,2,0) 4 (10,2,2,0) 5 (10,3,2,0) 3 (10,0,2,1)  2 (10,1,2,1) 4 (10,2,2,1) 5 (10,3,2,1) 3
        (11,0,2,0)  2 (11,1,2,0) 4 (11,2,2,0) 5 (11,3,2,0) 3 (11,0,2,1)  2 (11,1,2,1) 4 (11,2,2,1) 5 (11,3,2,1) 3
        ]
cap_ccc: [(4) 200 (5) 200 (6) 200]
cap_ccc_m: [    (0,4) 200 (1,4) 200 (2,4) 200
                (0,5) 200 (1,5) 200 (2,5) 200
                (0,6) 200 (1,6) 200 (2,6) 200
]
cost_ccc: [(4) 10 (5) 10 (6) 10]
max_ccc: 3
```

Figure 17 Example of a Main Data input file for the Reverse Multi Period Multi Material Model

9.2.1.9 *Basic Reverse and Direct Model*

The input required by the *Basic Reverse and Direct Model* is included into two .txt files that are similar to those required by the *Basic Reverse Model:* the **Main Data** file and **Travelling Costs** file. Because the direct shipping is taken into account in this model, a cost for direct shipping is included into the cost / distance matrix into Travelling Costs file. The direct costs could also be the distance or a function of it.

Table 13 FL Basic Reverse and Direct Model Data

Name	meaning	size	type
	First input file: Main Data		
coorx	x coordinates of the vertices	Array of vertices	double
coory	y coordinates of the vertices	Array of vertices	double
s_supp	The vertices are ordered starting from suppliers, then CCCs, and terminating with the construction sites. s_supp identifies the starting index of the suppliers (it is supposed to be 0) into the vertex array	Number	integer

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s_ccc	Starting index of the CCC into the vertex array	Number	integer
s_sites	Starting index of the sites into the vertex array	Number	integer
q	Material requests defined by origin (supplier), destination (construction site), and quantity.	Matrix (suppliers, construction sites)	double
r	Request for reverse logistics that is a quantity defined by its origin (a construction site) and its destination (supplier/dumpsite)	Matrix (construction site, suppliers)	double
cap_ccc	Capacity of each CCC	Array of CCCs	double
cost_ccc:	Costs of opening each CCC	Array of CCCs	double
max_ccc	Maximum number of CCCs that can be opened	Number	double
Second input file: Travelling Costs			
cost	Matrix of costs / distance among the vertices of the network. The cost between the same vertex is set to a high value to avoid that trip into the model. Into the same matrix it is included the cost for direct shipping, for instance in position (i,j) of the matrix, where i is a supplier and j is a construction site.	Vertex by vertex matrix	Double

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

```
coorx: [(0) 0 (1) 40 (2) 0 (3) 70 (4) 60 (5) 27 (6) 10 (7) 30 (8) 15 (9) 35 (10) 50 (11) 43]
coory: [(0) 0 (1)  0 (2) 50(3) 70 (4) 6  (5) 60 (6) 20 (7) 40 (8) 52 (9) 35 (10) 30 (11) 23]
s_supp: 0
s_ccc: 4
s_sites: 7
q: [    (0,7)   2 (1,7)  4 (2,7)  5 (3,7)  3
        (0,8)   2 (1,8)  4 (2,8)  5 (3,8)  3
        (0,9)   2 (1,9)  4 (2,9)  5 (3,9)  3
        (0,10)  2 (1,10) 4 (2,10) 5 (3,10) 3
        (0,11)  2 (1,11) 4 (2,11) 5 (3,11) 3
        ]
r: [    (7,0)   2 (7,1)  4 (7,2)  5 (7,3)  3
        (8,0)   2 (8,0)  4 (8,2)  5 (8,3)  3
        (9,0)   2 (9,1)  4 (9,2)  5 (9,3)  3
        (10,0)  2 (10,1) 4 (10,2) 5 (10,3) 3
        (11,0)  2 (11,1) 4 (11,2) 5 (11,3) 3
        ]
cap_ccc: [(4) 200 (5) 200 (6) 200]
cost_ccc: [(4) 10 (5) 10 (6) 10]
max_ccc: 3
```

Figure 18 Example of a Main Data input file for the Basic Reverse and Direct Model

9.2.1.10 *Stochastic Basic Model*

In order to solve more effectively the problem with the use of the Bender's decomposition for stochastic problems, the L-shaped method, we made use a C++ algorithm recalling the functions of Cplex, an IBM cutting-edge solver for mathematical programming. In this case the inputs to feed the algorithm are slightly different to those presented previously. The following information is required to be inserted in a precise order into the input .txt file as specified in Table 14. An example can be found in Figure 19. To be clarified that all data must be inserted into the same file and that a new important piece of information is required, the probability of each scenario.

Table 14 Stochastic Basic Model Data

Name	meaning	size	type
n_vertices	An integer number that gives the total number of suppliers, sites, CCCs, and dumpsites.	number	integer
n_suppliers	An integer providing the number of suppliers and dumpsites	number	integer
n_ccc	An integer providing the total number of evaluated CCC locations	number	integer
n_sites	An integer providing the total number of construction sites	number	Integer
n_scenarios	The number of stochastic scenarios considered	number	Integer

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

coor_x	An array of x coordinated of the vertices	Array of vertices	Double
coor_y	An array of y coordinated of the vertices	Array of vertices	Double
distance/cost	Matrix of distances / costs between each couple of vertices. The diagonal must have large enough values.	Matrix (n_vertices, n_vertices)	Double
demand	The 3-dimensional matrix defining the demand of materials with respect to its origin, its destination, and the stochastic scenario.	Three dimensional matrix (suppliers, construction sites, scenarios)	double
cap_ccc	The maximum capacities of the evaluated CCCs.	Array of CCCs	double
cost_ccc	The cost of opening the evaluated CCCs.	Array of CCCs	double
max_ccc	The maximum number of CCCs that can be opened	Number	integer
probability	Probability of each stochastic scenario, the sum of the probabilities must equal 1.	Array of scenarios	double

```
12
4
3
5
3
49.632963 49.724332 49.094425 50.456017 50.692273 50.082570 49.8451 49.4263 49.9561 50.975 50.1263 50.96663
6.130715  6.65637440 6.199099 4.8713836070 7.15564060 5.926008 6.25631  6.16548 6.7563 4.01470 7.56874 5.12458
999999  0.533541        0.542862        1.50444 1.47398 0.494016        0.246528        0.209567        0.704112        2.50571 1.5203  1.67062
0.533541        999999  0.778385        1.92913 1.08912 0.813492        0.417895        0.574282        0.252392        2.92278 0.99699 1.97223
0.542862        0.778385        999999  1.90178 1.86228 1.02519 0.752852        0.333573        1.02614 2.88239 1.71484 2.15864
1.50444 1.92913 1.90178 999999  2.29644 1.11879 1.51368 1.65378 1.95008 1.00162 2.71743 0.569942
1.47398 1.08912 1.86228 2.29644 999999  1.37249 1.23552 1.6072  0.83751 3.15364 0.700697        2.04951
0.494016        0.813492        1.02519 1.11879 1.37249 999999  0.406806        0.698597        0.839869        2.10939 1.64331 1.19325
0.246528        0.417895        0.752852        1.51368 1.23552 0.406806        999999  0.428536        0.512163        2.51028 1.34222 1.59331
0.209567        0.574282        0.333573        1.65378 1.6072  0.698597        0.428536        999999  0.793572        2.65034 1.56816 1.85906
0.704112        0.252392        1.02614 1.95008 0.83751 0.839869        0.512163        0.793572        999999  2.92481 0.830076        1.91929
2.50571 2.92278 2.88239 1.00162 3.15364 2.10939 2.51028 2.65034 2.92481 999999  3.65397 1.10991
1.5203  0.99699 1.71484 2.71743 0.700697        1.64331 1.34222 1.56816 0.830076        3.65397 999999  2.58458
1.67062 1.97223 2.15864 0.569942        2.04951 1.19325 1.59331 1.85906 1.91929 1.10991 2.58458 999999
1 1 1 1 1
1 1 1 1 1
1 1 1 1 1
1 1 1 1 1
2 2 2 2 2
2 2 2 2 2
2 2 2 2 2
2 2 2 2 2
3 3 3 3 3
3 3 3 3 3
3 3 3 3 3
3 3 3 3 3
100
10 10 10
3
0.3 0.4 0.3
```

Figure 19 Example of an input file for the Stochastic Basic Model

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

9.2.1.11 Stochastic Multi Period Multi Material Reverse Direct with different set of materials Model

As for the previous model, the *Stochastic Multi Period Multi Material Reverse Direct with different set of materials Model* requires only one .txt input file. Some new information is required to reflect the novel complexity of the model, such as: the number of different types of materials that must be supplied or disposed via CCC and the number of different material that can be supplied and returned directly. Other newly required data are the material depending capacities inside each CCC. However, the main novelty is the different method for reading the material demands; indeed, the increase of parameter on which the material demand can depend would have made very uneasy to read a multi-dimensional matrix full of null values anymore. The model still makes use of a multi-dimensional matrix to store data, but the data reading system requires only defining the indexes of the matrix and the positive values to be stored. For example, let us say that in scenario 1, in period 5, we must supply 500 of material 2 among the materials that must be supplied via CCC (mat_ccc) from supplier 3 to site 4; thus we will need to insert a line that includes this information for each material request. The line would be

<Scenario_id> <period_id> <material_id> <material_type_id> <supplier_id> <site_id quantity>

That for the example would be:

1 5 2 0 3 4 500

We recall that

- the material_type ids are the following: 0 for *mat_ccc*, 1 for *mat_ccc_rev*, 2 for *mat_both*, and 3 for *mat_both_rev*.
- the supplier and the site are respectively the origin and the destination for materials of types *mat_ccc* and *mat_both*.
- the supplier and the site are respectively the destination and the origin for materials of types *mat_ccc_rev* and *mat_both_rev*.
- the number of total lines n_demands representing the demands must be inserted before the demands.

Details the data required are reported in Table 15 and an example can be found in Figure 20.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

Table 15 Stochastic Multi Period Multi Material Reverse Direct with different set of materials model Data

Name	meaning	size	type
n_vertices	Integer number that gives the total number of suppliers, sites, CCCs, and dumpsites.	Number	integer
n_suppliers	Integer providing the number of suppliers and dumpsites	Number	integer
n_ccc	Integer providing the total number of evaluated CCC locations	Number	integer
n_sites	Integer providing the total number of construction sites	Number	integer
n_scenarios	Number of stochastic scenarios	Number	integer
n_mat_ccc	Number of materials that must be supplied via CCC	Number	integer
n_mat_ccc_rev	Number of materials that must be collected and returned via CCC	Number	integer
n_mat_both	Number of materials that can be supplied both directly or via CCC	Number	integer
n_mat_both_rev	Number of materials that can be collected and returned both directly or via CCC	Number	integer
n_periods	Number of periods	Number	integer
coor_x	x coordinated of the vertices	Array of vertices	double
coor_y	y coordinated of the vertices	Array of vertices	double
distance/cost	Matrix of distances / costs between each couple of vertices. The diagonal must have large enough values.	Matrix (n_vertices, n_vertices)	double
n_demands	Number of the lines representing the demands as expressed in the following line.	Number	integer

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

demand	List of lines including the indices of all the information regarding the demand quantity. Better explained: each line should have indicated the following numbers: • Scenario id of the demand • Period id of the demand • Material id of the demand • Material type id (0 for mat_ccc, 1 for mat_ccc_rev, 2 for mat_both,. 3 for mat_both_rev) • Supplier id of the demand (if material type is 0 or 2 this is the origin, the destination otherwise) • Site id of the demand (if material type is 0 or 2 this is the destination, the origin otherwise) • The quantity of the demand expressed in the desired unit (weight or volume)	List of lines (1,1,1,1,1,1,1)	(integer, integer, integer, integer, integer, integer, double)
cap_ccc	Maximum capacities of the evaluated CCCs.	Array of CCCs	double
cost_ccc	Cost of opening the evaluated CCCs.	Array of CCCs	double
max_ccc	Maximum number of CCCs that can be opened	Number	integer
cap_mat_ccc	Maximum capacity for each material of the mat_ccc type for each CCCs	Matrix (CCCs, mat_ccc)	double
cap_mat_ccc_rev	Maximum capacity for each material of the mat_ccc_rev type for each CCCs	Matrix (CCCs, mat_ccc_rev)	double
cap_mat_both	Maximum capacity for each material of the mat_both type for each CCCs	Matrix (CCCs, mat_both)	double

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cap_mat_both_rev	Maximum capacity for each material of the mat_both_rev type for each CCCs	Matrix (CCCs, mat_both_rev)	double
probability	Probability of each stochastic scenario, the sum of the probabilities must equal 1.	Array of scenarios	double

In Figure 20 one can find the first required data, the coordinates and the cost matrix (these not complete for page layout reasons), the number of request rows (730) and the first five request lines.

```
52
43
4
5
3
1
1
24
2
7
45.4827606      45.744472       45.7446036      45.7414426      44.5459624      45.9859208      45.418567       45.5701519      42.1219109
10.8674898      12.8470599      12.8460871      11.7264343      10.8442909      12.6200916      10.9300325      11.8962235      13.8403907
9999999 186.223 186.299 108.602 120.491 202.901 12.907  114.256 117.716 562.173 467.914 110.398 448.695 174.557 203.096 485.289 142.15  80.55
195.062 9999999 0.077   107.227 263.68  37.561  187.609 95.249  92.415  630.017 554.974 290.675 535.755 28.332  37.757  553.133 322.427 151.0
195.139 0.077   9999999 107.304 263.757 37.638  187.686 95.325  92.492  630.094 555.051 290.752 535.832 28.409  37.834  553.21  322.504 151.0
104.831 102.358 102.435 9999999 203.635 98.265  97.378  29.732  35.807  572.627 497.584 200.444 478.365 79.5    98.46   495.743 232.197 32.72
115.619 250.816 250.893 201.038 9999999 267.494 112.838 185.074 180.247 465.551 371.292 125.276 352.073 239.15  267.69  388.667 172.812 172.9
200.242 37.934  38.011  99.969  268.86  9999999 192.789 100.429 97.595  635.197 560.155 295.855 540.936 28.955  0.192   558.313 327.607 156.1
11.064  178.273 178.35  100.653 116.337 194.952 9999999 106.307 109.767 558.019 463.76  109.013 444.541 166.607 195.147 481.135 140.765 72.60
112.641 91.857  91.934  28.846  187.481 102.886 105.188 9999999 5.274   553.818 478.776 208.254 459.557 80.191  103.082 476.935 240.006 46.51
113.197 88.549  88.626  36.219  181.793 99.578  105.744 5.452   9999999 548.13  473.087 208.81  453.868 76.883  99.774  471.246 240.562 69.15
562.013 620.533 620.61  586.918 469.405 637.212 559.232 554.791 549.965 9999999 185.817 571.67  166.632 608.868 637.407 99.878  619.206 580.7
466.294 543.709 543.786 510.093 373.685 560.388 463.513 477.967 473.14  189.131 9999999 475.951 57.328  532.043 560.583 213.875 523.486 503.9
116.328 278.998 279.075 201.378 129.566 295.677 107.807 207.031 210.492 571.248 476.989 9999999 457.77  267.332 295.872 494.364 83.351  173.3
451.407 528.822 528.899 495.206 358.798 545.5   448.625 463.08  458.253 167.097 54.19   461.064 9999999 517.156 545.696 185.296 508.599 489.0
178.325 28.224  28.301  78.661  246.943 31.345  170.872 78.512  75.678  613.28  538.238 273.938 519.019 9999999 31.54   536.396 305.69  134.2
200.437 38.129  38.206  100.164 269.055 0.192   192.984 100.624 97.79   635.392 560.35  296.05  541.131 29.151  9999999 558.508 327.803 156.3
483.348 541.868 541.945 508.253 390.74  558.547 480.567 476.126 471.3   98.708  210.206 493.005 184.045 530.203 558.742 9999999 540.541 502.0
155.543 318.213 318.29  240.593 177.04  334.892 147.022 246.246 249.707 618.722 524.463 84.619  505.244 306.547 335.087 541.838 9999999 212.5
78.894  139.677 139.754 33.01   177.697 156.356 71.441  49.19   71.171  577.355 502.313 174.507 483.094 128.011 156.551 500.472 206.259 99999
36.943  199.982 200.059 122.362 103.082 216.661 22.246  128.015 131.476 544.764 450.506 80.012  431.287 188.316 216.856 467.88  143.251 94.31
120.42  283.09  283.167 205.47  208.897 299.769 111.899 211.123 214.584 650.579 556.32  67.474  537.101 271.424 299.964 573.695 35.956  177.4
115.495 278.165 278.242 200.544 212.604 294.843 106.974 206.198 209.658 654.285 560.027 100.435 540.808 266.499 295.038 577.402 63.555  172.4
115.739 278.409 278.486 200.789 212.848 295.087 107.218 206.442 209.903 654.53  560.271 100.679 541.052 266.743 295.283 577.646 63.799  172.7
118.871 241.738 241.815 204.29  10.973  258.417 116.09  175.996 171.169 456.473 362.215 128.528 342.995 230.072 258.612 379.589 176.064 176.2
129.925 292.595 292.672 214.975 205.829 309.274 121.404 220.628 224.089 647.511 553.252 70.486  534.033 280.929 309.469 570.627 32.888  186.9
504.45  327.608 327.685 416.616 573.068 348.109 496.997 404.637 401.803 939.405 864.363 600.063 845.144 345.92  348.304 862.522 631.816 460.4
562.047 620.567 620.644 586.951 469.439 637.246 559.266 554.825 549.998 0.125   185.851 571.704 166.666 608.901 637.441 99.911  619.24  580.7
100.68  144.442 144.519 5.031   199.484 100.867 93.227  32.262  38.409  582.026 506.984 196.293 487.765 82.102  101.063 505.142 228.046 29.62
36.432  188.422 188.499 110.802 107.353 205.101 27.783  116.455 119.916 549.035 454.777 132.663 435.558 176.756 205.296 472.151 164.416 82.75
116.089 267.384 267.461 201.508 14.773  284.063 113.308 207.161 196.815 482.119 387.861 111.926 368.642 255.719 284.258 405.236 159.462 173.4
256.902 419.571 419.648 341.951 248.571 436.25  248.38  347.604 351.065 690.253 595.994 155.049 576.775 407.905 436.445 613.369 129.607 313.9
562.013 620.533 620.61  586.918 469.405 637.212 559.232 554.791 549.965 0       185.817 571.67  166.632 608.868 637.407 99.878  619.206 580.7
134.735 297.405 297.482 219.785 204.102 314.084 126.214 225.438 228.899 645.784 551.526 74.803  532.307 285.739 314.279 568.901 31.161  191.7
346.59  424.005 424.082 390.389 253.982 440.684 343.809 358.263 353.436 376.242 193.251 365.369 222.581 412.34  440.879 400.985 412.905 384.2
98.284  261.323 261.4   183.703 63.195  278.002 95.503  189.356 192.817 504.877 410.618 84.223  391.399 249.657 278.197 427.993 131.758 155.6
165.779 42.885  42.962  69.118  234.398 37.782  158.326 65.966  63.133  600.735 525.692 261.393 506.473 12.356  37.977  523.851 293.145 121.7
164.931 327.601 327.678 249.981 183.602 344.28  156.41  255.634 259.095 625.283 531.025 91.18   511.806 315.935 344.475 548.4   12.699  221.9
245.922 408.591 408.668 330.971 229.808 425.27  237.4   336.625 340.085 671.49  504.068 136.286 484.849 396.925 425.465 594.606 111.035 302.9
113.599 263.833 263.91  199.018 7.39    280.512 110.818 198.091 193.264 478.568 384.31  123.256 365.091 252.167 280.707 401.684 170.791 170.9
159.595 322.264 322.341 244.644 206.157 338.943 151.073 250.297 253.758 647.839 553.581 113.736 534.362 310.598 339.138 570.955 35.336  216.5
244.658 303.178 303.255 269.562 152.05  319.857 241.877 237.436 232.609 320.869 311.566 254.315 257.314 291.512 320.052 243.985 301.851 263.3
77.042  137.826 137.903 34.156  175.846 154.505 69.589  44.757  69.32   575.504 500.462 172.656 481.243 126.16  154.7   498.62  204.408 2.611
10.828  171.768 171.845 94.148  123.684 188.446 10.022  99.801  103.262 565.366 471.107 120.975 451.888 160.102 188.642 488.482 152.727 66.09
14.343  172.855 172.932 95.235  116.758 189.534 5.694   100.888 104.349 558.439 464.181 113.567 444.962 161.189 189.729 481.556 145.319 67.18
13.285  175.4   175.477 97.78   118.308 192.079 3.636   103.433 106.894 559.99  465.731 115.599 446.512 163.734 192.274 483.106 147.351 69.73
16.318  169.945 170.022 92.325  119.649 186.624 7.022   97.978  101.439 561.331 467.072 116.459 447.853 158.279 186.819 484.447 148.211 64.27
10.738  173.984 174.061 96.363  125.692 190.662 12.03   102.017 105.477 567.374 473.115 122.983 453.896 162.318 190.857 490.49  154.735 68.31
18.501  167.65  167.727 90.03   131.164 184.329 9.205   95.684  99.144  572.846 478.587 127.973 459.368 155.985 184.524 495.962 159.726 61.98
11.94   177.569 177.646 99.948  121.94  194.247 8.278   105.602 109.062 563.622 469.363 119.231 450.144 165.903 194.442 486.738 150.983 71.9
19.336  171.694 171.771 94.074  118.264 188.373 10.687  99.728  103.188 559.946 465.687 115.073 446.468 160.028 188.568 483.062 146.826 66.02
16.531  171.762 171.839 94.142  115.664 188.441 7.882   99.795  103.256 557.346 463.088 112.474 443.869 160.096 188.636 480.462 144.226 66.09
19.336  171.694 171.771 94.074  118.264 188.93  4.727   100.285 103.745 557.836 463.577 112.963 444.358 160.585 189.125 480.952 144.716 66.58
16.531  171.762 171.839 94.142  115.664 185.9   6.927   97.255  100.715 561.236 466.978 116.364 447.759 157.556 186.095 484.352 148.116 63.55
730
0       4       0       0       39      2       991
0       5       0       0       39      2       277
0       6       0       0       39      2       108
0       0       0       1       0       2       1033
0       1       0       1       0       2       189
```

Figure 20 Example of Stochastic Multi Period Multi Material Reverse Direct with different set of materials Model Data

In Figure 21 one can find an highlight of an exaple input, in particular the last set of demands lines and the remaining required data.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

```
2         4         2         2         22        4         3751
2         4         4         2         5         4         431
2         4         4         2         9         4         473
2         4         4         2         25        4         1654
2         4         8         2         27        4         236
2         4         13        2         23        4         7547
2         4         16        2         19        4         8961
2         4         17        2         39        4         46041
2         4         18        2         6         4         37295
2         4         20        2         24        4         4740
2         4         21        2         18        4         3593
2         4         22        2         40        4         7949
2         5         4         2         14        4         23340
2         5         4         2         30        4         32860
2         5         8         2         27        4         5237
2         5         12        2         17        4         3054
2         5         13        2         31        4         3813
2         5         14        2         29        4         99705
2         5         19        2         26        4         11988
2         6         0         2         3         4         3168
2         6         2         2         37        4         153
2         6         4         2         5         4         1371
2         6         4         2         30        4         4452
2         6         10        2         34        4         4769
2         6         14        2         35        4         6560
2         6         15        2         21        4         3412
2         6         18        2         36        4         2248
2         6         19        2         26        4         713
2         6         22        2         11        4         12907
2         6         22        2         32        4         5110
2         6         23        2         33        4         1820
2         0         1         3         0         4         141
2         1         1         3         1         4         7136
2         2         1         3         1         4         20072
2         3         1         3         1         4         2977
2         5         1         3         1         4         2167
2         6         1         3         1         4         556
100000000
100000    100000    100000    100000
3
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
0.3       0.5       0.2
```

Figure 21 Other Example of Stochastic Multi Period Multi Material Reverse Direct with different set of materials model Data

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

9.2.1.12 *Multi Period with Inventory Model*

The input data required for *Multi Period with Inventory Model* must be inserted into two.txt files: the **Main Data** file and **Travelling Costs** file. The Main Data input file for *Multi Period with Inventory Model* includes, with respect to those required for the previous models, the following new input data linked to inventory: cost_invent, cap_in, cap_out. In Table 16 all the data are reported and an example is provided in Figure 22.

Table 16 FL Multi Period with Inventory Model Data

Name	meaning	size	type
	First input file: Main Data		
coorx	x coordinates of the vertices	Array of vertices	double
coory	y coordinates of the vertices	Array of vertices	double
s_supp	The vertices are ordered starting from suppliers, then CCCs, and terminating with the construction sites. s_supp identifies the starting index of the suppliers (it is supposed to be 0) into the vertex array	Number	integer
s_ccc	Starting index of the CCC into the vertex array	Number	integer
s_sites	Starting index of the sites into the vertex array	Number	integer
q	Material requests quantity, defined by origin (supplier), destination (construction site), and period [double].	Three dimensional Matrix (suppliers, construction sites, periods)	double
cap_ccc	Capacity of each CCC	Array of CCCs	double
cap_in	Capacity of handling material in entrance at the CCC	Array of CCCs	double
cap_out	Capacity of handling material exiting the CCC	Array of CCCs	double

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cost_ccc:	Costs of opening each CCC	Array of CCCs	double
cost_invent	Cost of storing one unit of material inside the CCC, that can be different for each CCC	Array of CCCs	double
max_ccc	Maximum number of CCCs that can be opened	Number	double
	Second input file: Travelling Cost		
cost	Matrix of costs /distance among the vertices of the network. The cost between the same vertex is set to a high value to avoid that trip into the model.	Vertex by vertex matrix	Double

```
coorx: [(0) 0 (1) 40 (2) 0 (3) 70 (4) 60 (5) 27 (6) 10 (7) 30 (8) 15 (9) 35 (10) 50 (11) 43]
coory: [(0) 0 (1)  0 (2) 50(3) 70 (4) 6  (5) 60 (6) 20 (7) 40 (8) 52 (9) 35 (10) 30 (11) 23]
s_supp: 0
s_ccc: 4
s_sites: 7
q: [     (0,7,0)   10 (1,7,0)  4 (2,7,0)  8 (3,7,0)  9
         (0,8,0)   10 (1,8,0)  4 (2,8,0)  8 (3,8,0)  9
         (0,9,0)   10 (1,9,0)  4 (2,9,0)  8 (3,9,0)  9
         (0,10,0)  10 (1,10,0) 4 (2,10,0) 8 (3,10,0) 9
         (0,11,0)  10 (1,11,0) 4 (2,11,0) 8 (3,11,0) 9
         (0,7,1)   1 (1,7,1)  2 (2,7,1)  9 (3,7,1)  3
         (0,8,1)   1 (1,8,1)  2 (2,8,1)  9 (3,8,1)  3
         (0,9,1)   1 (1,9,1)  2 (2,9,1)  9 (3,9,1)  3
         (0,10,1)  1 (1,10,1) 2 (2,10,1) 9 (3,10,1) 3
         (0,11,1)  1 (1,11,1) 2 (2,11,1) 9 (3,11,1) 3
         (0,7,2)   5 (1,7,2)  6 (2,7,2)  4 (3,7,2)  7
         (0,8,2)   5 (1,8,2)  6 (2,8,2)  4 (3,8,2)  7
         (0,9,2)   5 (1,9,2)  6 (2,9,2)  4 (3,9,2)  7
         (0,10,2)  5 (1,10,2) 6 (2,10,2) 4 (3,10,2) 7
         (0,11,2)  5 (1,11,2) 6 (2,11,2) 4 (3,11,2) 7
         ]
cap_ccc: [(4) 200 (5) 200 (6) 200]
cap_in: [(4) 100 (5) 100 (6) 100]
cap_out: [(4) 100 (5) 100 (6) 100]
cost_ccc: [(4) 10 (5) 10 (6) 10]
cost_invent: [(4) 10 (5) 10 (6) 10]
max_ccc: 3
```

Figure 22 Example of a Main Data input file for the Multi Period with Inventory Model

9.2.1.13 *Multi Period with Inventory and Reverse Logistics Model*

The input files needed for the *Multi Period with Inventory and Reverse Logistics Model* are two: the **Main Data** file and **Travelling Costs** file. The first file is similar to the one used for the *Multi Period with Inventory Model*, with the addition of the reverse logistic material requirements for each period. Details of the required data are given in Table 17 and an example is provided in Figure 23.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

Table 17 FL Multi Period with Inventory and Reverse Logistics Model Data

Name	meaning	size	type
	First input file: Main Data		
coorx	x coordinates of the vertices	Array of vertices	double
coory	y coordinates of the vertices	Array of vertices	double
s_supp	The vertices are ordered starting from suppliers, then CCCs, and terminating with the construction sites. s_supp identifies the starting index of the suppliers (it is supposed to be 0) into the vertex array	Number	integer
s_ccc	Starting index of the CCC into the vertex array	Number	integer
s_sites	Starting index of the sites into the vertex array	Number	integer
q	Material requests quantity defined by origin (supplier), destination (construction site), and period.	Three dimensional Matrix (suppliers, construction sites, periods)	double
r	Request for reverse logistics that is a quantity defined by its origin (a construction site) and its destination (supplier/dumpsite), and period	Three dimensional Matrix (constructio n site, suppliers, periods)	double
cap_ccc	Capacity of each CCC	Array of CCCs	double
cap_in	Capacity of handling material in entrance at the CCC	Array of CCCs	double
cap_out	Capacity of handling material exiting the CCC	Array of CCCs	double

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

cost_ccc:	Costs of opening each CCC	Array of CCCs	double
cost_invent	Cost of storing one unit of material inside the CCC, that can be different for each CCC	Array of CCCs	double
max_ccc	Maximum number of CCCs that can be opened	Number	double
	Second input file: Travelling Costs		
cost	Matrix of costs /distance among the vertices of the network. The cost between the same vertex is set to a high value to avoid that trip into the model.	Vertex by vertex matrix	Double

```
coorx: [(0) 0 (1) 40 (2) 0 (3) 70 (4) 60 (5) 27 (6) 10 (7) 30 (8) 15 (9) 35 (10) 50 (11) 43]
coory: [(0) 0 (1)  0 (2) 50(3) 70 (4) 6  (5) 60 (6) 20 (7) 40 (8) 52 (9) 35 (10) 30 (11) 23]
s_supp: 0
s_ccc: 4
s_sites: 7
q: [    (0,7,0)   10 (1,7,0)  4 (2,7,0)  8 (3,7,0)  9
        (0,8,0)   10 (1,8,0)  4 (2,8,0)  8 (3,8,0)  9
        (0,9,0)   10 (1,9,0)  4 (2,9,0)  8 (3,9,0)  9
        (0,10,0)  10 (1,10,0) 4 (2,10,0) 8 (3,10,0) 9
        (0,11,0)  10 (1,11,0) 4 (2,11,0) 8 (3,11,0) 9
        (0,7,1)   1 (1,7,1)  2 (2,7,1)  9 (3,7,1)  3
        (0,8,1)   1 (1,8,1)  2 (2,8,1)  9 (3,8,1)  3
        (0,9,1)   1 (1,9,1)  2 (2,9,1)  9 (3,9,1)  3
        (0,10,1)  1 (1,10,1) 2 (2,10,1) 9 (3,10,1) 3
        (0,11,1)  1 (1,11,1) 2 (2,11,1) 9 (3,11,1) 3
        (0,7,2)   5 (1,7,2)  6 (2,7,2)  4 (3,7,2)  7
        (0,8,2)   5 (1,8,2)  6 (2,8,2)  4 (3,8,2)  7
        (0,9,2)   5 (1,9,2)  6 (2,9,2)  4 (3,9,2)  7
        (0,10,2)  5 (1,10,2) 6 (2,10,2) 4 (3,10,2) 7
        (0,11,2)  5 (1,11,2) 6 (2,11,2) 4 (3,11,2) 7
        ]
r: [    (7,0,0)   2 (7,1,0)  4 (7,2,0)  5 (7,3,0)  3
        (8,0,0)   2 (8,0,0)  4 (8,2,0)  5 (8,3,0)  3
        (9,0,0)   2 (9,1,0)  4 (9,2,0)  5 (9,3,0)  3
        (10,0,0)  2 (10,1,0) 4 (10,2,0) 5 (10,3,0) 3
        (11,0,0)  2 (11,1,0) 4 (11,2,0) 5 (11,3,0) 3
        (7,0,1)   2 (7,1,1)  4 (7,2,1)  5 (7,3,1)  3
        (8,0,1)   2 (8,0,1)  4 (8,2,1)  5 (8,3,1)  3
        (9,0,1)   2 (9,1,1)  4 (9,2,1)  5 (9,3,1)  3
        (10,0,1)  2 (10,1,1) 4 (10,2,1) 5 (10,3,1) 3
        (11,0,1)  2 (11,1,1) 4 (11,2,1) 5 (11,3,1) 3
        (7,0,2)   2 (7,1,2)  4 (7,2,2)  5 (7,3,2)  3
        (8,0,2)   2 (8,0,2)  4 (8,2,2)  5 (8,3,2)  3
        (9,0,2)   2 (9,1,2)  4 (9,2,2)  5 (9,3,2)  3
        (10,0,2)  2 (10,1,2) 4 (10,2,2) 5 (10,3,2) 3
        (11,0,2)  2 (11,1,2) 4 (11,2,2) 5 (11,3,2) 3
        ]
cap_ccc: [(4) 200 (5) 200 (6) 200]
cap_in: [(4) 100 (5) 100 (6) 100]
cap_out: [(4) 100 (5) 100 (6) 100]
cost_ccc: [(4) 10 (5) 10 (6) 10]
cost_invent: [(4) 10 (5) 10 (6) 10]
max_ccc: 3
```

Figure 23 Example of a Main Data input file for the Multi Period with Inventory and Reverse Logistics Model

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

9.2.1.14 *Multi Period Multi Material with Inventory, Reverse Logistics and Direct Shipping Model*

The input files needed for the *Multi Period Multi Material with Inventory, Reverse Logistics and Direct Shipping Model* are two .txt files: the **Main Data** file and **Travelling Costs** file. The Main Data includes new data input. First of all the set of materials is separated into 4 sets: the materials that must be delivered to sites by making use of a CCC (CCC materials), materials that can be also directly shipped (both direct or via CCC materials), the materials that can be disposed only by using a CCC (CCC reverse materials), and the materials that can be disposed also by making use of direct shipping (both direct or via CCC reverse material). Thus, into the input file the materials will be considered in the given order. A Travelling Costs file including distance /costs data is also needed. See details in Table 18 and an example in Figure 24.

Table 18 Multi Period Multi Material with Inventory, Reverse Logistics and Direct Shipping Model Data

Name	meaning	size	type
	First input file: Main Data		
coorx	x coordinates of the vertices	Array of vertices	double
coory	y coordinates of the vertices	Array of vertices	double
s_supp	The vertices are ordered starting from suppliers, then CCCs, and terminating with the construction sites. s_supp identifies the starting index of the suppliers (it is supposed to be 0) into the vertex array	Number	integer
s_ccc	Starting index of the CCC into the vertex array	Number	integer
s_sites	Starting index of the sites into the vertex array	Number	integer
m_ccc	The first index (integer value) in the set of materials representing materials for delivery that must go via CCC; it is normally 0.	Number	integer
m_both	The first index (integer value) of the material that can be also supplied directly.	Number	integer

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

m_ccc_rev	The first index (integer value) of the reverse material that must be disposed by using a CCC.	Number	integer
m_both_rev	The first index of the reverse material that can also be directly disposed.	Number	integer
q_ccc	Material requests quantity defined by origin (supplier), destination (construction site), material that must be supplied via CCC (m_ccc) and period.	Four dimensional Matrix (suppliers, construction sites, m_ccc, periods)	double
q_both	Material requests quantity defined by origin (supplier), destination (construction site), material that can be supplied both via CCC or directly (m_both) and period.	Four dimensional Matrix (suppliers, construction sites, m_both, periods)	double
r_ccc	Request for reverse logistics that is a quantity defined by its origin (a construction site) and its destination (supplier/dumpsite), the material that must be returned via CCC (m_ ccc_rev) and period	Four dimensional Matrix (construction site, suppliers, m_ccc_rev, periods)	double
r_both	Request for reverse logistics that is a quantity defined by its origin (a construction site) and its destination (supplier/dumpsite), the material that can be returned both via CCC or directly (m_ both_rev) and period	Four dimensional Matrix (construction site, suppliers, m_both_rev, periods)	double
cap_ccc	Capacity of each CCC	Array of CCCs	double
cap_in	Capacity of handling material in entrance at the CCC	Array of CCCs	double
cap_out	Capacity of handling material exiting the CCC	Array of CCCs	double
cost_ccc:	Costs of opening each CCC	Array of CCCs	double

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cost_invent	Cost of storing one unit of material inside the CCC, that can be different for each CCC:	Array of CCCs	double
max_ccc	Maximum number of CCCs that can be opened	Number	double
Second input file: Travelling Costs			
cost	Matrix of costs /distance among the vertices of the network. The cost between the same vertex is set to a high value to avoid that trip into the model.	Vertex by vertex matrix	double

In Figure 24 one can see an example of the Main Data input file.

```
coorx: [(0) 0 (1) 40 (2) 0 (3) 70 (4) 60 (5) 27 (6) 10 (7) 30 (8) 15 (9) 35 (10) 50 (11) 43]
coory: [(0) 0 (1)  0 (2) 50(3) 70 (4) 6  (5) 60 (6) 20 (7) 40 (8) 52 (9) 35 (10) 30 (11) 23]
cap_ccc_m: [(4,0) 20 (4,1) 20 (4,2) 20 (4,3) 20 (4,4) 20 (4,5) 20 (4,6) 20
        (5,0) 20 (5,1) 20 (5,2) 20 (5,3) 20 (5,4) 20 (5,5) 20 (5,6) 20
        (6,0) 20 (6,1) 20 (6,2) 20 (6,3) 20 (6,4) 20 (6,5) 20 (6,6) 20
]
s_supp: 0
s_ccc: 4
s_sites: 7
m_ccc: 0
m_both: 2
m_ccc_rev: 3
m_both_rev: 5
q_ccc: [(0,7,0,0)  2   (0,7,1,0)  2   (0,7,0,1)  2   (0,7,1,1)  2   (1,7,0,0)  4   (1,7,1,0)  4   (1,7,0,1)  4   (1,7,1,1)  4
        (2,7,0,0)  5   (2,7,1,0)  5   (2,7,0,1)  5   (2,7,1,1)  5   (3,7,0,0)  3   (3,7,1,0)  3   (3,7,0,1)  3   (3,7,1,1)  3
        (0,8,0,0)  2   (0,8,1,0)  2   (0,8,0,1)  2   (0,8,1,1)  2   (1,8,0,0)  4   (1,8,1,0)  4   (1,8,0,1)  4   (1,8,1,1)  4
        (2,8,0,0)  5   (2,8,1,0)  5   (2,8,0,1)  5   (2,8,1,1)  5   (3,8,0,0)  3   (3,8,1,0)  3   (3,8,0,1)  3   (3,8,1,1)  3
        (0,9,0,0)  2   (0,9,1,0)  2   (0,9,0,1)  2   (0,9,1,1)  2   (1,9,0,0)  4   (1,9,1,0)  4   (1,9,0,1)  4   (1,9,1,1)  4
        (2,9,0,0)  5   (2,9,1,0)  5   (2,9,0,1)  5   (2,9,1,1)  5   (3,9,0,0)  3   (3,9,1,0)  3   (3,9,0,1)  3   (3,9,1,1)  3
        (0,10,0,0) 2   (0,10,1,0) 2   (0,10,0,1) 2   (0,10,1,1) 2   (1,10,0,0) 4   (1,10,1,0) 4   (1,10,0,1) 4   (1,10,1,1) 4
        (2,10,0,0) 5   (2,10,1,0) 5   (2,10,0,1) 5   (2,10,1,1) 5   (3,10,0,0) 3   (3,10,1,0) 3   (3,10,0,1) 3   (3,10,1,1) 3
        (0,11,0,0) 2   (0,11,1,0) 2   (0,11,0,1) 2   (0,11,1,1) 2   (1,11,0,0) 4   (1,11,1,0) 4   (1,11,0,1) 4   (1,11,1,1) 4
        (2,11,0,0) 5   (2,11,1,0) 5   (2,11,0,1) 5   (2,11,1,1) 5   (3,11,0,0) 3   (3,11,1,0) 3   (3,11,0,1) 3   (3,11,1,1) 3
]
q_both: [(0,7,2,0)  2 (0,7,2,1)  2     (1,7,2,0)  4    (1,7,2,1)  4   (2,7,2,0)  5    (2,7,2,1)  5   (3,7,2,0)  3    (3,7,2,1)  3
        (0,8,2,0)  2    (0,8,2,1)  2   (1,8,2,0)  4    (1,8,2,1)  4   (2,8,2,0)  5    (2,8,2,1)  5   (3,8,2,0)  3    (3,8,2,1)  3
        (0,9,2,0)  2    (0,9,2,1)  2   (1,9,2,0)  4    (1,9,2,1)  4   (2,9,2,0)  5    (2,9,2,1)  5   (3,9,2,0)  3    (3,9,2,1)  3
        (0,10,2,0) 2    (0,10,2,1) 2   (1,10,2,0) 4    (1,10,2,1) 4   (2,10,2,0) 5    (2,10,2,1) 5   (3,10,2,0) 3    (3,10,2,1) 3
        (0,11,2,0) 2    (0,11,2,1) 2   (1,11,2,0) 4    (1,11,2,1) 4   (2,11,2,0) 5    (2,11,2,1) 5   (3,11,2,0) 3    (3,11,2,1) 3
]
r_ccc: [(7,0,3,0) 2     (8,0,3,0) 2     (9,0,3,0) 2     (10,0,3,0) 2    (11,0,3,0) 2
        (7,1,3,0) 2     (8,1,3,0) 2     (9,1,3,0) 2     (10,1,3,0) 2    (11,1,3,0) 2
        (7,2,3,0) 2     (8,2,3,0) 2     (9,2,3,0) 2     (10,2,3,0) 2    (11,2,3,0) 2
        (7,3,3,0) 2     (8,3,3,0) 2     (9,3,3,0) 2     (10,3,3,0) 2    (11,3,3,0) 2
        (7,0,4,0) 2     (8,0,4,0) 2     (9,0,4,0) 2     (10,0,4,0) 2    (11,0,4,0) 2
        (7,1,4,0) 2     (8,1,4,0) 2     (9,1,4,0) 2     (10,1,4,0) 2    (11,1,4,0) 2
        (7,2,4,0) 2     (8,2,4,0) 2     (9,2,4,0) 2     (10,2,4,0) 2    (11,2,4,0) 2
        (7,3,4,0) 2     (8,3,4,0) 2     (9,3,4,0) 2     (10,3,4,0) 2    (11,3,4,0) 2
        (7,0,3,1) 2     (8,0,3,1) 2     (9,0,3,1) 2     (10,0,3,1) 2    (11,0,3,1) 2
        (7,1,3,1) 2     (8,1,3,1) 2     (9,1,3,1) 2     (10,1,3,1) 2    (11,1,3,1) 2
        (7,2,3,1) 2     (8,2,3,1) 2     (9,2,3,1) 2     (10,2,3,1) 2    (11,2,3,1) 2
        (7,3,3,1) 2     (8,3,3,1) 2     (9,3,3,1) 2     (10,3,3,1) 2    (11,3,3,1) 2
        (7,0,4,1) 2     (8,0,4,1) 2     (9,0,4,1) 2     (10,0,4,1) 2    (11,0,4,1) 2
        (7,1,4,1) 2     (8,1,4,1) 2     (9,1,4,1) 2     (10,1,4,1) 2    (11,1,4,1) 2
        (7,2,4,1) 2     (8,2,4,1) 2     (9,2,4,1) 2     (10,2,4,1) 2    (11,2,4,1) 2
        (7,3,4,1) 2     (8,3,4,1) 2     (9,3,4,1) 2     (10,3,4,1) 2    (11,3,4,1) 2
]
r_both: [|(7,0,5,0) 2    (8,0,5,0) 2     (9,0,5,0) 2     (10,0,5,0) 2    (11,0,5,0) 2
        (7,1,5,0) 2     (8,1,5,0) 2     (9,1,5,0) 2     (10,1,5,0) 2    (11,1,5,0) 2
        (7,2,5,0) 2     (8,2,5,0) 2     (9,2,5,0) 2     (10,2,5,0) 2    (11,2,5,0) 2
        (7,3,5,0) 2     (8,3,5,0) 2     (9,3,5,0) 2     (10,3,5,0) 2    (11,3,5,0) 2
        (7,0,6,0) 2     (8,0,6,0) 2     (9,0,6,0) 2     (10,0,6,0) 2    (11,0,6,0) 2
        (7,1,6,0) 2     (8,1,6,0) 2     (9,1,6,0) 2     (10,1,6,0) 2    (11,1,6,0) 2
        (7,2,6,0) 2     (8,2,6,0) 2     (9,2,6,0) 2     (10,2,6,0) 2    (11,2,6,0) 2
        (7,3,6,0) 2     (8,3,6,0) 2     (9,3,6,0) 2     (10,3,6,0) 2    (11,3,6,0) 2
        (7,0,5,1) 2     (8,0,5,1) 2     (9,0,5,1) 2     (10,0,5,1) 2    (11,0,5,1) 2
        (7,1,5,1) 2     (8,1,5,1) 2     (9,1,5,1) 2     (10,1,5,1) 2    (11,1,5,1) 2
        (7,2,5,1) 2     (8,2,5,1) 2     (9,2,5,1) 2     (10,2,5,1) 2    (11,2,5,1) 2
        (7,3,5,1) 2     (8,3,5,1) 2     (9,3,5,1) 2     (10,3,5,1) 2    (11,3,5,1) 2
        (7,0,6,1) 2     (8,0,6,1) 2     (9,0,6,1) 2     (10,0,6,1) 2    (11,0,6,1) 2
        (7,1,6,1) 2     (8,1,6,1) 2     (9,1,6,1) 2     (10,1,6,1) 2    (11,1,6,1) 2
        (7,2,6,1) 2     (8,2,6,1) 2     (9,2,6,1) 2     (10,2,6,1) 2    (11,2,6,1) 2
        (7,3,6,1) 2     (8,3,6,1) 2     (9,3,6,1) 2     (10,3,6,1) 2    (11,3,6,1) 2
]
cap_in: [(4) 100 (5) 100 (6) 100]
cap_out: [(4) 100 (5) 100 (6) 100]
cap_ccc: [(4) 200 (5) 200 (6) 200]
cost_ccc: [(4) 10 (5) 10 (6) 10]
cost_inv: [(4) 10 (5) 10 (6) 10]
max_ccc: 3
```

Figure 24 Example of a Main Data input file for the Multi Period with Inventory and Reverse Logistics Model

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

9.2.1.15 *Stochastic Multi Period Multi Material with Inventory, Reverse Logistics and Direct Shipping Model*

The *Stochastic Multi Period Multi Material with Inventory, Reverse Logistics and Direct Shipping Model* is the most complete model we presented for the facility location set of models. To solve the model L-shaped version we also made use of a C++ algorithm calling Cplex functions. The input file is one, is a text file, and it more complex. The following elements are those required in the input .txt file as reported in Table 19. An example is given in Figure 25 and Figure 26.

Table 19 Stochastic Multi Period Multi Material with Inventory, Reverse Logistics and Direct Shipping Model Data

Name	meaning	size	type
n_vertices	Integer number that gives the total number of suppliers, sites, CCCs, and dumpsites.	Number	integer
n_suppliers	Integer providing the number of suppliers and dumpsites	Number	integer
n_ccc	Integer providing the total number of evaluated CCC locations	Number	integer
n_sites	Integer providing the total number of construction sites	Number	integer
n_scenarios	Number of stochastic scenarios considered	Number	integer
n_mat_ccc	Number of materials that must be supplied via CCC	Number	integer
n_mat_ccc_rev	Number of materials that must be collected and disposed via CCC	Number	integer
n_mat_both	Number of materials that can be supplied both directly or via CCC	Number	integer
n_mat_both_rev	Number of materials that can be collected and disposed both directly or via CCC	Number	integer
n_periods	Number of considered periods	Number	integer
coor_x	Array of x coordinated of the vertices	Array of vertices	double
coor_y	Array of y coordinated of the vertices	Array of vertices	double

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distance/cost	Matrix of distances / costs between each couple of vertices, normally defined as the cost of travelling between two vertices. If the couple is represented by a supplier / dumpsite and a construction site, then it represents the cost of direct shipping. The diagonal must have large enough values.	Matrix (n_vertices , n_vertices)	double
n_demands	Number of the lines representing the demands as expressed in the following line. To ease the input feed firstly the number of total material request is needed. Thus the request will be listed as in the following, defining the scenario, the period, the material, the material type (that means 0 for *mat_ccc*, 1 for *mat_ccc_rev*, 2 for *mat_both*, and 3 for *mat_both_rev*), the supplier/dumpsite id, the construction site id, and finally the material request in kg/m2.	Number	integer
demand	List of lines including the indices of all the information regarding the demand quantity. Better explained: each line should have indicated the following numbers: • Scenario id of the demand • Period id of the demand • Material id of the demand • Material type id (0 for mat_ccc, 1 for mat_ccc_rev, 2 for mat_both,. 3 for mat_both_rev) • Supplier id of the demand (if material type is 0 or 2 this is the origin, the destination otherwise) • Site id of the demand (if	List of lines (1,1,1,1,1,1, 1)	(integer, integer, integer, integer, integer, integer, double)

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	material type is 0 or 2 this is the destination, the origin otherwise) • The quantity of the demand expressed in the desired unit (weight or volume)		
cap_ccc	Maximum capacities of each evaluated CCCs.	Array of CCCs	double
cap_in	Capacity of handling in entrance of each CCC.	Array of CCCs	double
cap_out	Capacity of handling in exit of each CCC.	Array of CCCs	double
cost_ccc	Cost of opening the evaluated CCCs.	Array of CCCs	double
cost_inventory	Cost of inventory in each CCC	Array of CCCs	double
max_ccc	the maximum number of CCCs that can be opened	Number	integer
cap_mat_ccc	Maximum capacity for each material of the *mat_ccc* type for each CCCs	Matrix (CCCs, mat_ccc)	double
cap_mat_ccc_rev	Maximum capacity for each material of the *mat_ccc_rev* type for each CCCs	Matrix (CCCs, mat_ccc_rev)	double
cap_mat_both	Maximum capacity for each material of the *mat_both* type for each CCCs	Matrix (CCCs, mat_both)	double
cap_mat_both_rev	Maximum capacity for each material of the *mat_both_rev* type for each CCCs	Matrix (CCCs, mat_both_rev)	double
probability	Probability of each stochastic scenario, the sum of the probabilities must equal 1.	Array of scenarios	double

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

In Figure 25 one can find the first required data, the coordinates and the cost matrix (these are not complete for page layout reasons), the number of request rows (1186) and the first five requests.

```
52
43
4
5
3
1
1
25
2
7
45.4827606      45.744472       45.7446036      45.7414426      44.5459624      45.9859208      45.418567       45.5701519      42.1
10.8674898      12.8470599      12.8460871      11.7264343      10.8442909      12.6200916      10.9300325      11.8962235      13.8
9999999 186.223 186.299 108.602 120.491 202.901 12.907  114.256 117.716 562.173 467.914 110.398 448.695 174.557 203.096 485.289 142.
195.062 9999999 0.077   107.227 263.68  37.561  187.609 95.249  92.415  630.017 554.974 290.675 535.755 28.332  37.757  553.133 322.
195.139 0.077   9999999 107.304 263.757 37.638  187.686 95.325  92.492  630.094 555.051 290.752 535.832 28.409  37.834  553.21  322.
104.831 102.358 102.435 9999999 203.635 98.265  97.378  29.732  35.807  572.627 497.584 200.444 478.365 79.5    98.46   495.743 232.
115.619 250.816 250.893 201.038 9999999 267.494 112.838 185.074 180.247 465.551 371.292 125.276 352.073 239.15  267.69  388.667 172.
200.242 37.934  38.011  99.969  268.86  9999999 192.789 100.429 97.595  635.197 560.155 295.855 540.936 28.955  0.192   558.313 327.
11.064  178.273 178.35  100.653 116.337 194.952 9999999 106.307 109.767 558.019 463.76  109.013 444.541 166.607 195.147 481.135 140.
112.641 91.857  91.934  28.846  187.481 102.886 105.188 9999999 5.274   553.818 478.776 208.254 459.557 80.191  103.082 476.935 240.
113.197 88.549  88.626  36.219  181.793 99.578  105.744 5.452   9999999 548.13  473.087 208.81  453.868 76.883  99.774  471.246 240.
562.013 620.533 620.61  586.918 469.405 637.212 559.232 554.791 549.965 9999999 185.817 571.67  166.632 608.868 637.407 99.878  619.
466.294 543.709 543.786 510.093 373.685 560.388 463.513 477.967 473.14  189.131 9999999 475.951 57.328  532.043 560.583 213.875 523.
116.328 278.998 279.075 201.378 129.566 295.677 107.807 207.031 210.492 571.248 476.989 9999999 457.77  267.332 295.872 494.364 83.3
451.407 528.822 528.899 495.206 358.798 545.5   448.625 463.08  458.253 167.097 54.19   461.064 9999999 517.156 545.696 185.296 508.
178.325 28.224  28.301  78.661  246.943 31.345  170.872 78.512  75.678  613.28  538.238 273.938 519.019 9999999 31.54   536.396 305.
200.437 38.129  38.206  100.164 269.055 0.192   192.984 100.624 97.79   635.392 560.35  296.05  541.131 29.151  9999999 558.508 327.
483.348 541.868 541.945 508.253 390.74  558.547 480.567 476.126 471.3   98.708  210.206 493.005 184.045 530.203 558.742 9999999 540.
155.543 318.213 318.29  240.593 177.04  334.892 147.022 246.246 249.707 618.722 524.463 84.619  505.244 306.547 335.087 541.838 9999
78.894  139.677 139.754 33.01   177.697 156.356 71.441  49.19   71.171  577.355 502.313 174.507 483.094 128.011 156.551 500.472 206.
36.943  199.982 200.059 122.362 103.082 216.661 22.246  128.015 131.476 544.764 450.506 80.012  431.287 188.316 216.856 467.88  143.
120.42  283.09  283.167 205.47  208.897 299.769 111.899 211.123 214.584 650.579 556.32  67.474  537.101 271.424 299.964 573.695 35.9
115.495 278.165 278.242 200.544 212.604 294.843 106.974 206.198 209.658 654.285 560.027 100.435 540.808 266.499 295.038 577.402 63.5
115.739 278.409 278.486 200.789 212.848 295.087 107.218 206.442 209.903 654.53  560.271 100.679 541.052 266.743 295.283 577.646 63.7
118.871 241.738 241.815 204.29  10.973  258.417 116.09  175.996 171.169 456.473 362.215 128.528 342.995 230.072 258.612 379.589 176.
129.925 292.595 292.672 214.975 205.829 309.274 121.404 220.628 224.089 647.511 553.252 70.486  534.033 280.929 309.469 570.627 32.8
504.45  327.608 327.685 416.616 573.068 348.109 496.997 404.637 401.803 939.405 864.363 600.063 845.144 345.92  348.304 862.522 631.
562.047 620.567 620.644 586.951 469.439 637.246 559.266 554.825 549.998 0.125   185.851 571.704 166.666 608.901 637.441 99.911  619.
100.68  144.442 144.519 5.031   199.484 100.867 93.227  32.262  38.409  582.026 506.984 196.293 487.765 82.102  101.063 505.142 228.
36.432  188.422 188.499 110.802 107.353 205.101 27.783  116.455 119.916 549.035 454.777 132.663 435.558 176.756 205.296 472.151 164.
116.089 267.384 267.461 201.508 14.773  284.063 113.308 207.161 196.815 482.119 387.861 111.926 368.642 255.719 284.258 405.236 159.
256.902 419.571 419.648 341.951 248.571 436.25  248.38  347.604 351.065 690.253 595.994 155.049 576.775 407.905 436.445 613.369 129.
562.013 620.533 620.61  586.918 469.405 637.212 559.232 554.791 549.965 0       185.817 571.67  166.632 608.868 637.407 99.878  619.
134.735 297.405 297.482 219.785 204.102 314.084 126.214 225.438 228.899 645.784 551.526 74.803  532.307 285.739 314.279 568.901 31.1
346.59  424.005 424.082 390.389 253.982 440.684 343.809 358.263 353.436 376.242 193.251 365.369 222.581 412.34  440.879 400.985 412.
98.284  261.323 261.4   183.703 63.195  278.002 95.503  189.356 192.817 504.877 410.618 84.223  391.399 249.657 278.197 427.993 131.
165.779 42.885  42.962  69.118  234.398 37.782  158.326 65.966  63.133  600.735 525.692 261.393 506.473 12.356  37.977  523.851 293.
164.931 327.601 327.678 249.981 183.602 344.28  156.41  255.634 259.095 625.283 531.025 91.18   511.806 315.935 344.475 548.4   12.6
245.922 408.591 408.668 330.971 229.808 425.27  237.4   336.625 340.085 671.49  504.068 136.286 484.849 396.925 425.465 594.606 111.
113.599 263.833 263.91  199.018 7.39    280.512 110.818 198.091 193.264 478.568 384.31  123.256 365.091 252.167 280.707 401.684 170.
159.595 322.264 322.341 244.644 206.157 338.943 151.073 250.297 253.758 647.839 553.581 113.736 534.362 310.598 339.138 570.955 35.3
244.658 303.178 303.255 269.562 152.05  319.857 241.877 237.436 232.609 320.869 311.566 254.315 257.314 291.512 320.052 243.985 301.
77.042  137.826 137.903 34.156  175.846 154.505 69.589  44.757  69.32   575.504 500.462 172.656 481.243 126.16  154.7   498.62  204.
10.828  171.768 171.845 94.148  123.684 188.446 10.022  99.801  103.262 565.366 471.107 120.975 451.888 160.102 188.642 488.482 152.
14.343  172.855 172.932 95.235  116.758 189.534 5.694   100.888 104.349 558.439 464.181 113.567 444.962 161.189 189.729 481.556 145.
13.285  175.4   175.477 97.78   118.308 192.079 3.636   103.433 106.894 559.99  465.731 115.599 446.512 163.734 192.274 483.106 147.
16.318  169.945 170.022 92.325  119.649 186.624 7.022   97.978  101.439 561.331 467.072 116.459 447.853 158.279 186.819 484.447 148.
10.738  173.984 174.061 96.363  125.692 190.662 12.03   102.017 105.477 567.374 473.115 122.983 453.896 162.318 190.857 490.49  154.
18.501  167.65  167.727 90.03   131.164 184.329 9.205   95.684  99.144  572.846 478.587 127.973 459.368 155.985 184.524 495.962 159.
11.94   177.569 177.646 99.948  121.94  194.247 8.278   105.602 109.062 563.622 469.363 119.231 450.144 165.903 194.442 486.738 150.
19.336  171.694 171.771 94.074  118.264 188.373 10.687  99.728  103.188 559.946 465.687 115.073 446.468 160.028 188.568 483.062 146.
16.531  171.762 171.839 94.142  115.664 188.441 7.882   99.795  103.256 557.346 463.088 112.474 443.869 160.096 188.636 480.462 144.
19.336  171.694 171.771 94.074  118.264 188.93  4.727   100.285 103.745 557.836 463.577 112.963 444.358 160.585 189.125 480.952 144.
16.531  171.762 171.839 94.142  115.664 185.9   6.927   97.255  100.715 561.236 466.978 116.364 447.759 157.556 186.095 484.352 148.
1186
0       4       0       0       39      0       750
0       5       0       0       39      0       1500
0       0       0       1       0       0       11700
0       1       0       1       0       0       3000
0       1       0       1       1       0       12000
```

Figure 25 Highlight of an Example of an input file for the Stochastic Multi Period Multi Material with Inventory, Reverse Logistics and Direct Shipping Model

In Figure 26 one can see the end of the material requests rows, the CCCs capacities and costs, the maximum number of CCCs that can be opened, and the probabilities of the scenarios.

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```
2         4         13        2         23        4         7547
2         4         16        2         19        4         8961
2         4         17        2         39        4         46041
2         4         18        2         6         4         37295
2         4         20        2         24        4         4740
2         4         21        2         18        4         3593
2         4         22        2         40        4         7949
2         5         4         2         14        4         23340
2         5         4         2         30        4         32860
2         5         8         2         27        4         5237
2         5         12        2         17        4         3054
2         5         13        2         31        4         3813
2         5         14        2         29        4         99705
2         5         19        2         26        4         11988
2         6         0         2         3         4         3168
2         6         2         2         37        4         153
2         6         4         2         5         4         1371
2         6         4         2         30        4         4452
2         6         10        2         34        4         4769
2         6         14        2         35        4         6560
2         6         15        2         21        4         3412
2         6         18        2         36        4         2248
2         6         19        2         26        4         713
2         6         22        2         11        4         12907
2         6         22        2         32        4         5110
2         6         23        2         33        4         1820
2         0         1         3         0         4         141
2         1         1         3         1         4         7136
2         2         1         3         1         4         20072
2         3         1         3         1         4         2977
2         5         1         3         1         4         2167
2         6         1         3         1         4         556
100000000           100000000           100000000           100000000
100000000           100000000           100000000           100000000
100000000           100000000           100000000           100000000
100000000           100000000           100000000           100000000
100       100       100       100
3
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
100000    100000    100000    100000
0.3       0.5       0.2
```

Figure 26 Other highlight of an Example of an input file for the Stochastic Multi Period Multi Material with Inventory, Reverse Logistics and Direct Shipping Model

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

9.2.2 Two-echelon Allocation Problems

The *Allocation to construction sites Model* and the *Allocation to suppliers Model* make use of two input .txt file, a general one, called **Main Data,** and a cost / distances input file, called **Travelling Costs**.

9.2.2.1 *Allocation to construction sites Model*

Definition of the required input data are given in Table 20, and an example can be found in Figure 27.

Table 20 Allocation to construction sites Model Data

Name	meaning	size	type
	First input file: Main Data		
coorx	x coordinates of the vertices	Array of vertices	double
coory	y coordinates of the vertices	Array of vertices	double
s_supp	The vertices are ordered starting from suppliers, then CCCs, and terminating with the construction sites. s_supp identifies the starting index of the suppliers (it is supposed to be 0) into the vertex array	Number	integer
s_ccc	Starting index of the CCC into the vertex array	Number	integer
s_sites	Starting index of the sites into the vertex array	Number	integer
m_ccc	The first index (integer value) in the set of materials representing materials for delivery that must go via CCC; it is normally 0.	Number	integer
m_both	The first index (integer value) of the material that can be also supplied directly.	Number	integer
m_ccc_rev	The first index (integer value) of the reverse material that must be disposed by using a CCC.	Number	integer

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m_both_rev	The first index of the reverse material that can also be directly disposed.	Number	integer
q_ccc	Material requests quantity defined by origin (supplier), destination (construction site), material that must be supplied via CCC (m_ccc) and period.	Four dimensional Matrix (suppliers, construction sites, m_ccc, periods)	double
q_both	Material requests quantity defined by origin (supplier), destination (construction site), material that can be supplied both via CCC or directly (m_both) and period.	Four dimensional Matrix (suppliers, construction sites, m_both, periods)	double
r_ccc	Request for reverse logistics that is a quantity defined by its origin (a construction site) and its destination (supplier/dumpsite), the material that must be returned via CCC (m_ ccc_rev) and period	Four dimensional Matrix (construction site, suppliers, m_ccc_rev, periods)	double
r_both	Request for reverse logistics that is a quantity defined by its origin (a construction site) and its destination (supplier/dumpsite), the material that can be returned both via CCC or directly (m_both_rev) and period	Four dimensional Matrix (construction site, suppliers, m_both_rev, periods)	double
cost_serv	Costs of serving from CCC a construction site. These are the cost of allocation.	Matrix (CCCs, construction sites)	double
cost_inv	Cost of inventory in a CCC	Array of CCCs	double
cap_ccc	Capacity of each CCC	Array of CCCs	double
cap_ccc_mat	Maximum capacity for each material in each opened CCC.	Matrix (CCCs, materials)	double

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cap_incoming	Capacity of handling material in entrance at the CCC	Array of CCCs	double
cap_outgoing	Capacity of handling material exiting the CCC	Array of CCCs	double
Second input file: Travelling Costs			
cost	Matrix of costs /distance among the vertices of the network. The cost between the same vertex is set to a high value to avoid that trip into the model. The cost between suppliers and construction sites define the direct shipping costs.	Vertex by vertex matrix	Double

```
coorx: [(0) 0 (1) 40 (2) 0 (3) 70 (4) 60 (5) 27 (6) 10 (7) 30 (8) 15 (9) 35 (10) 50 (11) 43]
coory: [(0) 0 (1)  0 (2) 50(3) 70 (4) 6  (5) 60 (6) 20 (7) 40 (8) 52 (9) 35 (10) 30 (11) 23]
s_supp: 0
s_ccc: 4
s_sites: 7
m_ccc: 0
m_both: 2
m_ccc_rev: 3
m_both_rev: 5
q_ccc: [(0,7,0,0)  2    (0,7,1,0)  2    (0,7,0,1)  2    (0,7,1,1)  2 (1,7,0,0)  4       (1,7,1,0)  4    (1,7,0,1)  4    (1,7,1,1)  4
        (2,7,0,0)  5    (2,7,1,0)  5    (2,7,0,1)  5    (2,7,1,1)  5    (3,7,0,0)  3    (3,7,1,0)  3    (3,7,0,1)  3    (3,7,1,1)  3
        (0,8,0,0)  2    (0,8,1,0)  2    (0,8,0,1)  2    (0,8,1,1)  2    (1,8,0,0)  4    (1,8,1,0)  4    (1,8,0,1)  4    (1,8,1,1)  4
        (2,8,0,0)  5    (2,8,1,0)  5    (2,8,0,1)  5    (2,8,1,1)  5    (3,8,0,0)  3    (3,8,1,0)  3    (3,8,0,1)  3    (3,8,1,1)  3
        (0,9,0,0)  2    (0,9,1,0)  2    (0,9,0,1)  2    (0,9,1,1)  2    (1,9,0,0)  4    (1,9,1,0)  4    (1,9,0,1)  4    (1,9,1,1)  4
        (2,9,0,0)  5    (2,9,1,0)  5    (2,9,0,1)  5    (2,9,1,1)  5    (3,9,0,0)  3    (3,9,1,0)  3    (3,9,0,1)  3    (3,9,1,1)  3
        (0,10,0,0) 2    (0,10,1,0) 2    (0,10,0,1) 2    (0,10,1,1) 2    (1,10,0,0) 4    (1,10,1,0) 4    (1,10,0,1) 4    (1,10,1,1) 4
        (2,10,0,0) 5    (2,10,1,0) 5    (2,10,0,1) 5    (2,10,1,1) 5    (3,10,0,0) 3    (3,10,1,0) 3    (3,10,0,1) 3    (3,10,1,1) 3
        (0,11,0,0) 2    (0,11,1,0) 2    (0,11,0,1) 2    (0,11,1,1) 2    (1,11,0,0) 4    (1,11,1,0) 4    (1,11,0,1) 4    (1,11,1,1) 4
        (2,11,0,0) 5    (2,11,1,0) 5    (2,11,0,1) 5    (2,11,1,1) 5    (3,11,0,0) 3    (3,11,1,0) 3    (3,11,0,1) 3    (3,11,1,1) 3
]
q_both: [(0,7,2,0)  2   (0,7,2,1) 2     (1,7,2,0)  4    (1,7,2,1)  4    (2,7,2,0)  5    (2,7,2,1)  5    (3,7,2,0)  3    (3,7,2,1)  3
         (0,8,2,0)  2   (0,8,2,1)  2    (1,8,2,0)  4    (1,8,2,1)  4    (2,8,2,0)  5    (2,8,2,1)  5    (3,8,2,0)  3    (3,8,2,1)  3
         (0,9,2,0)  2   (0,9,2,1)  2    (1,9,2,0)  4    (1,9,2,1)  4    (2,9,2,0)  5    (2,9,2,1)  5    (3,9,2,0)  3    (3,9,2,1)  3
         (0,10,2,0) 2   (0,10,2,1) 2    (1,10,2,0) 4    (1,10,2,1) 4    (2,10,2,0) 5    (2,10,2,1) 5    (3,10,2,0) 3    (3,10,2,1) 3
         (0,11,2,0) 2   (0,11,2,1) 2    (1,11,2,0) 4    (1,11,2,1) 4    (2,11,2,0) 5    (2,11,2,1) 5    (3,11,2,0) 3    (3,11,2,1) 3
]
r_ccc: [(7,0,3,0) 2 (8,0,3,0) 2 (9,0,3,0) 2 (10,0,3,0) 2 (11,0,3,0) 2 (7,1,3,0) 2 (8,1,3,0) 2 (9,1,3,0) 2 (10,1,3,0) 2 (11,1,3,0) 2
        (7,2,3,0) 2 (8,2,3,0) 2 (9,2,3,0) 2 (10,2,3,0) 2 (11,2,3,0) 2 (7,3,3,0) 2 (8,3,3,0) 2 (9,3,3,0) 2 (10,3,3,0) 2 (11,3,3,0) 2
        (7,0,4,0) 2 (8,0,4,0) 2 (9,0,4,0) 2 (10,0,4,0) 2 (11,0,4,0) 2 (7,1,4,0) 2 (8,1,4,0) 2 (9,1,4,0) 2 (10,1,4,0) 2 (11,1,4,0) 2
        (7,2,4,0) 2 (8,2,4,0) 2 (9,2,4,0) 2 (10,2,4,0) 2 (11,2,4,0) 2 (7,3,4,0) 2 (8,3,4,0) 2 (9,3,4,0) 2 (10,3,4,0) 2 (11,3,4,0) 2
        (7,0,3,1) 2 (8,0,3,1) 2 (9,0,3,1) 2 (10,0,3,1) 2 (11,0,3,1) 2 (7,1,3,1) 2 (8,1,3,1) 2 (9,1,3,1) 2 (10,1,3,1) 2 (11,1,3,1) 2
        (7,2,3,1) 2 (8,2,3,1) 2 (9,2,3,1) 2 (10,2,3,1) 2 (11,2,3,1) 2 (7,3,3,1) 2 (8,3,3,1) 2 (9,3,3,1) 2 (10,3,3,1) 2 (11,3,3,1) 2
        (7,0,4,1) 2 (8,0,4,1) 2 (9,0,4,1) 2 (10,0,4,1) 2 (11,0,4,1) 2 (7,1,4,1) 2 (8,1,4,1) 2 (9,1,4,1) 2 (10,1,4,1) 2 (11,1,4,1) 2
        (7,2,4,1) 2 (8,2,4,1) 2 (9,2,4,1) 2 (10,2,4,1) 2 (11,2,4,1) 2 (7,3,4,1) 2 (8,3,4,1) 2 (9,3,4,1) 2 (10,3,4,1) 2 (11,3,4,1) 2
        ]
r_both: [(7,0,5,0) 2 (8,0,5,0) 2 (9,0,5,0) 2 (10,0,5,0) 2 (11,0,5,0) 2 (7,1,5,0) 2 (8,1,5,0) 2 (9,1,5,0) 2(10,1,5,0) 2 (11,1,5,0) 2
        (7,2,5,0) 2 (8,2,5,0) 2 (9,2,5,0) 2 (10,2,5,0) 2 (11,2,5,0) 2 (7,3,5,0) 2 (8,3,5,0) 2 (9,3,5,0) 2 (10,3,5,0) 2 (11,3,5,0) 2
        (7,0,6,0) 2 (8,0,6,0) 2 (9,0,6,0) 2 (10,0,6,0) 2 (11,0,6,0) 2 (7,1,6,0) 2 (8,1,6,0) 2 (9,1,6,0) 2 (10,1,6,0) 2 (11,1,6,0) 2
        (7,2,6,0) 2 (8,2,6,0) 2 (9,2,6,0) 2 (10,2,6,0) 2 (11,2,6,0) 2 (7,3,6,0) 2 (8,3,6,0) 2 (9,3,6,0) 2 (10,3,6,0) 2 (11,3,6,0) 2
        (7,0,5,1) 2 (8,0,5,1) 2 (9,0,5,1) 2 (10,0,5,1) 2 (11,0,5,1) 2 (7,1,5,1) 2 (8,1,5,1) 2 (9,1,5,1) 2 (10,1,5,1) 2 (11,1,5,1) 2
        (7,2,5,1) 2 (8,2,5,1) 2 (9,2,5,1) 2 (10,2,5,1) 2 (11,2,5,1) 2 (7,3,5,1) 2 (8,3,5,1) 2 (9,3,5,1) 2 (10,3,5,1) 2 (11,3,5,1) 2
        (7,0,6,1) 2 (8,0,6,1) 2 (9,0,6,1) 2 (10,0,6,1) 2 (11,0,6,1) 2 (7,1,6,1) 2 (8,1,6,1) 2 (9,1,6,1) 2 (10,1,6,1) 2 (11,1,6,1) 2
        (7,2,6,1) 2 (8,2,6,1) 2 (9,2,6,1) 2 (10,2,6,1) 2 (11,2,6,1) 2 (7,3,6,1) 2 (8,3,6,1) 2 (9,3,6,1) 2 (10,3,6,1) 2 (11,3,6,1) 2
]
cost_serv: [(4,7) 100 (4,8) 100 (4,9) 100 (4,10) 100 (4,11) 100
        (5,7) 100 (5,8) 100 (5,9) 100 (5,10) 100 (5,11) 100
        (6,7) 100 (6,8) 100 (6,9) 100 (6,10) 100 (6,11) 100
]
cost_inv: [(4) 10 (5) 10 (6) 10]
cap_ccc: [(4) 100 (5) 100 (6) 100]
cap_ccc_mat: [(4,0) 20 (4,1) 20 (4,2) 20 (4,3) 20 (4,4) 20 (4,5) 20 (4,6) 20
        (5,0) 20 (5,1) 20 (5,2) 20 (5,3) 20 (5,4) 20 (5,5) 20 (5,6) 20
        (6,0) 20 (6,1) 20 (6,2) 20 (6,3) 20 (6,4) 20 (6,5) 20 (6,6) 20
]
cap_incoming: [(4) 100 (5) 100 (6) 100]
cap_outgoing: [(4) 100 (5) 100 (6) 100]
```

Figure 27 Example of an input file for the Allocation to construction sites Model

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9.2.2.2 *Allocation to suppliers Model*

With respect to a typical input file for the *Allocation to construction site Model*, the one needed to the *Allocation to suppliers Model* differs only for the cost of allocation, the cost_serv. The required data are defined in Table 21 and an example is provided in Figure 28 Example of an input file for the Allocation to suppliers Model.

Table 21 Allocation to suppliers Model Data

Name	meaning	size	type
	First input file: Main Data		
coorx	x coordinates of the vertices	Array of vertices	double
coory	y coordinates of the vertices	Array of vertices	double
s_supp	The vertices are ordered starting from suppliers, then CCCs, and terminating with the construction sites. s_supp identifies the starting index of the suppliers (it is supposed to be 0) into the vertex array	Number	integer
s_ccc	Starting index of the CCC into the vertex array	Number	integer
s_sites	Starting index of the sites into the vertex array	Number	integer
m_ccc	The first index (integer value) in the set of materials representing materials for delivery that must go via CCC; it is normally 0.	Number	integer
m_both	The first index (integer value) of the material that can be also supplied directly.	Number	integer
m_ccc_rev	The first index (integer value) of the reverse material that must be disposed by using a CCC.	Number	integer
m_both_rev	The first index of the reverse material that can also be directly disposed.	Number	integer

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q_ccc	Material requests quantity defined by origin (supplier), destination (construction site), material that must be supplied via CCC (m_ccc) and period.	Four dimensional Matrix (suppliers, construction sites, m_ccc, periods)	double
q_both	Material requests quantity defined by origin (supplier), destination (construction site), material that can be supplied both via CCC or directly (m_both) and period.	Four dimensional Matrix (suppliers, construction sites, m_both, periods)	double
r_ccc	Request for reverse logistics that is a quantity defined by its origin (a construction site) and its destination (supplier/dumpsite), the material that must be returned via CCC (m_ ccc_rev) and period	Four dimensional Matrix (construction site, suppliers, m_ccc_rev, periods)	double
r_both	Request for reverse logistics that is a quantity defined by its origin (a construction site) and its destination (supplier/dumpsite), the material that can be returned both via CCC or directly (m_both_rev) and period	Four dimensional Matrix (construction site, suppliers, m_both_rev, periods)	double
cost_serv	Cost of allocation a supplier / dumpsite to a CCC.	Matrix (suppliers, CCCs)	double
cost_inv	Cost of inventory in a CCC	Array of CCCs	double
cap_ccc	Capacity of each CCC	Array of CCCs	double
cap_ccc_mat	Maximum capacity for each material in each opened CCC.	Matrix (CCCs, materials)	double

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

cap_incoming	Capacity of handling material in entrance at the CCC	Array of double CCCs
cap_outgoing	Capacity of handling material exiting the CCC	Array of double CCCs
	Second input file: Travelling Costs	
cost	Matrix of costs /distance among the vertices of the network. The cost between the same vertex is set to a high value to avoid that trip into the model. The cost between suppliers and construction sites define the direct shipping costs.	Vertex by Double vertex matrix

```
coorx: [(0) 0 (1) 40 (2) 0 (3) 70 (4) 60 (5) 27 (6) 10 (7) 30 (8) 15 (9) 35 (10) 50 (11) 43]
coory: [(0) 0 (1)  0 (2) 50(3) 70 (4) 6  (5) 60 (6) 20 (7) 40 (8) 52 (9) 35 (10) 30 (11) 23]
s_supp: 0
s_ccc: 4
s_sites: 7
m_ccc: 0
m_both: 2
m_ccc_rev: 3
m_both_rev: 5
q_ccc: [
        (0,7,0,0)  2    (0,7,1,0)  2 (0,7,0,1)  2       (0,7,1,1)  2 (1,7,0,0)  4       (1,7,1,0)  4 (1,7,0,1)  4       (1,7,1,1)  4
        (2,7,0,0)  5    (2,7,1,0)  5 (2,7,0,1)  5       (2,7,1,1)  5 (3,7,0,0)  3       (3,7,1,0)  3 (3,7,0,1)  3       (3,7,1,1)  3
        (0,8,0,0)  2    (0,8,1,0)  2 (0,8,0,1)  2       (0,8,1,1)  2 (1,8,0,0)  4       (1,8,1,0)  4 (1,8,0,1)  4       (1,8,1,1)  4
        (2,8,0,0)  5    (2,8,1,0)  5 (2,8,0,1)  5       (2,8,1,1)  5 (3,8,0,0)  3       (3,8,1,0)  3 (3,8,0,1)  3       (3,8,1,1)  3
        (0,9,0,0)  2    (0,9,1,0)  2 (0,9,0,1)  2       (0,9,1,1)  2 (1,9,0,0)  4       (1,9,1,0)  4 (1,9,0,1)  4       (1,9,1,1)  4
        (2,9,0,0)  5    (2,9,1,0)  5 (2,9,0,1)  5       (2,9,1,1)  5 (3,9,0,0)  3       (3,9,1,0)  3 (3,9,0,1)  3       (3,9,1,1)  3
        (0,10,0,0) 2    (0,10,1,0) 2 (0,10,0,1) 2       (0,10,1,1) 2 (1,10,0,0) 4       (1,10,1,0) 4 (1,10,0,1) 4       (1,10,1,1) 4
        (2,10,0,0) 5    (2,10,1,0) 5 (2,10,0,1) 5       (2,10,1,1) 5 (3,10,0,0) 3       (3,10,1,0) 3 (3,10,0,1) 3       (3,10,1,1) 3
        (0,11,0,0) 2    (0,11,1,0) 2 (0,11,0,1) 2       (0,11,1,1) 2 (1,11,0,0) 4       (1,11,1,0) 4 (1,11,0,1) 4       (1,11,1,1) 4
        (2,11,0,0) 5    (2,11,1,0) 5 (2,11,0,1) 5       (2,11,1,1) 5 (3,11,0,0) 3       (3,11,1,0) 3 (3,11,0,1) 3       (3,11,1,1) 3
]
q_both: [(0,7,2,0)  2 (0,7,2,1)  2 (1,7,2,0)  4 (1,7,2,1)  4 (2,7,2,0)  5 (2,7,2,1)  5 (3,7,2,0)  3 (3,7,2,1)  3
            (0,8,2,0)  2 (0,8,2,1)  2 (1,8,2,0)  4 (1,8,2,1)  4 (2,8,2,0)  5 (2,8,2,1)  5 (3,8,2,0)  3 (3,8,2,1)  3
            (0,9,2,0)  2 (0,9,2,1)  2 (1,9,2,0)  4 (1,9,2,1)  4 (2,9,2,0)  5 (2,9,2,1)  5 (3,9,2,0)  3 (3,9,2,1)  3
            (0,10,2,0) 2 (0,10,2,1) 2 (1,10,2,0) 4 (1,10,2,1) 4 (2,10,2,0) 5 (2,10,2,1) 5 (3,10,2,0) 3 (3,10,2,1) 3
            (0,11,2,0) 2 (0,11,2,1) 2 (1,11,2,0) 4 (1,11,2,1) 4 (2,11,2,0) 5 (2,11,2,1) 5 (3,11,2,0) 3 (3,11,2,1) 3
           ]
r_ccc: [
           (7,0,3,0) 2 (8,0,3,0) 2 (9,0,3,0) 2 (10,0,3,0) 2 (11,0,3,0) 2 (7,1,3,0) 2 (8,1,3,0) 2 (9,1,3,0) 2 (10,1,3,0) 2 (11,1,3,0) 2
           (7,2,3,0) 2 (8,2,3,0) 2 (9,2,3,0) 2 (10,2,3,0) 2 (11,2,3,0) 2 (7,3,3,0) 2 (8,3,3,0) 2 (9,3,3,0) 2 (10,3,3,0) 2 (11,3,3,0) 2
           (7,0,4,0) 2 (8,0,4,0) 2 (9,0,4,0) 2 (10,0,4,0) 2 (11,0,4,0) 2 (7,1,4,0) 2 (8,1,4,0) 2 (9,1,4,0) 2 (10,1,4,0) 2 (11,1,4,0) 2
           (7,2,4,0) 2 (8,2,4,0) 2 (9,2,4,0) 2 (10,2,4,0) 2 (11,2,4,0) 2 (7,3,4,0) 2 (8,3,4,0) 2 (9,3,4,0) 2 (10,3,4,0) 2 (11,3,4,0) 2
           (7,0,3,1) 2 (8,0,3,1) 2 (9,0,3,1) 2 (10,0,3,1) 2 (11,0,3,1) 2 (7,1,3,1) 2 (8,1,3,1) 2 (9,1,3,1) 2 (10,1,3,1) 2 (11,1,3,1) 2
           (7,2,3,1) 2 (8,2,3,1) 2 (9,2,3,1) 2 (10,2,3,1) 2 (11,2,3,1) 2 (7,3,3,1) 2 (8,3,3,1) 2 (9,3,3,1) 2 (10,3,3,1) 2 (11,3,3,1) 2
           (7,0,4,1) 2 (8,0,4,1) 2 (9,0,4,1) 2 (10,0,4,1) 2 (11,0,4,1) 2 (7,1,4,1) 2 (8,1,4,1) 2 (9,1,4,1) 2 (10,1,4,1) 2 (11,1,4,1) 2
           (7,2,4,1) 2 (8,2,4,1) 2 (9,2,4,1) 2 (10,2,4,1) 2 (11,2,4,1) 2 (7,3,4,1) 2 (8,3,4,1) 2 (9,3,4,1) 2 (10,3,4,1) 2 (11,3,4,1) 2
        ]
r_both: [
           (7,0,5,0) 2 (8,0,5,0) 2 (9,0,5,0) 2 (10,0,5,0) 2 (11,0,5,0) 2 (7,1,5,0) 2 (8,1,5,0) 2 (9,1,5,0) 2 (10,1,5,0) 2 (11,1,5,0) 2
           (7,2,5,0) 2 (8,2,5,0) 2 (9,2,5,0) 2 (10,2,5,0) 2 (11,2,5,0) 2 (7,3,5,0) 2 (8,3,5,0) 2 (9,3,5,0) 2 (10,3,5,0) 2 (11,3,5,0) 2
           (7,0,6,0) 2 (8,0,6,0) 2 (9,0,6,0) 2 (10,0,6,0) 2 (11,0,6,0) 2 (7,1,6,0) 2 (8,1,6,0) 2 (9,1,6,0) 2 (10,1,6,0) 2 (11,1,6,0) 2
           (7,2,6,0) 2 (8,2,6,0) 2 (9,2,6,0) 2 (10,2,6,0) 2 (11,2,6,0) 2 (7,3,6,0) 2 (8,3,6,0) 2 (9,3,6,0) 2 (10,3,6,0) 2 (11,3,6,0) 2
           (7,0,5,1) 2 (8,0,5,1) 2 (9,0,5,1) 2 (10,0,5,1) 2 (11,0,5,1) 2 (7,1,5,1) 2 (8,1,5,1) 2 (9,1,5,1) 2 (10,1,5,1) 2 (11,1,5,1) 2
           (7,2,5,1) 2 (8,2,5,1) 2 (9,2,5,1) 2 (10,2,5,1) 2 (11,2,5,1) 2 (7,3,5,1) 2 (8,3,5,1) 2 (9,3,5,1) 2 (10,3,5,1) 2 (11,3,5,1) 2
           (7,0,6,1) 2 (8,0,6,1) 2 (9,0,6,1) 2 (10,0,6,1) 2 (11,0,6,1) 2 (7,1,6,1) 2 (8,1,6,1) 2 (9,1,6,1) 2 (10,1,6,1) 2 (11,1,6,1) 2
           (7,2,6,1) 2 (8,2,6,1) 2 (9,2,6,1) 2 (10,2,6,1) 2 (11,2,6,1) 2 (7,3,6,1) 2 (8,3,6,1) 2 (9,3,6,1) 2 (10,3,6,1) 2 (11,3,6,1) 2
        ]
cost_serv: [(0,4) 100 (1,4) 100 (2,4) 100 (3,4) 100
            (0,5) 100 (1,5) 100 (2,5) 100 (3,5) 100
            (0,6) 100 (1,6) 100 (2,6) 100 (3,6) 100
]
cost_inv: [(4) 10 (5) 10 (6) 10]
cap_ccc: [(4) 100 (5) 100 (6) 100]
cap_ccc_mat: [(4,0) 20 (4,1) 20 (4,2) 20 (4,3) 20 (4,4) 20 (4,5) 20 (4,6) 20
        (5,0) 20 (5,1) 20 (5,2) 20 (5,3) 20 (5,4) 20 (5,5) 20 (5,6) 20
        (6,0) 20 (6,1) 20 (6,2) 20 (6,3) 20 (6,4) 20 (6,5) 20 (6,6) 20
]
cap_incoming: [(4) 100 (5) 100 (6) 100]
cap_outgoing: [(4) 100 (5) 100 (6) 100]
```

Figure 28 Example of an input file for the Allocation to suppliers Model

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

9.2.3 Capacitated Vehicle Routing Problems

The input required by the *Capacitated Vehicle Routing Problems* are the following:

- Network map files;
- Points file;
- Requests file;
- Vehicles file.

Network map is a set of file in shapefile format: three files with extensions .shp, .dbf, .shx. The network file is a standard shapefile containing the arcs which describe the roads of the (portion) of city to be considered.

Points is a file in shapefile format, representing the vertices of the considered network. The Points file must have the same name of the network followed by "_Points". The Points shapefile considers all the vertices we can use in several scenarios. The subset of sites to be considered in a specific scenario is given in the *request.csv* file.

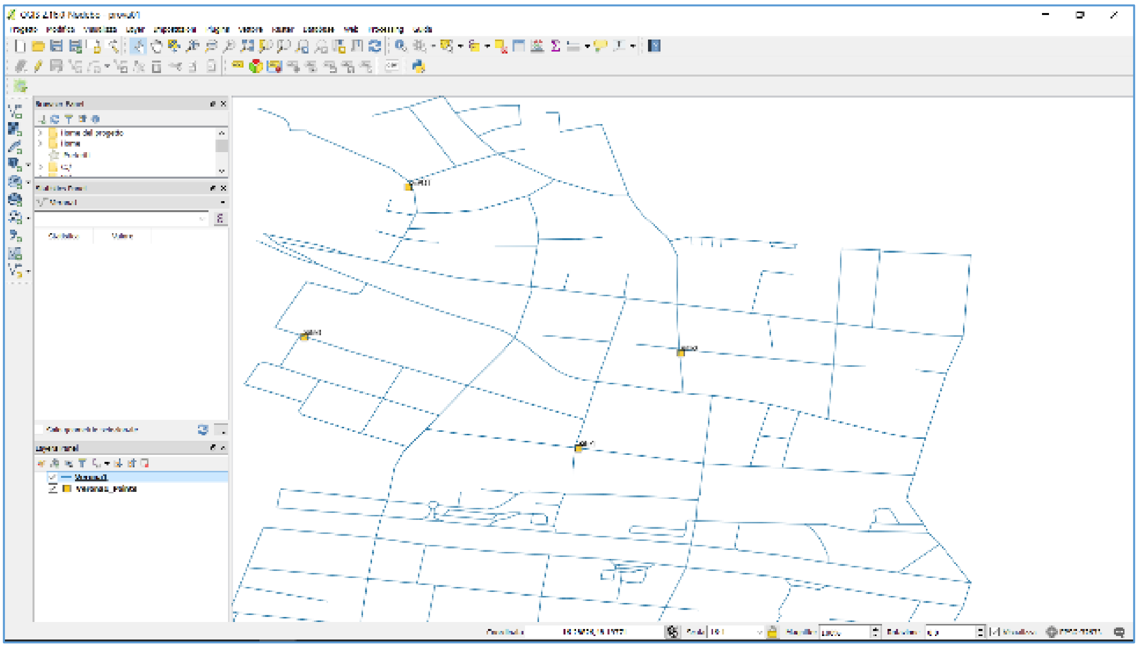


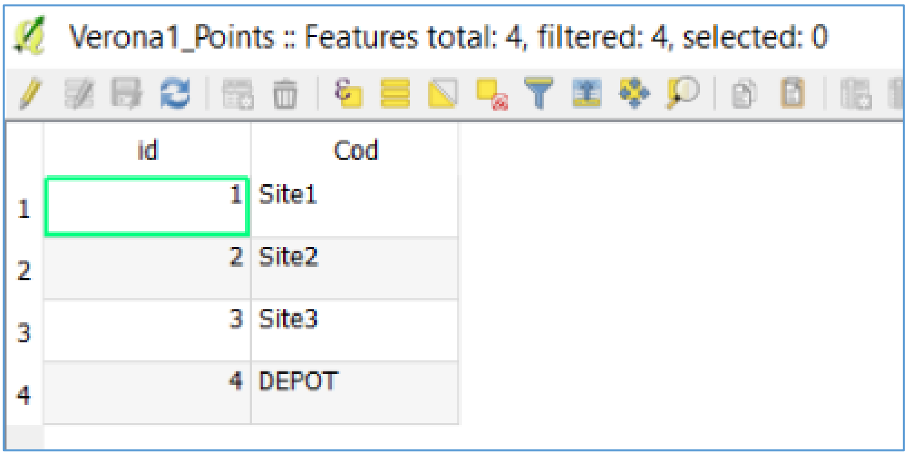
Figure 29 A sample of a Verona scenario (using QGIS[4]) with three sites, and a depot

The Points shapefile must have an attribute table containing a field "Cod" giving the string to be used to identify the point (e.g. "Site01", "Hospital", etc.). However, there must be a single point having code "DEPOT". See, e.g., Figure 30.

[4] https://www.qgis.org/it/site/

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

The Points file is a shapefile containing all the relevant points, i.e., the DEPOT (or starting point of the vehicles, e.g. a CCC) and the construction sites that could be considered.



Verona1_Points :: Features total: 4, filtered: 4, selected: 0

	id	Cod
1	1	Site1
2	2	Site2
3	3	Site3
4	4	DEPOT

Figure 30 Example of an attribute table of Points file with three generic sites and one depot

Requests file in .csv format, containing the material requests. The Requests file must have the same name of the network, followed by the scenario we are considering, followed by "_Requests", e.g., *Verona1_Requests*.

Each line of the Requests file is made as follows:

<Request Code> <Customer code> <Request>

An explanation of the used data can be found in Table 22, and an example in Figure 31.

Table 22 Requests file Data

Name	meaning	size	type
	Input file: Requests		
Request code	Identification number of the request	Number	integer
Customer code	The code of the customer of the request	String	char
Request	Material request	Number	double

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

Req. Code	Point Cod	Request
1	Site1	100
2	Site2	50
3	Site3	30

Figure 31 Requests file Example

Vehicles file in .csv format, containing the specifics of the vehicles. The Vehicles file must have the same name of network, followed by the scenario we are considering, followed by "_Vehicles", e.g., *Verona1_Vehicles.*

Each line of the Vehicles file is made as follows:

<Vehicle Id> <Capacity>

An explanation of the used data can be found in Table 23, and an example in Figure 31.

Table 23 Vehicles file Data

Name	meaning	size	type
	Input file: Vehicles		
Id	Identification number of the vehicles	Number	integer
Capacity	Capacity of the vehicle	Number	double

id	Capacity
1	1000
2	1000
3	1200

Figure 32 Vehicles file example

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

9.2.4 Inventory vs Transport Problems

9.2.4.1 Basic Model

The input files needed for the *Inventory vs Transport Basic Model* are two: the **Main Data** file and **Travelling Costs** file. The Main Data input file for the *Inventory vs Transport basic Model* requires coordinates of the vertices in this order: the suppliers, the CCC, and the construction sites. We recall that these models are solved for cases with only one CCC. Other data are required regarding vehicles, such as vehicles' costs, capacity, and material that can be carried on the vehicles. A second file including distance / costs is also required, the Travelling Costs file. The definitions of required data are provided in Table 24. A data file example is given in Figure 33.

Table 24 Inventory vs Transport Basic Model Data

Name	meaning	size	type
	First input file: Main Data		
coorx	x coordinates of the vertices	Array of vertices	double
coory	y coordinates of the vertices	Array of vertices	double
s_supp	The index into the vertices array where the suppliers start, it is supposed to be 0.	Number	integer
s_sites	The index into the vertices array where the sites start (for construction, the CCC will be located at the end of the suppliers and before the sites).	Number	integer
q	Material request, defined by its origin (supplier), its destination (construction site), the material, and the period of request.	Matrix (suppliers, construction sites)	double
cost_veh	Cost of using one vehicle of one type	Array of vehicles	double
cap_veh	capacity of each vehicle type	Array of vehicles	double
mat_veh	A matrix that has materials is rows and vehicles in columns. In each space there is a 1 if the material can be carried on that vehicle, 0 otherwise.	Matrix of (materials, vehicles)	double

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

cost_inv	Inventory cost for one unit of material	Number	double
cap_mat	Maximum storage capacity into the CCC for each material	Array of materials	double
fixed_x	The flow incoming into the CCC from the supplier, it is defined by the supplier, the construction site, the material and the period. This decision is fixed and thus an input.	Four dimensional Matrix (suppliers, construction sites, materials, periods)	double
Second input file: Travelling Cost			
cost_dist	Costs /distance between the CCC and the construction sites.	Matrix (constructions sites)	Double

```
coorx: [(0) 0 (1) 40 (2) 0 (3) 70 (4) 60 (5) 30 (6) 15 (7) 35 (8) 50 (9) 43]
coory: [(0) 0 (1)  0 (2) 50 (3) 70 (4) 6  (5) 40 (6) 52 (7) 35 (8) 30 (9) 23]
s_supp: 0
s_sites: 5
q: [
        (0,5,0,0) 2 (1,5,0,0) 4 (2,5,0,0) 5 (3,5,0,0) 3        (0,5,0,1) 2 (1,5,0,1) 4 (2,5,0,1) 5 (3,5,0,1) 3
        (0,6,0,0) 2 (1,6,0,0) 4 (2,6,0,0) 5 (3,6,0,0) 3        (0,6,0,1) 2 (1,6,0,1) 4 (2,6,0,1) 5 (3,6,0,1) 3
        (0,7,0,0) 2 (1,7,0,0) 4 (2,7,0,0) 5 (3,7,0,0) 3        (0,7,0,1) 2 (1,7,0,1) 4 (2,7,0,1) 5 (3,7,0,1) 3
        (0,8,0,0) 2 (1,8,0,0) 4 (2,8,0,0) 5 (3,8,0,0) 3        (0,8,0,1) 2 (1,8,0,1) 4 (2,8,0,1) 5 (3,8,0,1) 3
        (0,9,0,0) 2 (1,9,0,0) 4 (2,9,0,0) 5 (3,9,0,0) 3        (0,9,0,1) 2 (1,9,0,1) 4 (2,9,0,1) 5 (3,9,0,1) 3
        (0,5,1,0) 2 (1,5,1,0) 4 (2,5,1,0) 5 (3,5,1,0) 3        (0,5,1,1) 2 (1,5,1,1) 4 (2,5,1,1) 5 (3,5,1,1) 3
        (0,6,1,0) 2 (1,6,1,0) 4 (2,6,1,0) 5 (3,6,1,0) 3        (0,6,1,1) 2 (1,6,1,1) 4 (2,6,1,1) 5 (3,6,1,1) 3
        (0,7,1,0) 2 (1,7,1,0) 4 (2,7,1,0) 5 (3,7,1,0) 3        (0,7,1,1) 2 (1,7,1,1) 4 (2,7,1,1) 5 (3,7,1,1) 3
        (0,8,1,0) 2 (1,8,1,0) 4 (2,8,1,0) 5 (3,8,1,0) 3        (0,8,1,1) 2 (1,8,1,1) 4 (2,8,1,1) 5 (3,8,1,1) 3
        (0,9,1,0) 2 (1,9,1,0) 4 (2,9,1,0) 5 (3,9,1,0) 3        (0,9,1,1) 2 (1,9,1,1) 4 (2,9,1,1) 5 (3,9,1,1) 3
        (0,5,2,0) 2 (1,5,2,0) 4 (2,5,2,0) 5 (3,5,2,0) 3        (0,5,2,1) 2 (1,5,2,1) 4 (2,5,2,1) 5 (3,5,2,1) 3
        (0,6,2,0) 2 (1,6,2,0) 4 (2,6,2,0) 5 (3,6,2,0) 3        (0,6,2,1) 2 (1,6,2,1) 4 (2,6,2,1) 5 (3,6,2,1) 3
        (0,7,2,0) 2 (1,7,2,0) 4 (2,7,2,0) 5 (3,7,2,0) 3        (0,7,2,1) 2 (1,7,2,1) 4 (2,7,2,1) 5 (3,7,2,1) 3
        (0,8,2,0) 2 (1,8,2,0) 4 (2,8,2,0) 5 (3,8,2,0) 3        (0,8,2,1) 2 (1,8,2,1) 4 (2,8,2,1) 5 (3,8,2,1) 3
        (0,9,2,0) 2 (1,9,2,0) 4 (2,9,2,0) 5 (3,9,2,0) 3        (0,9,2,1) 2 (1,9,2,1) 4 (2,9,2,1) 5 (3,9,2,1) 3
]
cost_veh: [(0) 10 (1) 10 (2) 10]
cap_veh:[(0) 30 (1) 20 (2) 30]
mat_veh: [
        (0,0) 1 (0,1) 1 (0,2) 0
        (1,0) 1 (1,1) 0 (1,2) 1
        (2,0) 0 (2,1) 1 (2,2) 1
 ]
cost_inv: 10
cap_mat: [(0) 10 (1) 15 (2) 10 ]
fixed_x:[
        (0,5,0,0) 2 (1,5,0,0) 4 (2,5,0,0) 5 (3,5,0,0) 3        (0,5,0,1) 2 (1,5,0,1) 4 (2,5,0,1) 5 (3,5,0,1) 3
        (0,6,0,0) 2 (1,6,0,0) 4 (2,6,0,0) 5 (3,6,0,0) 3        (0,6,0,1) 2 (1,6,0,1) 4 (2,6,0,1) 5 (3,6,0,1) 3
        (0,7,0,0) 2 (1,7,0,0) 4 (2,7,0,0) 5 (3,7,0,0) 3        (0,7,0,1) 2 (1,7,0,1) 4 (2,7,0,1) 5 (3,7,0,1) 3
        (0,8,0,0) 2 (1,8,0,0) 4 (2,8,0,0) 5 (3,8,0,0) 3        (0,8,0,1) 2 (1,8,0,1) 4 (2,8,0,1) 5 (3,8,0,1) 3
        (0,9,0,0) 2 (1,9,0,0) 4 (2,9,0,0) 5 (3,9,0,0) 3        (0,9,0,1) 2 (1,9,0,1) 4 (2,9,0,1) 5 (3,9,0,1) 3
        (0,5,1,0) 2 (1,5,1,0) 4 (2,5,1,0) 5 (3,5,1,0) 3        (0,5,1,1) 2 (1,5,1,1) 4 (2,5,1,1) 5 (3,5,1,1) 3
        (0,6,1,0) 2 (1,6,1,0) 4 (2,6,1,0) 5 (3,6,1,0) 3        (0,6,1,1) 2 (1,6,1,1) 4 (2,6,1,1) 5 (3,6,1,1) 3
        (0,7,1,0) 2 (1,7,1,0) 4 (2,7,1,0) 5 (3,7,1,0) 3        (0,7,1,1) 2 (1,7,1,1) 4 (2,7,1,1) 5 (3,7,1,1) 3
        (0,8,1,0) 2 (1,8,1,0) 4 (2,8,1,0) 5 (3,8,1,0) 3        (0,8,1,1) 2 (1,8,1,1) 4 (2,8,1,1) 5 (3,8,1,1) 3
        (0,9,1,0) 2 (1,9,1,0) 4 (2,9,1,0) 5 (3,9,1,0) 3        (0,9,1,1) 2 (1,9,1,1) 4 (2,9,1,1) 5 (3,9,1,1) 3
        (0,5,2,0) 2 (1,5,2,0) 4 (2,5,2,0) 5 (3,5,2,0) 3        (0,5,2,1) 2 (1,5,2,1) 4 (2,5,2,1) 5 (3,5,2,1) 3
        (0,6,2,0) 2 (1,6,2,0) 4 (2,6,2,0) 5 (3,6,2,0) 3        (0,6,2,1) 2 (1,6,2,1) 4 (2,6,2,1) 5 (3,6,2,1) 3
        (0,7,2,0) 2 (1,7,2,0) 4 (2,7,2,0) 5 (3,7,2,0) 3        (0,7,2,1) 2 (1,7,2,1) 4 (2,7,2,1) 5 (3,7,2,1) 3
        (0,8,2,0) 2 (1,8,2,0) 4 (2,8,2,0) 5 (3,8,2,0) 3        (0,8,2,1) 2 (1,8,2,1) 4 (2,8,2,1) 5 (3,8,2,1) 3
        (0,9,2,0) 2 (1,9,2,0) 4 (2,9,2,0) 5 (3,9,2,0) 3        (0,9,2,1) 2 (1,9,2,1) 4 (2,9,2,1) 5 (3,9,2,1) 3
]
```

Figure 33 Example of an input file for Inventory vs Transport Basic Model

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

9.2.4.2 Model with possible anticipation

The input files needed for the *Inventory vs Transport Model with possible anticipation* are two: the **Main Data** file and **Travelling Costs** file. The input files for the *Model with possible anticipation* are very similar to the previous ones. The only new datum is: gamma in the Main Data file. One can find details in Table 25 and an example in Figure 34.

Table 25 Inventory vs Transport Model with possible anticipation Data

Name	meaning	size	type
	First input file: Main Data		
coorx	x coordinates of the vertices	Array of vertices	double
coory	y coordinates of the vertices	Array of vertices	double
s_supp	The index into the vertices array where the suppliers start, it is supposed to be 0.	Number	integer
s_sites	The index into the vertices array where the sites start (for construction, the CCC will be located at the end of the suppliers and before the sites).	Number	integer
q	Material request, defined by its origin (supplier), its destination (construction site), the material, and the period of request.	Matrix (suppliers, construction sites)	double
cost_veh	Cost of using one vehicle of one type	Array of vehicles	double
cap_veh	Capacity of each vehicle type	Array of vehicles	double
mat_veh	A matrix that has materials is rows and vehicles in columns. In each space there is a 1 if the material can be carried on that vehicle, 0 otherwise.	Matrix of (materials, vehicles)	double
cost_inv	Inventory cost for one unit of material	Number	double
cap_mat	Maximum storage capacity into the CCC for each material	Array of materials	double

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fixed_x	The flow incoming into the CCC from the supplier, it is defined by the supplier, the construction site, the material and the period. This decision is fixed and thus an input.	Four dimensional Matrix (suppliers, construction sites, materials, periods)	double
gamma	Cost for anticipating the material arrival into the construction site	Number	double
	Second input file: Travelling Cost		
cost_dist	Costs /distance between the CCC and the construction sites.	Matrix (constructions sites)	double

```
coorx: [(0) 0 (1) 40 (2) 0 (3) 70 (4) 60 (5) 30 (6) 15 (7) 35 (8) 50 (9) 43]
coory: [(0) 0 (1)  0 (2) 50 (3) 70 (4) 6  (5) 40 (6) 52 (7) 35 (8) 30 (9) 23]
s_supp: 0
s_sites: 5
q: [
        (0,5,0,0) 2 (1,5,0,0) 4 (2,5,0,0) 5 (3,5,0,0) 3        (0,5,0,1) 2 (1,5,0,1) 4 (2,5,0,1) 5 (3,5,0,1) 3
        (0,6,0,0) 2 (1,6,0,0) 4 (2,6,0,0) 5 (3,6,0,0) 3        (0,6,0,1) 2 (1,6,0,1) 4 (2,6,0,1) 5 (3,6,0,1) 3
        (0,7,0,0) 2 (1,7,0,0) 4 (2,7,0,0) 5 (3,7,0,0) 3        (0,7,0,1) 2 (1,7,0,1) 4 (2,7,0,1) 5 (3,7,0,1) 3
        (0,8,0,0) 2 (1,8,0,0) 4 (2,8,0,0) 5 (3,8,0,0) 3        (0,8,0,1) 2 (1,8,0,1) 4 (2,8,0,1) 5 (3,8,0,1) 3
        (0,9,0,0) 2 (1,9,0,0) 4 (2,9,0,0) 5 (3,9,0,0) 3        (0,9,0,1) 2 (1,9,0,1) 4 (2,9,0,1) 5 (3,9,0,1) 3
        (0,5,1,0) 2 (1,5,1,0) 4 (2,5,1,0) 5 (3,5,1,0) 3        (0,5,1,1) 2 (1,5,1,1) 4 (2,5,1,1) 5 (3,5,1,1) 3
        (0,6,1,0) 2 (1,6,1,0) 4 (2,6,1,0) 5 (3,6,1,0) 3        (0,6,1,1) 2 (1,6,1,1) 4 (2,6,1,1) 5 (3,6,1,1) 3
        (0,7,1,0) 2 (1,7,1,0) 4 (2,7,1,0) 5 (3,7,1,0) 3        (0,7,1,1) 2 (1,7,1,1) 4 (2,7,1,1) 5 (3,7,1,1) 3
        (0,8,1,0) 2 (1,8,1,0) 4 (2,8,1,0) 5 (3,8,1,0) 3        (0,8,1,1) 2 (1,8,1,1) 4 (2,8,1,1) 5 (3,8,1,1) 3
        (0,9,1,0) 2 (1,9,1,0) 4 (2,9,1,0) 5 (3,9,1,0) 3        (0,9,1,1) 2 (1,9,1,1) 4 (2,9,1,1) 5 (3,9,1,1) 3
        (0,5,2,0) 2 (1,5,2,0) 4 (2,5,2,0) 5 (3,5,2,0) 3        (0,5,2,1) 2 (1,5,2,1) 4 (2,5,2,1) 5 (3,5,2,1) 3
        (0,6,2,0) 2 (1,6,2,0) 4 (2,6,2,0) 5 (3,6,2,0) 3        (0,6,2,1) 2 (1,6,2,1) 4 (2,6,2,1) 5 (3,6,2,1) 3
        (0,7,2,0) 2 (1,7,2,0) 4 (2,7,2,0) 5 (3,7,2,0) 3        (0,7,2,1) 2 (1,7,2,1) 4 (2,7,2,1) 5 (3,7,2,1) 3
        (0,8,2,0) 2 (1,8,2,0) 4 (2,8,2,0) 5 (3,8,2,0) 3        (0,8,2,1) 2 (1,8,2,1) 4 (2,8,2,1) 5 (3,8,2,1) 3
        (0,9,2,0) 2 (1,9,2,0) 4 (2,9,2,0) 5 (3,9,2,0) 3        (0,9,2,1) 2 (1,9,2,1) 4 (2,9,2,1) 5 (3,9,2,1) 3
]
cost_veh: [(0) 10 (1) 10 (2) 10]
cap_veh:[(0) 30 (1) 20 (2) 30]
mat_veh: [
        (0,0) 1 (0,1) 1 (0,2) 0
        (1,0) 1 (1,1) 0 (1,2) 1
        (2,0) 0 (2,1) 1 (2,2) 1
 ]
cost_inv: 10
cap_mat: [(0) 10 (1) 15 (2) 10 ]
fixed_x:[
        (0,5,0,0) 2 (1,5,0,0) 4 (2,5,0,0) 5 (3,5,0,0) 3        (0,5,0,1) 2 (1,5,0,1) 4 (2,5,0,1) 5 (3,5,0,1) 3
        (0,6,0,0) 2 (1,6,0,0) 4 (2,6,0,0) 5 (3,6,0,0) 3        (0,6,0,1) 2 (1,6,0,1) 4 (2,6,0,1) 5 (3,6,0,1) 3
        (0,7,0,0) 2 (1,7,0,0) 4 (2,7,0,0) 5 (3,7,0,0) 3        (0,7,0,1) 2 (1,7,0,1) 4 (2,7,0,1) 5 (3,7,0,1) 3
        (0,8,0,0) 2 (1,8,0,0) 4 (2,8,0,0) 5 (3,8,0,0) 3        (0,8,0,1) 2 (1,8,0,1) 4 (2,8,0,1) 5 (3,8,0,1) 3
        (0,9,0,0) 2 (1,9,0,0) 4 (2,9,0,0) 5 (3,9,0,0) 3        (0,9,0,1) 2 (1,9,0,1) 4 (2,9,0,1) 5 (3,9,0,1) 3
        (0,5,1,0) 2 (1,5,1,0) 4 (2,5,1,0) 5 (3,5,1,0) 3        (0,5,1,1) 2 (1,5,1,1) 4 (2,5,1,1) 5 (3,5,1,1) 3
        (0,6,1,0) 2 (1,6,1,0) 4 (2,6,1,0) 5 (3,6,1,0) 3        (0,6,1,1) 2 (1,6,1,1) 4 (2,6,1,1) 5 (3,6,1,1) 3
        (0,7,1,0) 2 (1,7,1,0) 4 (2,7,1,0) 5 (3,7,1,0) 3        (0,7,1,1) 2 (1,7,1,1) 4 (2,7,1,1) 5 (3,7,1,1) 3
        (0,8,1,0) 2 (1,8,1,0) 4 (2,8,1,0) 5 (3,8,1,0) 3        (0,8,1,1) 2 (1,8,1,1) 4 (2,8,1,1) 5 (3,8,1,1) 3
        (0,9,1,0) 2 (1,9,1,0) 4 (2,9,1,0) 5 (3,9,1,0) 3        (0,9,1,1) 2 (1,9,1,1) 4 (2,9,1,1) 5 (3,9,1,1) 3
        (0,5,2,0) 2 (1,5,2,0) 4 (2,5,2,0) 5 (3,5,2,0) 3        (0,5,2,1) 2 (1,5,2,1) 4 (2,5,2,1) 5 (3,5,2,1) 3
        (0,6,2,0) 2 (1,6,2,0) 4 (2,6,2,0) 5 (3,6,2,0) 3        (0,6,2,1) 2 (1,6,2,1) 4 (2,6,2,1) 5 (3,6,2,1) 3
        (0,7,2,0) 2 (1,7,2,0) 4 (2,7,2,0) 5 (3,7,2,0) 3        (0,7,2,1) 2 (1,7,2,1) 4 (2,7,2,1) 5 (3,7,2,1) 3
        (0,8,2,0) 2 (1,8,2,0) 4 (2,8,2,0) 5 (3,8,2,0) 3        (0,8,2,1) 2 (1,8,2,1) 4 (2,8,2,1) 5 (3,8,2,1) 3
        (0,9,2,0) 2 (1,9,2,0) 4 (2,9,2,0) 5 (3,9,2,0) 3        (0,9,2,1) 2 (1,9,2,1) 4 (2,9,2,1) 5 (3,9,2,1) 3
]
gamma: 10
```

Figure 34 Example of an input file for Inventory vs Transport Model with possible anticipation

9.2.4.3 *Model with possible anticipation and reverse logistics*

The input files needed for the *Inventory vs Transport Model with possible anticipation and reverse logistics* are two: the **Main Data** file and **Travelling Costs** file. The input .txt files are very similar to the previous presented ones. In

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this case it is also required the reverse logistics demand r in the Main Data file. Detailed explanation can be found in Table 26 and an example can be found in Figure 35.

Table 26 Inventory vs Transport Model with possible anticipation and reverse logistics Data

Name	meaning	size	type
	First input file: Main Data		
coorx	x coordinates of the vertices	Array of vertices	double
coory	y coordinates of the vertices	Array of vertices	double
s_supp	The index into the vertices array where the suppliers start, it is supposed to be 0.	Number	integer
s_sites	The index into the vertices array where the sites start (for construction, the CCC will be located at the end of the suppliers and before the sites).	Number	integer
q	Material request, defined by its origin (supplier), its destination (construction site), the material, and the period of request.	Matrix (suppliers, construction sites)	double
r	Reverse logistics demand, defined by its origin (construction site), its destination supplier/dumpsite, the material, and the period of the request.	Matrix (construction sites, supplier /dumpsites)	double
cost_veh	Cost of using one vehicle of one type	Array of vehicles	double
cap_veh	Capacity of each vehicle type	Array of vehicles	double
mat_veh	A matrix that has materials is rows and vehicles in columns. In each space there is a 1 if the material can be carried on that vehicle, 0 otherwise.	Matrix of (materials, vehicles)	double
cost_inv	Inventory cost for one unit of material	Number	double

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cap_mat	Maximum storage capacity into the CCC for each material	Array of materials	double
fixed_x	The flow incoming into the CCC from the supplier, it is defined by the supplier, the construction site, the material and the period. This decision is fixed and thus an input.	Four dimensional Matrix (suppliers, construction sites, materials, periods)	double
gamma	Cost for anticipating the material arrival into the construction site	Number	double
Second input file: Travelling Costs			
cost_dist	Costs /distance between the CCC and the construction sites.	Matrix (constructions sites)	Double

```
coorx: [(0) 0 (1) 40 (2) 0 (3) 70 (4) 60 (5) 30 (6) 15 (7) 35 (8) 50 (9) 43]
coory: [(0) 0 (1)  0 (2) 50 (3) 70 (4) 6  (5) 40 (6) 52 (7) 35 (8) 30 (9) 23]
s_supp: 0
s_sites: 5
q: [
        (0,5,0,0) 2 (1,5,0,0) 4 (2,5,0,0) 5 (3,5,0,0) 3        (0,5,0,1) 2 (1,5,0,1) 4 (2,5,0,1) 5 (3,5,0,1) 3
        (0,6,0,0) 2 (1,6,0,0) 4 (2,6,0,0) 5 (3,6,0,0) 3        (0,6,0,1) 2 (1,6,0,1) 4 (2,6,0,1) 5 (3,6,0,1) 3
        (0,7,0,0) 2 (1,7,0,0) 4 (2,7,0,0) 5 (3,7,0,0) 3        (0,7,0,1) 2 (1,7,0,1) 4 (2,7,0,1) 5 (3,7,0,1) 3
        (0,8,0,0) 2 (1,8,0,0) 4 (2,8,0,0) 5 (3,8,0,0) 3        (0,8,0,1) 2 (1,8,0,1) 4 (2,8,0,1) 5 (3,8,0,1) 3
        (0,9,0,0) 2 (1,9,0,0) 4 (2,9,0,0) 5 (3,9,0,0) 3        (0,9,0,1) 2 (1,9,0,1) 4 (2,9,0,1) 5 (3,9,0,1) 3
        (0,5,1,0) 2 (1,5,1,0) 4 (2,5,1,0) 5 (3,5,1,0) 3        (0,5,1,1) 2 (1,5,1,1) 4 (2,5,1,1) 5 (3,5,1,1) 3
        (0,6,1,0) 2 (1,6,1,0) 4 (2,6,1,0) 5 (3,6,1,0) 3        (0,6,1,1) 2 (1,6,1,1) 4 (2,6,1,1) 5 (3,6,1,1) 3
        (0,7,1,0) 2 (1,7,1,0) 4 (2,7,1,0) 5 (3,7,1,0) 3        (0,7,1,1) 2 (1,7,1,1) 4 (2,7,1,1) 5 (3,7,1,1) 3
        (0,8,1,0) 2 (1,8,1,0) 4 (2,8,1,0) 5 (3,8,1,0) 3        (0,8,1,1) 2 (1,8,1,1) 4 (2,8,1,1) 5 (3,8,1,1) 3
        (0,9,1,0) 2 (1,9,1,0) 4 (2,9,1,0) 5 (3,9,1,0) 3        (0,9,1,1) 2 (1,9,1,1) 4 (2,9,1,1) 5 (3,9,1,1) 3
        (0,5,2,0) 2 (1,5,2,0) 4 (2,5,2,0) 5 (3,5,2,0) 3        (0,5,2,1) 2 (1,5,2,1) 4 (2,5,2,1) 5 (3,5,2,1) 3
        (0,6,2,0) 2 (1,6,2,0) 4 (2,6,2,0) 5 (3,6,2,0) 3        (0,6,2,1) 2 (1,6,2,1) 4 (2,6,2,1) 5 (3,6,2,1) 3
        (0,7,2,0) 2 (1,7,2,0) 4 (2,7,2,0) 5 (3,7,2,0) 3        (0,7,2,1) 2 (1,7,2,1) 4 (2,7,2,1) 5 (3,7,2,1) 3
        (0,8,2,0) 2 (1,8,2,0) 4 (2,8,2,0) 5 (3,8,2,0) 3        (0,8,2,1) 2 (1,8,2,1) 4 (2,8,2,1) 5 (3,8,2,1) 3
        (0,9,2,0) 2 (1,9,2,0) 4 (2,9,2,0) 5 (3,9,2,0) 3        (0,9,2,1) 2 (1,9,2,1) 4 (2,9,2,1) 5 (3,9,2,1) 3
]
r: [
        (5,0,0,0)     2 (5,1,0,0)    4 (5,2,0,0)    5 (5,3,0,0)    3       (5,0,0,1)     2 (5,1,0,1)    4 (5,2,0,1)    5 (5,3,0,1)    3
        (6,0,0,0)     2 (6,0,0,0)    4 (6,2,0,0)    5 (6,3,0,0)    3       (6,0,0,1)     2 (6,0,0,1)    4 (6,2,0,1)    5 (6,3,0,1)    3
        (7,0,0,0)     2 (7,1,0,0)    4 (7,2,0,0)    5 (7,3,0,0)    3       (7,0,0,1)     2 (7,1,0,1)    4 (7,2,0,1)    5 (7,3,0,1)    3
        (8,0,0,0)     2 (8,1,0,0)    4 (8,2,0,0)    5 (8,3,0,0)    3       (8,0,0,1)     2 (8,1,0,1)    4 (8,2,0,1)    5 (8,3,0,1)    3
        (9,0,0,0)     2 (9,1,0,0)    4 (9,2,0,0)    5 (9,3,0,0)    3       (9,0,0,1)     2 (9,1,0,1)    4 (9,2,0,1)    5 (9,3,0,1)    3
        (5,0,1,0)     2 (5,1,1,0)    4 (5,2,1,0)    5 (5,3,1,0)    3       (5,0,1,1)     2 (5,1,1,1)    4 (5,2,1,1)    5 (5,3,1,1)    3
        (6,0,1,0)     2 (6,0,1,0)    4 (6,2,1,0)    5 (6,3,1,0)    3       (6,0,1,1)     2 (6,0,1,1)    4 (6,2,1,1)    5 (6,3,1,1)    3
        (7,0,1,0)     2 (7,1,1,0)    4 (7,2,1,0)    5 (7,3,1,0)    3       (7,0,1,1)     2 (7,1,1,1)    4 (7,2,1,1)    5 (7,3,1,1)    3
        (8,0,1,0)     2 (8,1,1,0)    4 (8,2,1,0)    5 (8,3,1,0)    3       (8,0,1,1)     2 (8,1,1,1)    4 (8,2,1,1)    5 (8,3,1,1)    3
        (9,0,1,0)     2 (9,1,1,0)    4 (9,2,1,0)    5 (9,3,1,0)    3       (9,0,1,1)     2 (9,1,1,1)    4 (9,2,1,1)    5 (9,3,1,1)    3
        (5,0,2,0)     2 (5,1,2,0)    4 (5,2,2,0)    5 (5,3,2,0)    3       (5,0,2,1)     2 (5,1,2,1)    4 (5,2,2,1)    5 (5,3,2,1)    3
        (6,0,2,0)     2 (6,0,2,0)    4 (6,2,2,0)    5 (6,3,2,0)    3       (6,0,2,1)     2 (6,0,2,1)    4 (6,2,2,1)    5 (6,3,2,1)    3
        (7,0,2,0)     2 (7,1,2,0)    4 (7,2,2,0)    5 (7,3,2,0)    3       (7,0,2,1)     2 (7,1,2,1)    4 (7,2,2,1)    5 (7,3,2,1)    3
        (8,0,2,0)     2 (8,1,2,0)    4 (8,2,2,0)    5 (8,3,2,0)    3       (8,0,2,1)     2 (8,1,2,1)    4 (8,2,2,1)    5 (8,3,2,1)    3
        (9,0,2,0)     2 (9,1,2,0)    4 (9,2,2,0)    5 (9,3,2,0)    3       (9,0,2,1)     2 (9,1,2,1)    4 (9,2,2,1)    5 (9,3,2,1)    3
]
cost_veh: [(0) 10 (1) 10 (2) 10]
cap_veh:[(0) 30 (1) 20 (2) 30]
mat_veh: [
        (0,0) 1 (0,1) 1 (0,2) 0
        (1,0) 1 (1,1) 0 (1,2) 1
        (2,0) 0 (2,1) 1 (2,2) 1
 ]
cost_inv: 10
cap_mat: [(0) 10 (1) 15 (2) 10 ]
fixed_x:[
        (0,5,0,0) 2 (1,5,0,0) 4 (2,5,0,0) 5 (3,5,0,0) 3 (0,5,0,1) 2 (1,5,0,1) 4 (2,5,0,1) 5 (3,5,0,1) 3
        (0,6,0,0) 2 (1,6,0,0) 4 (2,6,0,0) 5 (3,6,0,0) 3 (0,6,0,1) 2 (1,6,0,1) 4 (2,6,0,1) 5 (3,6,0,1) 3
        (0,7,0,0) 2 (1,7,0,0) 4 (2,7,0,0) 5 (3,7,0,0) 3 (0,7,0,1) 2 (1,7,0,1) 4 (2,7,0,1) 5 (3,7,0,1) 3
        (0,8,0,0) 2 (1,8,0,0) 4 (2,8,0,0) 5 (3,8,0,0) 3 (0,8,0,1) 2 (1,8,0,1) 4 (2,8,0,1) 5 (3,8,0,1) 3
        (0,9,0,0) 2 (1,9,0,0) 4 (2,9,0,0) 5 (3,9,0,0) 3 (0,9,0,1) 2 (1,9,0,1) 4 (2,9,0,1) 5 (3,9,0,1) 3
        (0,5,1,0) 2 (1,5,1,0) 4 (2,5,1,0) 5 (3,5,1,0) 3 (0,5,1,1) 2 (1,5,1,1) 4 (2,5,1,1) 5 (3,5,1,1) 3
        (0,6,1,0) 2 (1,6,1,0) 4 (2,6,1,0) 5 (3,6,1,0) 3 (0,6,1,1) 2 (1,6,1,1) 4 (2,6,1,1) 5 (3,6,1,1) 3
        (0,7,1,0) 2 (1,7,1,0) 4 (2,7,1,0) 5 (3,7,1,0) 3 (0,7,1,1) 2 (1,7,1,1) 4 (2,7,1,1) 5 (3,7,1,1) 3
        (0,8,1,0) 2 (1,8,1,0) 4 (2,8,1,0) 5 (3,8,1,0) 3 (0,8,1,1) 2 (1,8,1,1) 4 (2,8,1,1) 5 (3,8,1,1) 3
        (0,9,1,0) 2 (1,9,1,0) 4 (2,9,1,0) 5 (3,9,1,0) 3 (0,9,1,1) 2 (1,9,1,1) 4 (2,9,1,1) 5 (3,9,1,1) 3
        (0,5,2,0) 2 (1,5,2,0) 4 (2,5,2,0) 5 (3,5,2,0) 3 (0,5,2,1) 2 (1,5,2,1) 4 (2,5,2,1) 5 (3,5,2,1) 3
        (0,6,2,0) 2 (1,6,2,0) 4 (2,6,2,0) 5 (3,6,2,0) 3 (0,6,2,1) 2 (1,6,2,1) 4 (2,6,2,1) 5 (3,6,2,1) 3
        (0,7,2,0) 2 (1,7,2,0) 4 (2,7,2,0) 5 (3,7,2,0) 3 (0,7,2,1) 2 (1,7,2,1) 4 (2,7,2,1) 5 (3,7,2,1) 3
        (0,8,2,0) 2 (1,8,2,0) 4 (2,8,2,0) 5 (3,8,2,0) 3 (0,8,2,1) 2 (1,8,2,1) 4 (2,8,2,1) 5 (3,8,2,1) 3
        (0,9,2,0) 2 (1,9,2,0) 4 (2,9,2,0) 5 (3,9,2,0) 3 (0,9,2,1) 2 (1,9,2,1) 4 (2,9,2,1) 5 (3,9,2,1) 3
]
gamma: 10
```

Figure 35 Example of an input file for Inventory vs Transport Model with possible anticipation and reverse logistics

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

9.2.5 Input check

We performed several checks on the input data: mainly consistency checks. In particular we checked

- That all inserted data is consistent with the previously inserted data, typically the size of the sets.
- That all the inserted data is non-negative.
- That the material requests respect the imposed capacities.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

9.3 Output

The output will be provided in two formats:

- **Written form output**, that can be data file or on screen output. Those express the optimal solution obtained in each of the scenarios proposed. This means the value of the objective function and of all the variables. These values can thus be used to compute KPIs.
- **Graphical output**, that can be provided, depending on the problem, into two forms:
    - The one proposed by the solver,
    - Output provided with the use of mapping programs.

In the following we describe the output for the detected problems.

9.3.1 Output for Facility Location Models

9.3.1.1 *Basic Model and other models*

The Output for *Basic Model*, *Multi material Model*, *Multi period Model*, *Multi material multi period Model* are very similar, thus we will explain it just once.

The **Graphical output** provided by the solver reports the set of vertices located respecting the given coordinates, each of them with its number label depicted by different color:

- black for CCCs,
- light blue for suppliers,
- magenta for construction sites.

The solution is depicted with green arcs among the vertices and with a red label reporting the amount of flow on each arc. An example of the graphical output for the *Basic Model* is given in Figure 36.

The **Written output** reports the detailed solution of the optimized model:

- the objective function value,
- the opened CCCs,
- the material flows.

The material flows are reported with respect of origin, destination, and used CCCs in the *Basic Model*. In case of *Multi Material* and / or *Multi Period*, also the material and the period identifiers are reported. An example of the written output for the *Basic Model* is given in Figure 37.

The FICO Xpress solver also reports detailed information on the model and on the solving algorithm, such as number of variables, constraints, non-zeros, before and after the pre-solving phase. Information on used algorithms for the linear programming relaxation is given, such as the type and the number of

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iterations, and iterations. Moreover, insight on the branch-and-bound algorithm are provided, such as the depth of the branching tree, the best lower bound value, the optimal value (or the best upper bound value), the percentage gap between them, and the solving time. See e.g. Figure 38.

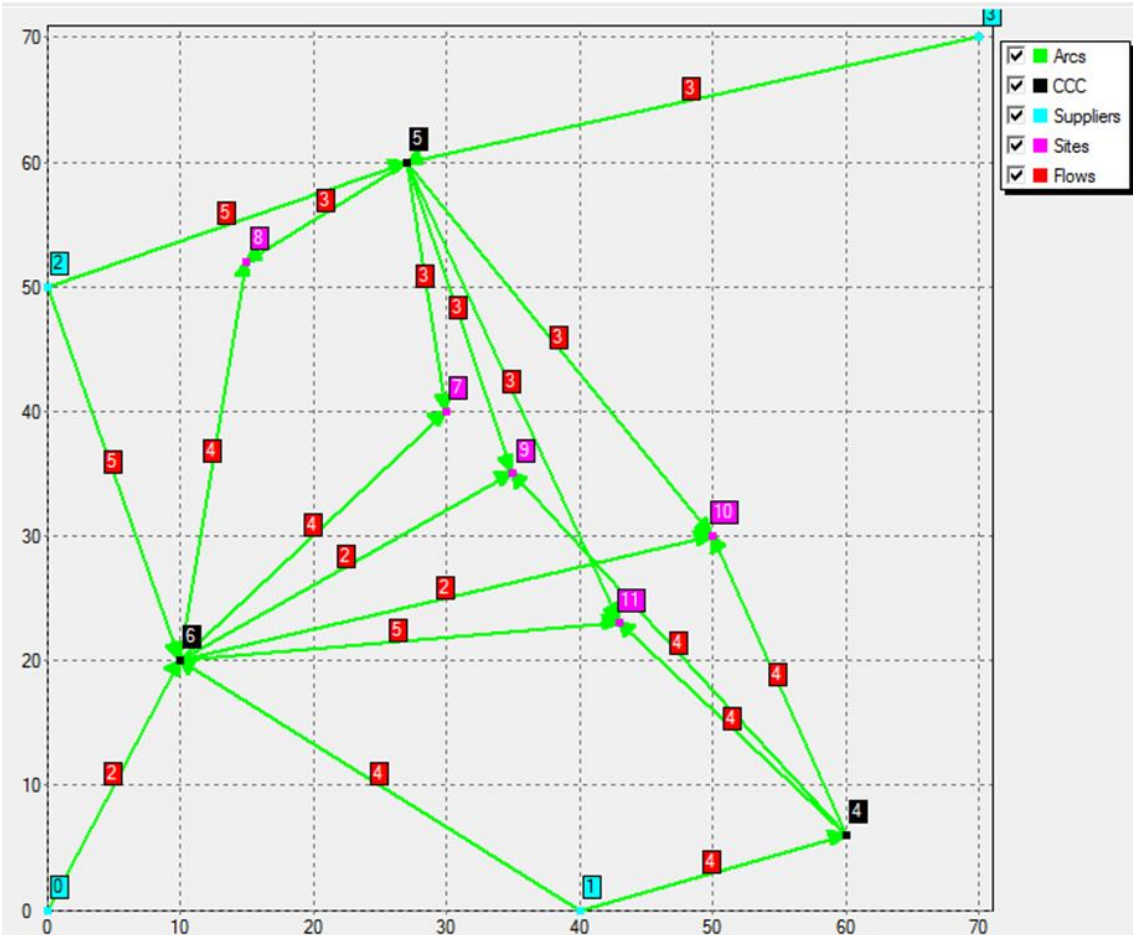

Figure 36 Example of graphical output for the FL Basic Model

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```
MODEL RESULTS
   Objective Value = 4189.38
   Open CCC number 4
   Open CCC number 5
   Open CCC number 6
 Flows
   g[0,7,6]= 2
   g[0,8,6]= 2
   g[0,9,6]= 2
   g[0,10,6]= 2
   g[0,11,6]= 2
   g[1,7,6]= 4
   g[1,8,6]= 4
   g[1,9,4]= 4
   g[1,10,4]= 4
   g[1,11,4]= 4
   g[2,7,5]= 5
   g[2,8,5]= 5
   g[2,9,5]= 5
   g[2,10,5]= 5
   g[2,11,6]= 5
   g[3,7,5]= 3
   g[3,8,5]= 3
   g[3,9,5]= 3
   g[3,10,5]= 3
   g[3,11,5]= 3
End running model
```

Figure 37 Example of the FL Basic Model written output.

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Matrix:		Presolved:	
Rows(constraints):	24	Rows(constraints):	23
Columns(variables):	63	Columns(variables):	63
Nonzero elements:	126	Nonzero elements:	123
Global entities:	3	Global entities:	3
Sets:	0	Sets:	0
Set members:	0	Set members:	0

Overall status: **Finished global search.**

LP relaxation:		Global search:	
Algorithm:	**Simplex dual**	Current node:	1
Simplex iterations:	23	Depth:	1
Objective:	4169.38	Active nodes:	0
Status:	Unfinished	Best bound:	4189.38
Time:	0.0s	Best solution:	4189.38
		Gap:	0%
		Status:	Solution is optimal.
		Time:	0.0s

Time overheads:

Progress graphs:	0.0s
Writing output:	0.0s
Pausing:	0.0s
Updating status:	0.0s

Figure 38 Example of details on the algorithms results for the LF Basic Model

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9.3.1.2 *Basic Reverse Model and other Reverse Models*

The *Basic reverse Model*, the *Reverse Multi Material Model*, the *Reverse Multi Period Model*, and the *Reverse Multi Period Multi Material Model* share very similar outputs, thus we will explain just one of them.

The **Graphical output** provided by the solver reports the set of vertices located respecting the given coordinates, each of them with its number label depicted by using with different color:

- black for CCCs,
- light blue for suppliers,
- and magenta for construction sites.

The flows of the solution:

- The supply flows solution is depicted with green arcs among the vertices and with a red label reporting the amount of flow on each arc.
- The reverse flow solution is depicted with yellow arcs among the vertices and with a blue label reporting the amount of flow on each arc.

An example of the graphical output for the *Basic Reverse Model* is given in Figure 39.

The **Written output** reports the detailed solution of the optimized model:

- the objective function value,
- the opened CCCs,
- the material flows.

The material flows, both supply and reverse flows, are reported with respect of origin, destination, and used CCC in the *Basic Reverse Model*. In case of *Multi Material* and / or *Multi Period*, also the material and the period identifiers are reported. An example of the written output for the *Basic Reverse Model* is given in Figure 37.

The FICO Xpress solver also reports detailed information on the model and on the algorithm, that is exactly the same as for all the models, thus we will not describe it from now on and refer the reader to the previous subsection.

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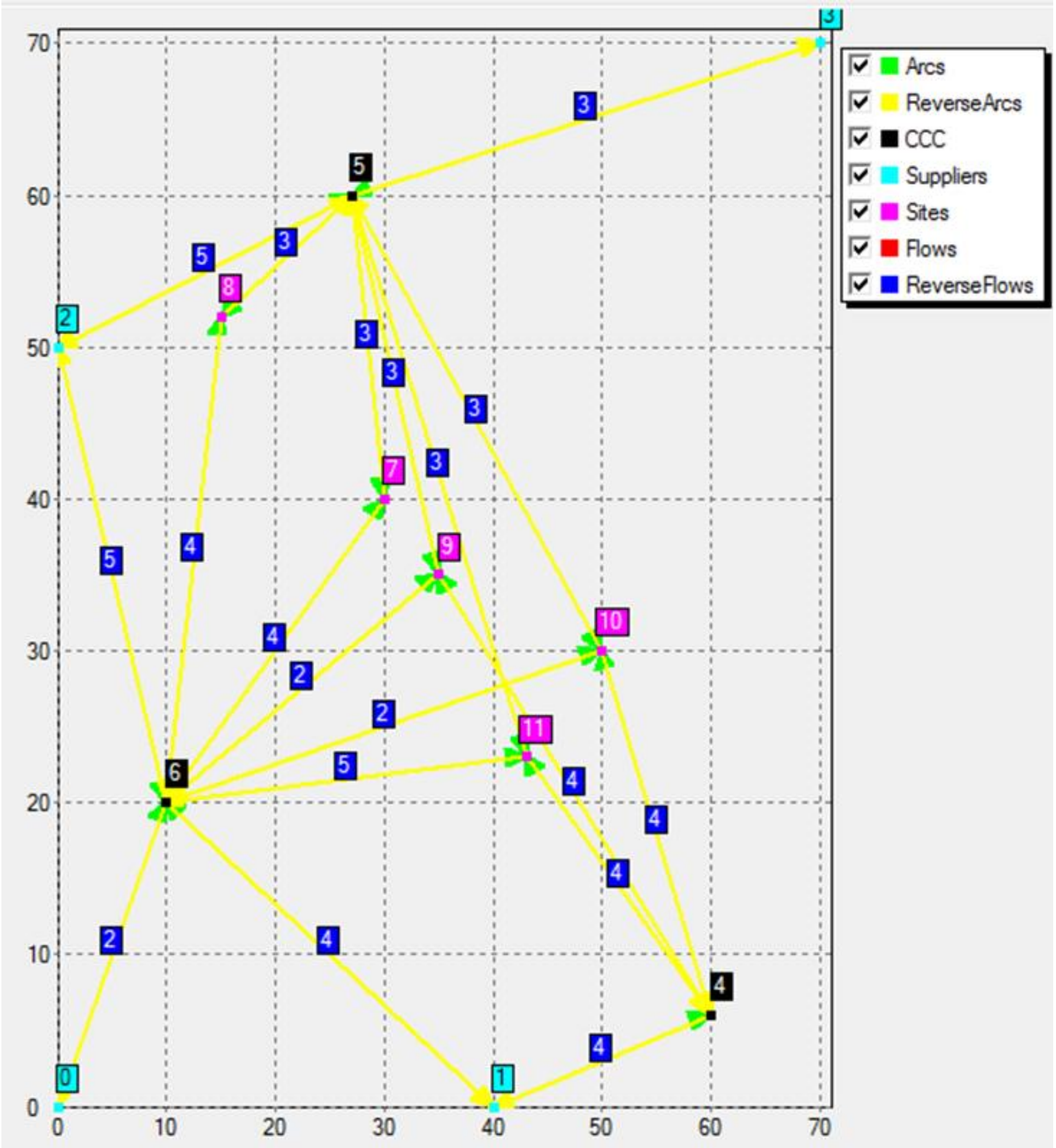

Figure 39 Example of graphical output for the FL Basic Reverse Model

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```
MODEL RESULTS
   Objective Function= 8184.48
   Open CCC = 4
   Open CCC = 5
   Open CCC = 6
  Supply flows
   g[0,7,6]= 2
   g[0,8,6]= 2
   g[0,9,6]= 2
   g[0,10,6]= 2
   g[0,11,6]= 2
   g[1,7,6]= 4
   g[1,8,6]= 4
   g[1,9,4]= 4
   g[1,10,4]= 4
   g[1,11,4]= 4
   g[2,7,5]= 5
   g[2,8,5]= 5
   g[2,9,5]= 5
   g[2,10,5]= 5
   g[2,11,6]= 5
   g[3,7,5]= 3
   g[3,8,5]= 3
   g[3,9,5]= 3
   g[3,10,5]= 3
   g[3,11,5]= 3
  Reverse flows
   f[7,0,6]= 2
   f[7,1,6]= 4
   f[7,2,5]= 5
   f[7,3,5]= 3
   f[8,0,6]= 4
   f[8,2,5]= 5
   f[8,3,5]= 3
```

Figure 40 Example of graphical output for the FL Basic Reverse Model

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9.3.1.3 *Basic Reverse and Direct Model*

The *Basic Reverse and Direct Model* also provides graphical and written outputs, and the information on the algorithm.

The **Graphical output** provided by the solver reports the set of vertices located respecting the given coordinates, each of them with its number label depicted by using different colours:

- black for CCCs,
- light blue for suppliers,
- and magenta for construction sites.

The flows of the solution:

- The supply flows solution is depicted with green arcs among the vertices and with a red label reporting the amount of flow on each arc (this is applied to both the direct and non-direct flows).
- The reverse flow solution is depicted with yellow arcs among the vertices and with a blue label reporting the amount of flow on each arc (this is applied to both the direct and non-direct reverse flows).

An example of the graphical output for the *Basic Reverse and direct Model* is given in Figure 39.

The **Written output** reports the detailed solution of the optimized model:

- the objective function value,
- the opened CCCs,
- the material flows.

The material flows, both supply and reverse flows, are reported with respect of origin, destination, and used CCC in the Basic Reverse Model. Clearly, the direct and direct reverse flows just report the origin and destination. An example of the written output for the *Basic Reverse and direct Model* is given in Figure 42.

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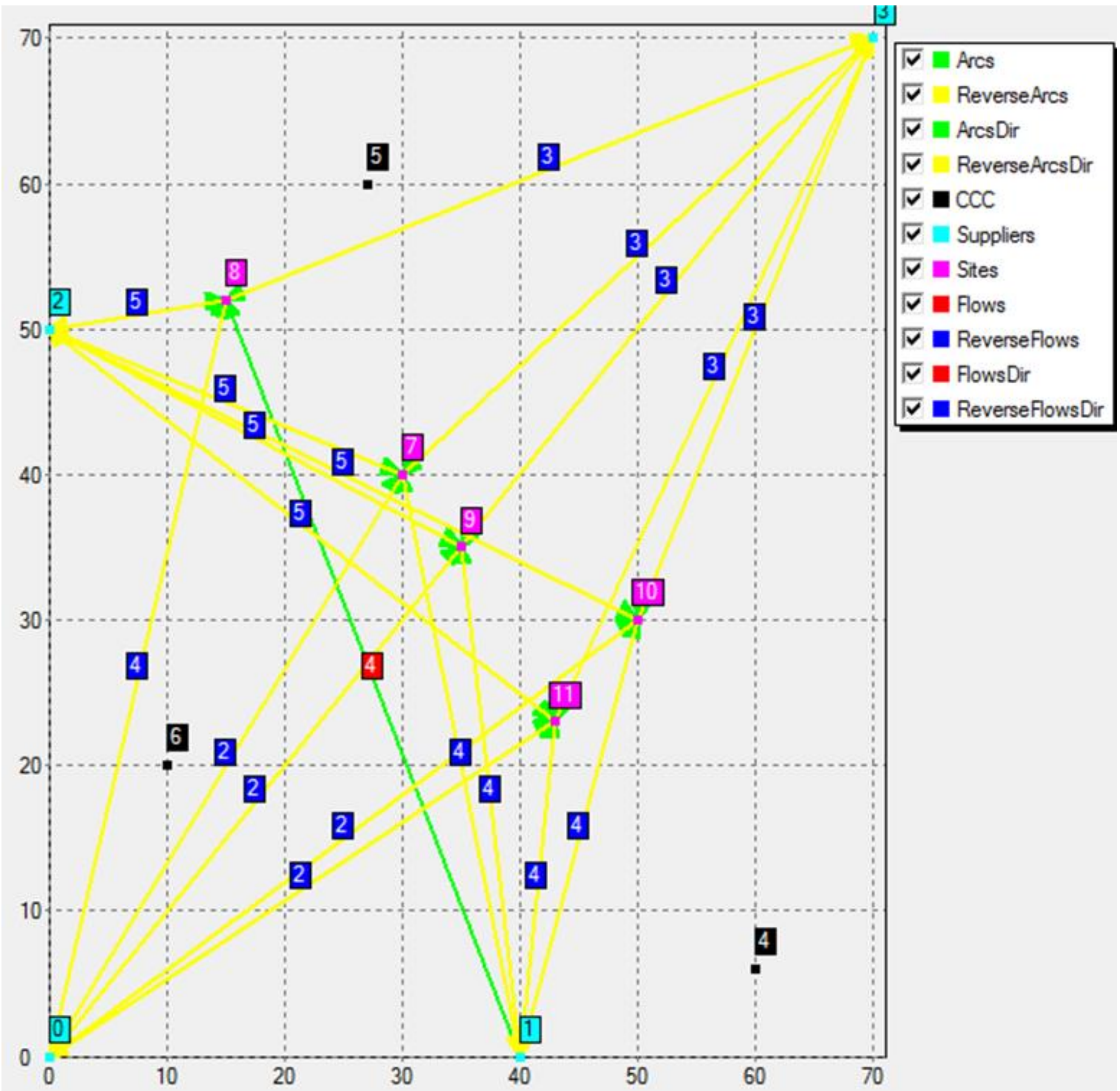

Figure 41 Example of graphical output for the FL Basic Reverse and direct Model

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```
MODEL RESULTS
   z= 5258.6
 Flows
 Reverse Flows
 Direct Flows
   x[0,7]= 2
   x[0,8]= 2
   x[0,9]= 2
   x[0,10]= 2
   x[0,11]= 2
   x[1,7]= 4
   x[1,8]= 4
   x[1,9]= 4
   x[1,10]= 4
   x[1,11]= 4
   x[2,7]= 5
   x[2,8]= 5
   x[2,9]= 5
   x[2,10]= 5
   x[2,11]= 5
   x[3,7]= 3
   x[3,8]= 3
   x[3,9]= 3
   x[3,10]= 3
   x[3,11]= 3
 Reverse Direct Flows
   w[7,0]= 2
   w[7,1]= 4
   w[7,2]= 5
   w[7,3]= 3
   w[8,0]= 4
   w[8,2]= 5
   w[8,3]= 3
   w[9,0]= 2
   w[9,1]= 4
   w[9,2]= 5
   w[9,3]= 3
```

Figure 42 Example of graphical output for the FL Basic Reverse and direct Model

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

9.3.1.4 *Stochastic Basic Model*

The output for the *Stochastic Basic Model* is represented by both graphical and written output.

The **graphical output** makes use of the Google Maps API. In particular, one graphical output is created for each scenario. The vertices are located on the map:

- the suppliers / dumpsites are represented by a red marker,
- the construction sites are represented by a yellow marker,
- and the CCCs are represented by a green marker, if opened, or by a small white square, if not activated.

The material flows of the depicted scenario are represented by the arcs (arrows) whose dimensions depend on the amount of material to be transported on it. In Figure 43 can be found an example for one scenario, where one can see four construction sites, four suppliers, an opened CCC, and two not activated CCCs.

In Figure 43 can be found an example for one scenario, where one can see four construction sites, four suppliers, one opened CCC, and two not activated CCCs.

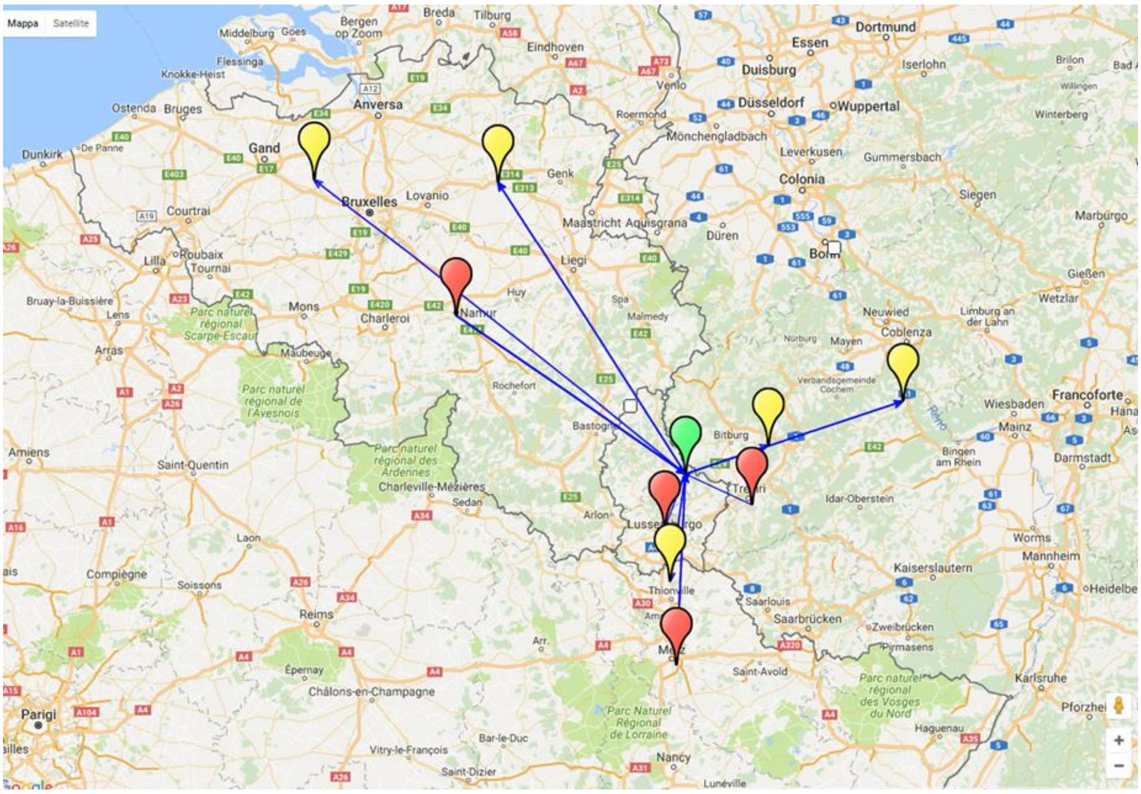

Figure 43 Example of graphical output for the solution of one scenario of the Stochastic basic Model

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The **written output** can be found on a text file where the following information is depicted:

- The CCCs to be opened
- The cost of opening CCCs
- For each scenario: The transport from each origin to each destination via which CCC.
- The cost of transportation
- The objective function value

An example can be found in Figure 44.

Moreover, we use the Cplex dedicated functions to print the problem model and the solution of all the variables into two separate files.

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```
SOLUTION

open ccc 2
Cost of opening CCCs 10
Sceanrio 0
Transport from supplier 0 to site 0 passing by 2
Transport from supplier 0 to site 1 passing by 2
Transport from supplier 0 to site 2 passing by 2
Transport from supplier 0 to site 3 passing by 2
Transport from supplier 0 to site 4 passing by 2
Transport from supplier 1 to site 0 passing by 2
Transport from supplier 1 to site 1 passing by 2
Transport from supplier 1 to site 2 passing by 2
Transport from supplier 1 to site 3 passing by 2
Transport from supplier 1 to site 4 passing by 2
Transport from supplier 2 to site 0 passing by 2
Transport from supplier 2 to site 1 passing by 2
Transport from supplier 2 to site 2 passing by 2
Transport from supplier 2 to site 3 passing by 2
Transport from supplier 2 to site 4 passing by 2
Transport from supplier 3 to site 0 passing by 2
Transport from supplier 3 to site 1 passing by 2
Transport from supplier 3 to site 2 passing by 2
Transport from supplier 3 to site 3 passing by 2
Transport from supplier 3 to site 4 passing by 2
Sceanrio 1
Transport from supplier 0 to site 0 passing by 2
Transport from supplier 0 to site 1 passing by 2
Transport from supplier 0 to site 2 passing by 2
Transport from supplier 0 to site 3 passing by 2
Transport from supplier 0 to site 4 passing by 2
Transport from supplier 1 to site 0 passing by 2
Transport from supplier 1 to site 1 passing by 2
Transport from supplier 1 to site 2 passing by 2
Transport from supplier 1 to site 3 passing by 2
Transport from supplier 1 to site 4 passing by 2
Transport from supplier 2 to site 0 passing by 2
Transport from supplier 2 to site 1 passing by 2
Transport from supplier 2 to site 2 passing by 2
Transport from supplier 2 to site 3 passing by 2
Transport from supplier 2 to site 4 passing by 2
Transport from supplier 3 to site 0 passing by 2
Transport from supplier 3 to site 1 passing by 2
Transport from supplier 3 to site 2 passing by 2
Transport from supplier 3 to site 3 passing by 2
Transport from supplier 3 to site 4 passing by 2
Sceanrio 2
Transport from supplier 0 to site 0 passing by 2
Transport from supplier 0 to site 1 passing by 2
Transport from supplier 0 to site 2 passing by 2
Transport from supplier 0 to site 3 passing by 2
Transport from supplier 0 to site 4 passing by 2
Transport from supplier 1 to site 0 passing by 2
Transport from supplier 1 to site 1 passing by 2
Transport from supplier 1 to site 2 passing by 2
Transport from supplier 1 to site 3 passing by 2
Transport from supplier 1 to site 4 passing by 2
Transport from supplier 2 to site 0 passing by 2
Transport from supplier 2 to site 1 passing by 2
Transport from supplier 2 to site 2 passing by 2
Transport from supplier 2 to site 3 passing by 2
Transport from supplier 2 to site 4 passing by 2
Transport from supplier 3 to site 0 passing by 2
Transport from supplier 3 to site 1 passing by 2
Transport from supplier 3 to site 2 passing by 2
Transport from supplier 3 to site 3 passing by 2
Transport from supplier 3 to site 4 passing by 2
Cost of transportation 89.0527
objective function 99.0527
```

Figure 44 Example of written output for the solution of one scenario of the Stochastic basic Model

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9.3.1.5 *Stochastic Multi Period Multi Material Reverse Direct with different set of materials Model*

The output for the *Stochastic Multi Period Multi Material Reverse Direct with different set of materials Model* is represented by both graphical and written output.

The **graphical output** makes use of the Google Maps API. In particular, one graphical output is created for each scenario and each period. The vertices are located on the map: the suppliers /dumpsites are represented by a red marker, the construction sites are represented by a yellow marker, and the CCCs are represented by a green marker, if opened, or by a small white square, if not activated. The material flows of the depicted scenario are represented by the arcs (arrows) whose dimensions depend on the amount of material to be transported on it. More precisely, the represented components are:

- The vertices (each vertex shows its number when the pointer stops on it):
  - The suppliers /dumpsites (in red)
  - The construction sites (in yellow)
  - The CCCs: in green if opened, or as a small white square if not opened.
- The material flows: each material flow is represented with respect to its size.
  - Materials that must be shipped via CCC (blue);
  - Materials that can be shipped directly from suppliers to construction sites but that makes use of a CCC (red);
  - Materials that is directly shipped from suppliers to construction sites (green);
  - Reverse Logistics Materials that must be shipped via CCC (yellow);
  - Reverse Logistics Materials that can be shipped directly from construction site to dumpsite, but that makes use of a CCC (light blue);
  - Reverse Logistics Material that is directly shipped from construction sites to dumpsites (fuchsia).

In Figure 45 can be found an example for one scenario, where one can see four construction sites, four suppliers, one opened CCC, and two not activated CCCs.

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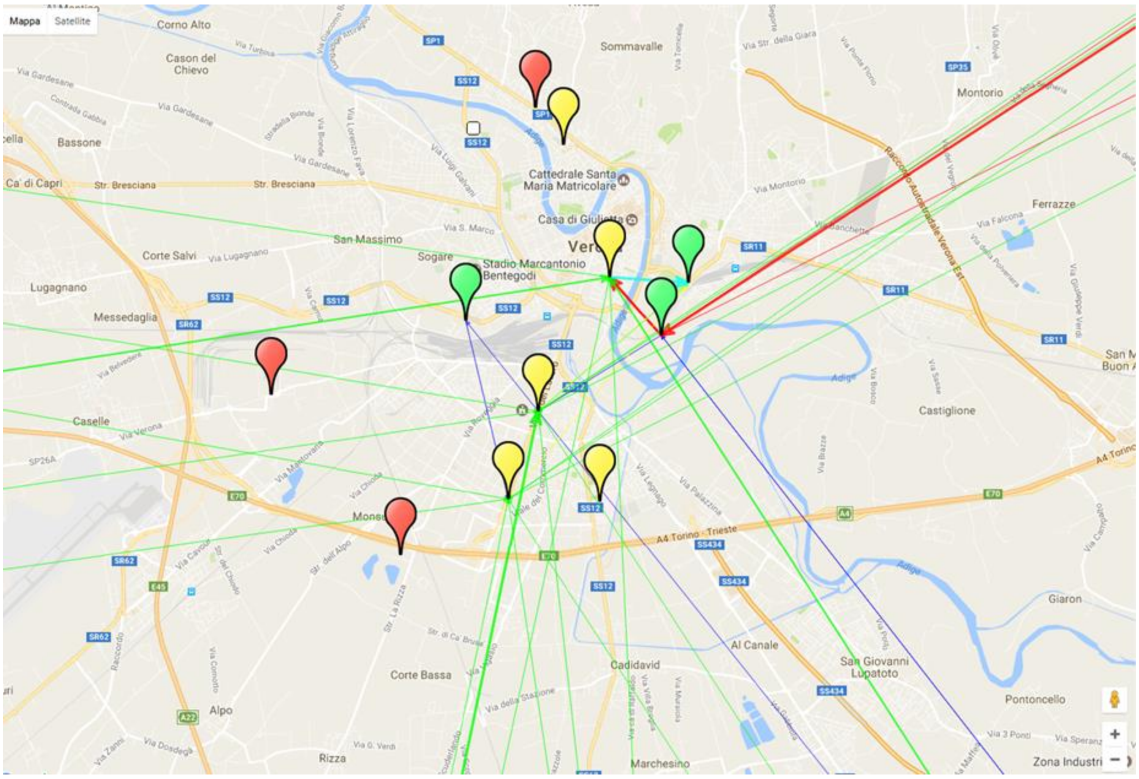

Figure 45 Example of graphical output for the solution of one scenario of the Stochastic Multi Period Multi Material Reverse Direct with different set of materials Model

The **written output** is a text file that reports:

- The objective value,
- The opened CCC
- The cost of opening CCCs
- The material flows divided by scenario, period, origin, destination and material type
- The cost of transportation

A highlight of an example can be found in Figure 46

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```
***********Solution!***********

Objective value 2.70786e+008
Open CCC 0
Open CCC 1
Open CCC 3
Cost of opening CCCs 300000
Scenario 0
Period 0
Transport from site 2 to supplier 0 passing by 0 of reverse material via CCC 0 : 1033
Transport from site 3 to supplier 0 passing by 0 of reverse material via CCC 0 : 1144
Transport from site 3 to supplier 0 passing by 0 of reverse material via CCC (that could be supplied directly) 1 : 6859
Transport from site 4 to supplier 0 passing by 0 of reverse material via CCC 0 : 8578
Period 1
Transport from site 2 to supplier 0 passing by 0 of reverse material via CCC 0 : 189
Transport from site 3 to supplier 0 passing by 0 of reverse material via CCC 0 : 1717
Transport from site 4 to supplier 0 passing by 0 of reverse material via CCC 0 : 1047
Transport directly from supplier 1 to site 2 of supply material 0 : 9340
Transport from site 3 to supplier 1 passing by 3 of reverse material via CCC (that could be supplied directly) 1 : 1528
Transport directly from supplier 1 to site 3 of supply material 0 : 7781
Transport from site 4 to supplier 1 passing by 3 of reverse material via CCC (that could be supplied directly) 1 : 4982
Transport directly from supplier 1 to site 4 of supply material 0 : 53064
Transport directly from supplier 2 to site 2 of supply material 0 : 356
Transport directly from supplier 2 to site 2 of supply material 1 : 1738
Transport directly from supplier 2 to site 3 of supply material 0 : 2543
Transport directly from supplier 2 to site 3 of supply material 1 : 9874
Transport directly from supplier 2 to site 4 of supply material 0 : 9230
Transport directly from supplier 2 to site 4 of supply material 1 : 3219
Transport directly from supplier 8 to site 2 of supply material 6 : 162
Transport directly from supplier 8 to site 3 of supply material 6 : 1113
Transport from supplier 8 to site 4 passing by 1 of supply material via CCC (that could be supplied directly) 6 : 3596
Transport directly from supplier 11 to site 2 of supply material 4 : 1915
Transport directly from supplier 11 to site 3 of supply material 4 : 1078
Transport directly from supplier 11 to site 4 of supply material 4 : 7384
Transport directly from supplier 12 to site 2 of supply material 5 : 5202
Transport directly from supplier 12 to site 3 of supply material 5 : 3001
Transport directly from supplier 12 to site 4 of supply material 5 : 23140
Transport directly from supplier 14 to site 2 of supply material 4 : 1293
Transport directly from supplier 14 to site 3 of supply material 4 : 7821
Transport from supplier 14 to site 4 passing by 1 of supply material via CCC (that could be supplied directly) 4 : 3957
Transport directly from supplier 38 to site 2 of supply material 4 : 2381
Transport directly from supplier 38 to site 3 of supply material 4 : 2231
Transport directly from supplier 38 to site 4 of supply material 4 : 10643
Period 2
Transport from site 2 to supplier 0 passing by 0 of reverse material via CCC 0 : 470
Transport from site 3 to supplier 0 passing by 0 of reverse material via CCC 0 : 5611
Transport from site 4 to supplier 0 passing by 0 of reverse material via CCC 0 : 4259
Transport from site 2 to supplier 1 passing by 3 of reverse material via CCC 0 : 916
Transport from site 3 to supplier 1 passing by 3 of reverse material via CCC 0 : 7491
Transport from site 3 to supplier 1 passing by 3 of reverse material via CCC (that could be supplied directly) 1 : 1023
Transport from site 4 to supplier 1 passing by 3 of reverse material via CCC 0 : 4727
Transport from site 4 to supplier 1 passing by 3 of reverse material via CCC (that could be supplied directly) 1 : 6513
Transport directly from supplier 3 to site 2 of supply material 0 : 713
Transport directly from supplier 3 to site 2 of supply material 3 : 470
Transport directly from supplier 3 to site 3 of supply material 0 : 8209
Transport directly from supplier 3 to site 3 of supply material 3 : 332
Transport directly from supplier 3 to site 4 of supply material 0 : 4465
Transport directly from supplier 3 to site 4 of supply material 3 : 2343
Transport directly from supplier 5 to site 2 of supply material 2 : 1181
Transport directly from supplier 5 to site 3 of supply material 2 : 6222
Transport from supplier 5 to site 4 passing by 1 of supply material via CCC (that could be supplied directly) 2 : 2003
Transport directly from supplier 19 to site 2 of supply material 16 : 380
Transport directly from supplier 19 to site 3 of supply material 16 : 2079
Transport directly from supplier 19 to site 4 of supply material 16 : 9229
Transport directly from supplier 23 to site 2 of supply material 13 : 211
Transport directly from supplier 23 to site 3 of supply material 13 : 144
Transport directly from supplier 23 to site 4 of supply material 13 : 544
Transport directly from supplier 34 to site 2 of supply material 10 : 374
Transport directly from supplier 34 to site 3 of supply material 10 : 1998
Transport from supplier 34 to site 4 passing by 1 of supply material via CCC (that could be supplied directly) 10 : 1383
```

Figure 46 Highlight of a written output example for the Stochastic Multi Period Multi Material Reverse Direct with different set of materials Model

Moreover, we use the Cplex dedicated functions to print the problem model and the solution of all the variables into two separate files.

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9.3.1.6 *Inventory Models*

The *Multi period with Inventory and Reverse Logistics Model*, the *Multi Period with Inventory and Reverse Logistics Model*, and the *Multi Period Multi Material with Inventory, Reverse Logistics and Direct Shipping Model* have very similar graphical outputs with respect to the *Basic Models* and *Reverse Models*. On the other hand, the written output represents the new variables: the supply and reverse flows in both the first and second echelons, and the inventory variables.

```
MODEL RESULTS
   z= 20537.3
   Open CCC = 4
   Open CCC = 5
   Open CCC = 6
   1st echelon Flows
   g_over[0,7,6,0]= 10
   g_over[0,7,6,1]= 1
   g_over[0,7,6,2]= 5
   g_over[0,8,6,0]= 10
   g_over[0,8,6,1]= 1
   g_over[0,8,6,2]= 5
   g_over[0,9,6,0]= 10
   g_over[0,9,6,1]= 1
   g_over[0,9,6,2]= 5
   g_over[0,10,6,0]= 10
   g_over[0,10,6,1]= 1
   g_over[0,10,6,2]= 5
   g_over[0,11,6,0]= 10
   g_over[0,11,6,1]= 1
   g_over[0,11,6,2]= 5
   g_over[1,7,6,0]= 4
   g_over[1,7,6,1]= 2
   g_over[1,7,6,2]= 6
   g_over[1,8,6,0]= 4
   g_over[1,8,6,1]= 2
   g_over[1,8,6,2]= 6
   g_over[1,9,4,0]= 4
   g_over[1,9,4,1]= 2
   g_over[1,9,4,2]= 6
   g_over[1,10,4,0]= 4
   g_over[1,10,4,1]= 2
   g_over[1,10,4,2]= 6
   g_over[1,11,4,0]= 4
   g_over[1,11,4,1]= 2
   g_over[1,11,4,2]= 6
```

Figure 47 Example of graphical output for the FL Basic Reverse Model

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

9.3.1.7 *Stochastic Multi Period Multi Material with Inventory, Reverse Logistics and Direct Shipping Model*

The *Stochastic Multi Period Multi Material with Inventory, Reverse Logistics and Direct Shipping Model* is the most complex of the Facility Location Models. We solve this problem by means of the Cplex solver with an algorithm coded in C++. The output is represented by means of a .html file created for each period and scenario. The .html output can be opened with a normal browser. It makes use of the Google APIs and shows a new map with the solution representation. The represented components are:

- The vertices (each vertex shows its number when the pointer stops on it):
  - The suppliers /dumpsites (in red)
  - The construction sites (in yellow)
  - The CCCs: in green if opened, or as a small white square if not opened.
- The material flows: each material flow is represented with respect to its size.
  - Materials that must be shipped via CCC (blue);
  - Materials that can be shipped directly from suppliers to construction sites but that makes use of a CCC (red);
  - Materials that is directly shipped from suppliers to construction sites (green);
  - Reverse Logistics Materials that must be shipped via CCC (yellow);
  - Reverse Logistics Materials that can be shipped directly from construction site to dumpsite, but that makes use of a CCC (light blue);
  - Reverse Logistics Material that is directly shipped from construction sites to dumpsites (fuchsia);
- Inventory: in correspondence to each opened CCC two columns are reported representing two types of materials, each of the columns representing the inventory size, we have:
  - The inventory of material to be supplied (green).
  - The inventory of material to be dumped (reverse logistics material) (red).

An example of solution is provided in Figure 48.

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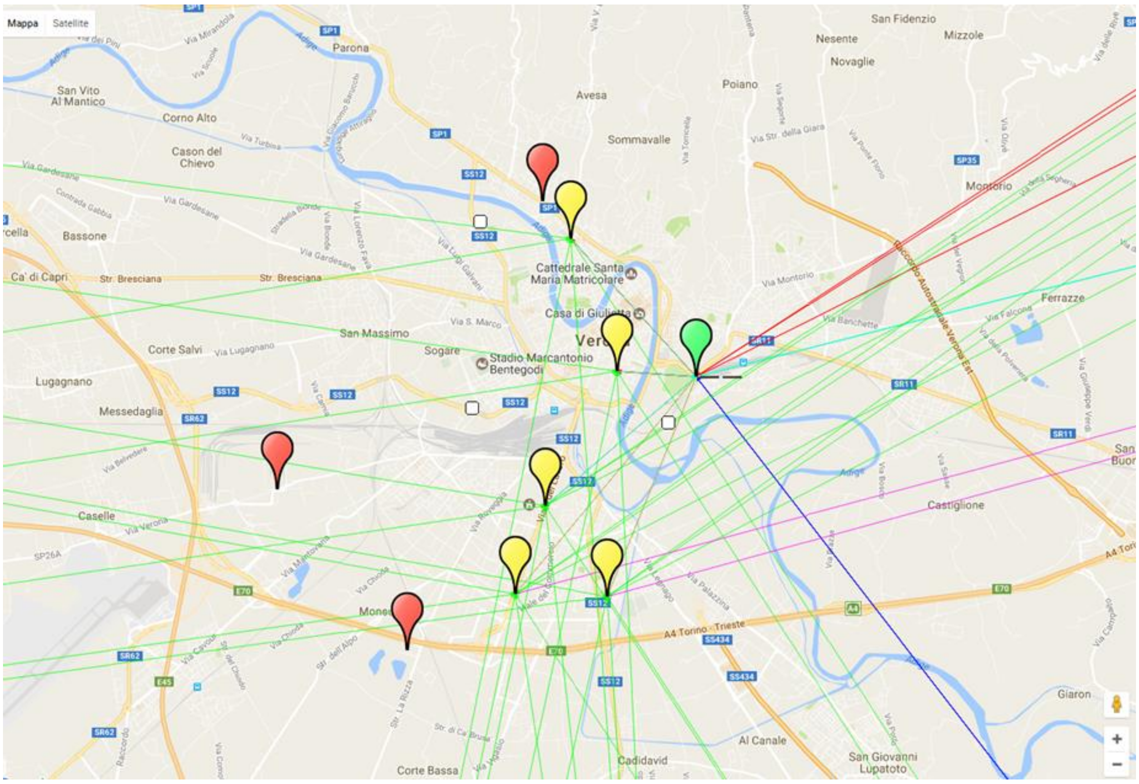

Figure 48 Output of the Stochastic Multi period multi material with inventory, reverse logistics and direct shipping Model (one period and one scenario)

The **written output** is reported into a text file providing the following information:

- objective value
- The opened CCCs
- The cost of opening the CCCs
- The flows for each scenario
- The cost of CCC transportation
- The cost of direct transportation
- The cost of inventory

An highlight can be found in Figure 49, where one can see that the non-negative variables are reported with the specification of the origin, destination, used CCC (if non-direct shipping), period, material, and scenario.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 633338.

```
***********Solution!***********

objective value 6.63676e+008
open CCC 3
Cost of opening CCCs 1e+008

Sceanrio 0
flow_mat_ccc_rev_over(j=0, i=0, h=3, t=0, m=0, s=0) = 11700
flow_mat_ccc_rev_under(j=0, i=0, h=3, t=0, m=0, s=0) = 11700
w_direct_rev(i=0, j=0, t=0, m=1, s=0) = 7500
flow_mat_ccc_rev_over(j=0, i=0, h=3, t=1, m=0, s=0) = 3000
flow_mat_ccc_rev_under(j=0, i=0, h=3, t=1, m=0, s=0) = 3000
flow_mat_ccc_rev_over(j=1, i=0, h=3, t=0, m=0, s=0) = 474
flow_mat_ccc_rev_under(j=1, i=0, h=3, t=0, m=0, s=0) = 474
w_direct_rev(i=0, j=1, t=0, m=1, s=0) = 430
flow_mat_ccc_rev_over(j=1, i=0, h=3, t=1, m=0, s=0) = 156
flow_mat_ccc_rev_under(j=1, i=0, h=3, t=1, m=0, s=0) = 156
flow_mat_ccc_rev_over(j=2, i=0, h=3, t=0, m=0, s=0) = 1033
flow_mat_ccc_rev_under(j=2, i=0, h=3, t=0, m=0, s=0) = 1033
w_direct_rev(i=0, j=2, t=0, m=1, s=0) = 717
flow_mat_ccc_rev_over(j=2, i=0, h=3, t=1, m=0, s=0) = 189
flow_mat_ccc_rev_under(j=2, i=0, h=3, t=1, m=0, s=0) = 189
flow_mat_ccc_rev_over(j=2, i=0, h=3, t=2, m=0, s=0) = 470
flow_mat_ccc_rev_under(j=2, i=0, h=3, t=2, m=0, s=0) = 470
w_direct_rev(i=0, j=2, t=3, m=0, s=0) = 218
flow_mat_ccc_rev_over(j=3, i=0, h=3, t=0, m=0, s=0) = 1144
flow_mat_ccc_rev_under(j=3, i=0, h=3, t=0, m=0, s=0) = 1144
w_direct_rev(i=0, j=3, t=0, m=1, s=0) = 6859
flow_mat_ccc_rev_over(j=3, i=0, h=3, t=1, m=0, s=0) = 1717
flow_mat_ccc_rev_under(j=3, i=0, h=3, t=1, m=0, s=0) = 1717
flow_mat_ccc_rev_over(j=3, i=0, h=3, t=2, m=0, s=0) = 5611
flow_mat_ccc_rev_under(j=3, i=0, h=3, t=2, m=0, s=0) = 5611
w_direct_rev(i=0, j=3, t=3, m=0, s=0) = 125
flow_mat_ccc_rev_over(j=4, i=0, h=3, t=0, m=0, s=0) = 8578
flow_mat_ccc_rev_under(j=4, i=0, h=3, t=0, m=0, s=0) = 8578
w_direct_rev(i=0, j=4, t=0, m=1, s=0) = 4643
flow_mat_ccc_rev_over(j=4, i=0, h=3, t=1, m=0, s=0) = 1047
flow_mat_ccc_rev_under(j=4, i=0, h=3, t=1, m=0, s=0) = 1047
flow_mat_ccc_rev_over(j=4, i=0, h=3, t=2, m=0, s=0) = 4259
flow_mat_ccc_rev_under(j=4, i=0, h=3, t=2, m=0, s=0) = 4259
w_direct_rev(i=0, j=4, t=3, m=0, s=0) = 852
flow_mat_both_over(i=1, j=0, h=3, t=1, m=0, s=0) = 88640
flow_mat_both_under(i=1, j=0, h=3, t=1, m=0, s=0) = 88640
flow_mat_ccc_rev_over(j=0, i=1, h=3, t=1, m=0, s=0) = 12000
flow_mat_both_rev_over(j=0, i=1, h=3, t=1, m=1, s=0) = 21800
flow_mat_ccc_rev_under(j=0, i=1, h=3, t=1, m=0, s=0) = 12000
flow_mat_both_rev_under(j=0, i=1, h=3, t=1, m=1, s=0) = 21800
flow_mat_ccc_rev_over(j=0, i=1, h=3, t=2, m=0, s=0) = 20000
flow_mat_both_rev_over(j=0, i=1, h=3, t=2, m=1, s=0) = 22800
flow_mat_ccc_rev_under(j=0, i=1, h=3, t=2, m=0, s=0) = 20000
flow_mat_both_rev_under(j=0, i=1, h=3, t=2, m=1, s=0) = 22800
flow_mat_ccc_rev_over(j=0, i=1, h=3, t=3, m=0, s=0) = 15000
flow_mat_both_rev_over(j=0, i=1, h=3, t=3, m=0, s=0) = 200
flow_mat_both_rev_over(j=0, i=1, h=3, t=3, m=1, s=0) = 12000
flow_mat_ccc_rev_under(j=0, i=1, h=3, t=3, m=0, s=0) = 15000
flow_mat_both_rev_under(j=0, i=1, h=3, t=3, m=0, s=0) = 200
flow_mat_both_rev_under(j=0, i=1, h=3, t=3, m=1, s=0) = 12000
flow_mat_ccc_rev_over(j=0, i=1, h=3, t=5, m=0, s=0) = 19000
flow_mat_both_rev_over(j=0, i=1, h=3, t=5, m=1, s=0) = 19500
flow_mat_ccc_rev_under(j=0, i=1, h=3, t=5, m=0, s=0) = 19000
flow_mat_both_rev_under(j=0, i=1, h=3, t=5, m=1, s=0) = 19500
flow_mat_ccc_rev_over(j=0, i=1, h=3, t=6, m=0, s=0) = 11000
flow_mat_both_rev_over(j=0, i=1, h=3, t=6, m=1, s=0) = 8000
flow_mat_ccc_rev_under(j=0, i=1, h=3, t=6, m=0, s=0) = 11000
flow_mat_both_rev_under(j=0, i=1, h=3, t=6, m=1, s=0) = 8000
flow_mat_ccc_rev_over(j=1, i=1, h=3, t=1, m=0, s=0) = 552
flow_mat_ccc_rev_under(j=1, i=1, h=3, t=1, m=0, s=0) = 552
x_direct(i=1, j=1, t=1, m=0, s=0) = 379
w_direct_rev(i=1, j=1, t=1, m=1, s=0) = 107
flow_mat_ccc_rev_over(j=1, i=1, h=3, t=2, m=0, s=0) = 800
```

Figure 49 Highlight of the written output of Stochastic Multi Period Multi Material Reverse Direct with different set of materials Model

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9.3.2 Output for the Allocation Problems

The allocation problem **graphical output** is provided by the solver. Firstly the vertices are represented: the suppliers (light blue), the construction sites (magenta), and the CCCs (black). The allocation of one vertex to another is represented by the arcs (green). In Figure 50 one can see the allocation between CCCs and construction sites, while in Figure 51 one can see the allocation between the CCCs and the suppliers.

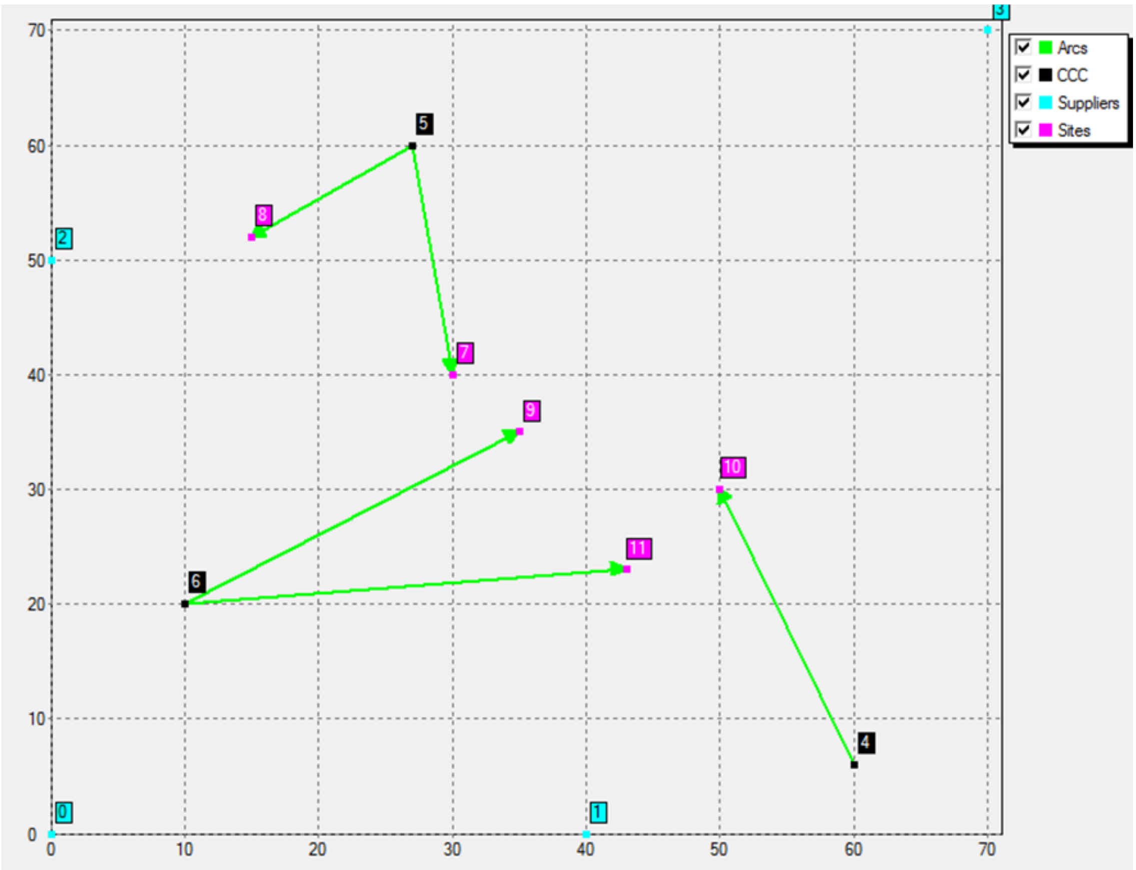

Figure 50 Allocation to construction sites graphical output

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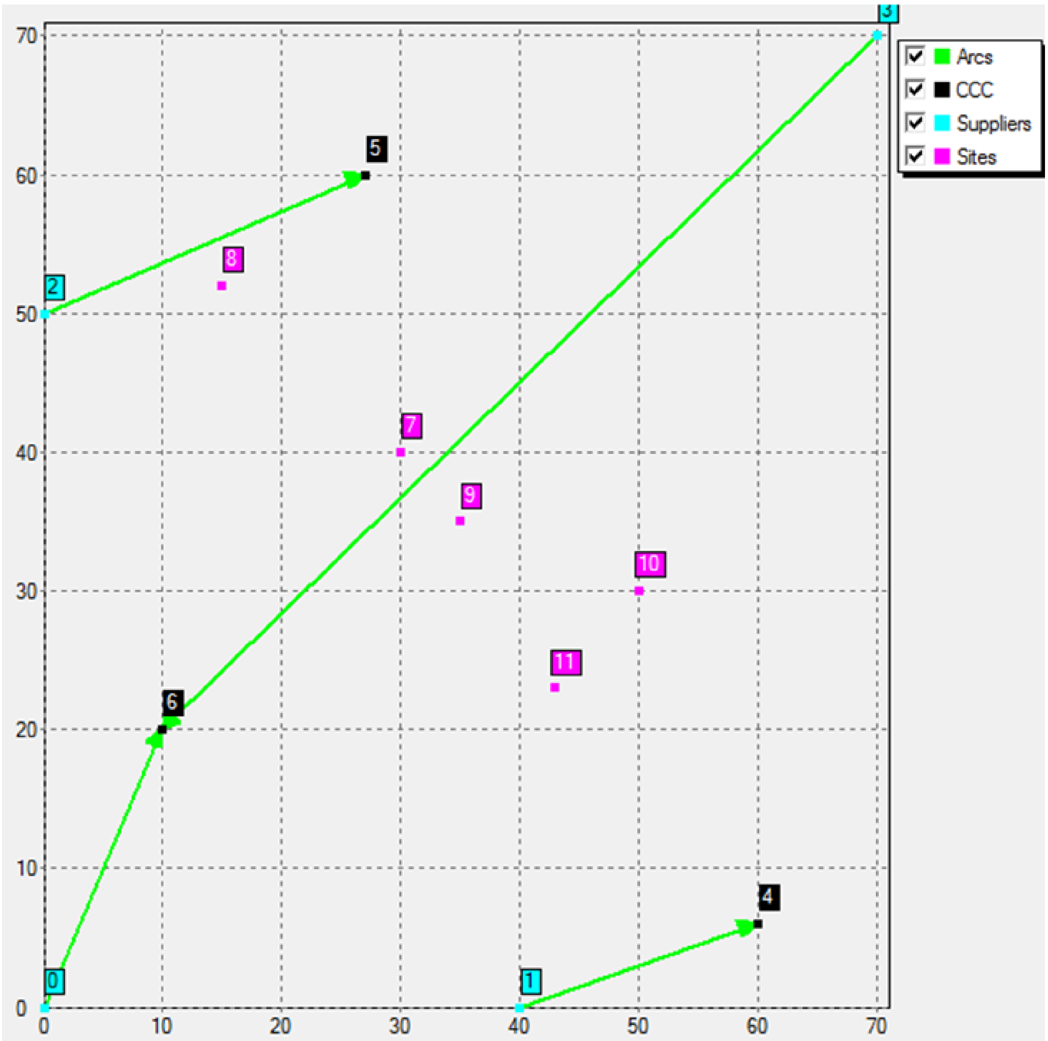

Figure 51 Allocation to suppliers graphical output

The **written output** reports the optimal value, the allocations and the material flows that follow the decided allocations. A highlight of an example is reported in Figure 52 and Figure 53.

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```
Model Results
        Optimal Value = 45087.2
Allocation
        Site 7 allocated to CCC 5
        Site 8 allocated to CCC 5
        Site 9 allocated to CCC 6
        Site 10 allocated to CCC 4
        Site 11 allocated to CCC 6
Flows
Period0
Via CCC4
Entering
Material ccc0
From supplier 0 to CCC 4 (final destination site 10) 2
From supplier 1 to CCC 4 (final destination site 10) 4
From supplier 2 to CCC 4 (final destination site 10) 5
From supplier 3 to CCC 4 (final destination site 10) 3
Material ccc1
From supplier 0 to CCC 4 (final destination site 10) 2
From supplier 1 to CCC 4 (final destination site 10) 4
From supplier 2 to CCC 4 (final destination site 10) 5
From supplier 3 to CCC 4 (final destination site 10) 3
Material both2
Material ccc rev3
From site 10 to CCC 4 (final destination dump 0) 2
From site 10 to CCC 4 (final destination dump 1) 2
From site 10 to CCC 4 (final destination dump 2) 2
From site 10 to CCC 4 (final destination dump 3) 2
Material ccc rev4
From site 10 to CCC 4 (final destination dump 0) 2
From site 10 to CCC 4 (final destination dump 1) 2
From site 10 to CCC 4 (final destination dump 2) 2
From site 10 to CCC 4 (final destination dump 3) 2
Material both5
Material both6
Exiting
Material ccc0
From CCC4 to site10 (initial origin supplier 0) 2
```

Figure 52 Highlight of written output for the Allocation to construction sites Model

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```
Model Results
        Optimal Value = 44243.8
Allocation
        Supplier 0 allocated to CCC 6
        Supplier 1 allocated to CCC 4
        Supplier 2 allocated to CCC 5
        Supplier 3 allocated to CCC 6
Flows
Period0
Via CCC4
Entering
Material ccc0
From supplier 1 to CCC 4 (final destination site 7) 4
From supplier 1 to CCC 4 (final destination site 8) 4
From supplier 1 to CCC 4 (final destination site 9) 4
From supplier 1 to CCC 4 (final destination site 10) 4
From supplier 1 to CCC 4 (final destination site 11) 4
Material ccc1
From supplier 1 to CCC 4 (final destination site 7) 4
From supplier 1 to CCC 4 (final destination site 8) 4
From supplier 1 to CCC 4 (final destination site 9) 4
From supplier 1 to CCC 4 (final destination site 10) 4
From supplier 1 to CCC 4 (final destination site 11) 4
Material both2
Material ccc rev3
From site 7 to CCC 4 (final destination dump 1) 2
From site 8 to CCC 4 (final destination dump 1) 2
From site 9 to CCC 4 (final destination dump 1) 2
From site 10 to CCC 4 (final destination dump 1) 2
From site 11 to CCC 4 (final destination dump 1) 2
Material ccc rev4
From site 7 to CCC 4 (final destination dump 1) 2
From site 8 to CCC 4 (final destination dump 1) 2
From site 9 to CCC 4 (final destination dump 1) 2
From site 10 to CCC 4 (final destination dump 1) 2
From site 11 to CCC 4 (final destination dump 1) 2
Material both5
Material both6
```

Figure 53 Highlight of written output for the Allocation to suppliers Model

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9.3.3 Output CVRP

As for the other algorithms, also the one used to solve the CVRP will provide a **graphical output** and a **written output**.

The **graphical output** represents the solution in QGis and is made of two shapefiles:

- one file containing the arcs of the graph used for the optimization (it is a translation of the network file into an internal format). The file name will be composed as follows: the name of the network as given in input, followed by the scenario we are considering, followed by "_FSarcs", e.g., *Verona1_* FSarcs.
- One file for the vertices of the internal graph. The name of the file will be the name of the network as given in input, followed by the scenario we are considering, followed by "_FSpoints", e.g., *Verona1_* FSpoints.

An example of the graphical output can be found in Figure 54

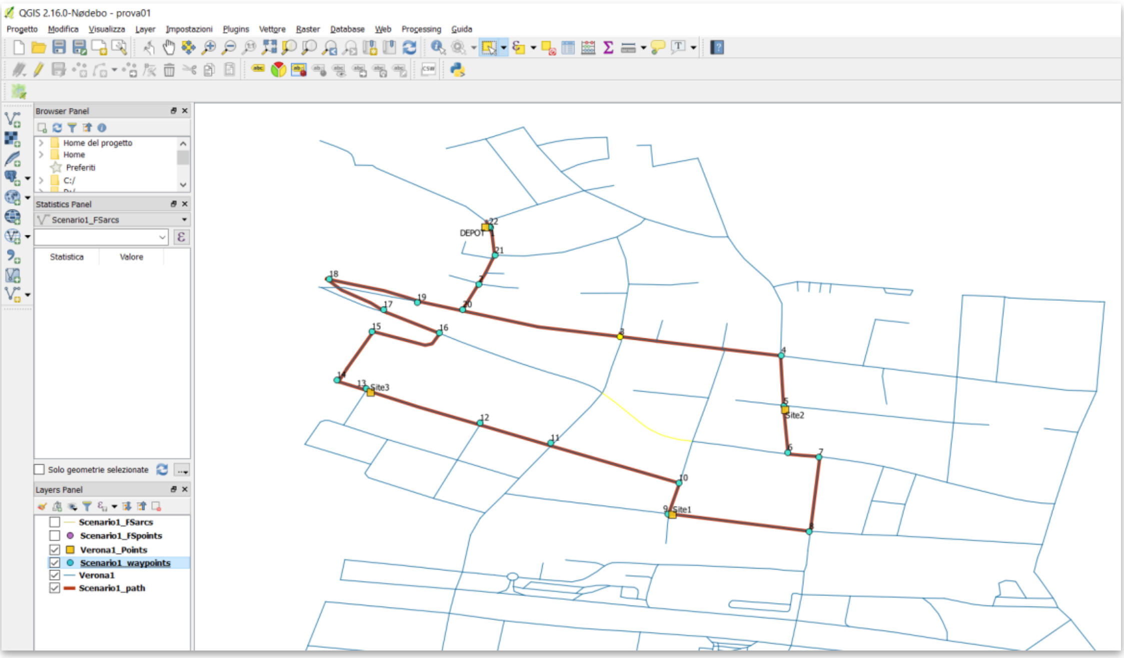

Figure 54 Sample output on QGis for one optimal route

The **written output** is made of the Routes file, which is a .txt file that reports the optimal routes with the following format:

- In the first line it reports the total number of routes,
- For each route
  - It is reported the route cardinality (the depot is always the first and the last point, so it is considered two times)
  - And the code of the visited vertices.

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The name of the Route file is the name of the network as given in input, followed by the scenario we are considering, followed by "_routes", e.g., *Verona1_routes.txt*. AN example of this file can be found in Figure 55.

```
      1
      5
DEPOT
Site2
Site1
Site3
DEPOT
```

Figure 55 Example of a Routes .txt file for a simple scenario

Another output is the log file in .txt format, that is generic log file containing several data and process information, including (last lines) messages on possible errors preventing the correct execution. The file name is made with the name of the network, of the scenario, followed by "_log.txt", e.g., *Verona1_log.txt*.

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9.3.4 Output Inventory vs Transport Problems

The output of the Inventory vs Transport Problems are very similar so we summarize them into one section.

The **graphical output** makes use of the function for graphic representation of the FICO Xpress software. The graphical output represents the CCC (black), the construction sites (magenta), and the connections between them (green arcs). One can see the number of vehicles needed for each site from the CCC in a red label. An example is given in Figure 56.

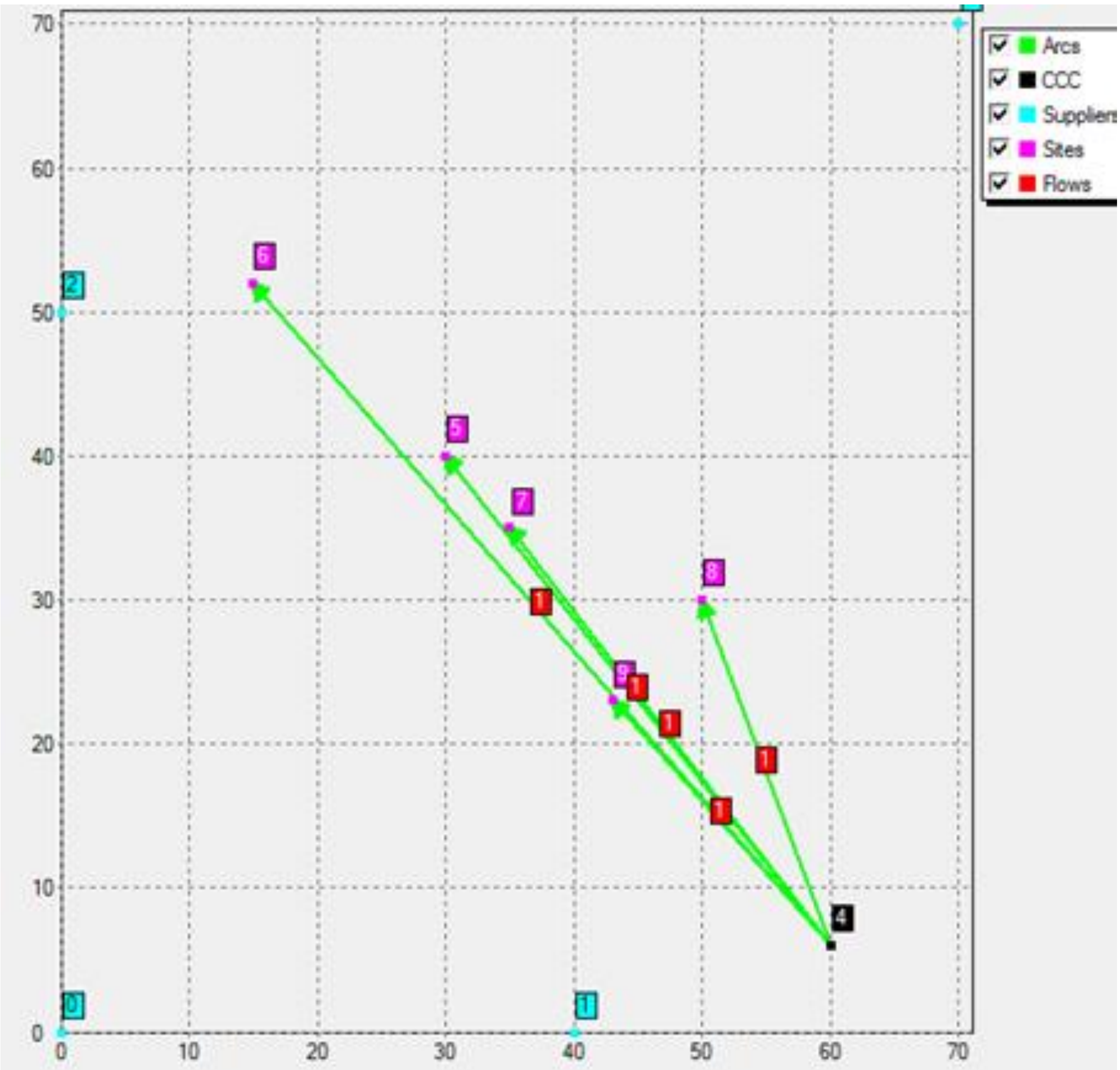

Figure 56 Example of the graphical output for the Basic Inventory vs Transport Problem

The **written output** of the Basic Model, whose example can be found in Figure 57, reports:

- The objective value,
- The number of vehicles used for each type,

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- The material flows,
- The materials stored into the CCC.

In the case of the possible anticipation the output also shows the amount of material arrived and stored on site. In case of reverse logistics the reverse flows are also reported.

```
Model Results
   Objective value = 15841.9
   Number of vehicles 0 to site 5 in period 0 : 1
   Number of vehicles 0 to site 5 in period 1 : 1
   Number of vehicles 2 to site 5 in period 0 : 1
   Number of vehicles 2 to site 5 in period 1 : 1
   Number of vehicles 0 to site 6 in period 0 : 1
   Number of vehicles 0 to site 6 in period 1 : 1
   Number of vehicles 2 to site 6 in period 0 : 1
   Number of vehicles 2 to site 6 in period 1 : 1
   Number of vehicles 0 to site 7 in period 0 : 1
   Number of vehicles 0 to site 7 in period 1 : 1
   Number of vehicles 2 to site 7 in period 0 : 1
   Number of vehicles 2 to site 7 in period 1 : 1
   Number of vehicles 0 to site 8 in period 0 : 1
   Number of vehicles 0 to site 8 in period 1 : 1
   Number of vehicles 2 to site 8 in period 0 : 1
   Number of vehicles 2 to site 8 in period 1 : 1
   Number of vehicles 0 to site 9 in period 0 : 1
   Number of vehicles 0 to site 9 in period 1 : 1
   Number of vehicles 2 to site 9 in period 0 : 1
   Number of vehicles 2 to site 9 in period 1 : 1
   Flow on vehicles 0 of material 0 from supplier 0 to site 5 in period 0 : 2
   Flow on vehicles 0 of material 1 from supplier 0 to site 5 in period 0 : 2
   Flow on vehicles 0 of material 0 from supplier 0 to site 5 in period 1 : 2
   Flow on vehicles 2 of material 2 from supplier 0 to site 5 in period 0 : 2
   Flow on vehicles 2 of material 1 from supplier 0 to site 5 in period 1 : 2
   Flow on vehicles 2 of material 2 from supplier 0 to site 5 in period 1 : 2
   Flow on vehicles 0 of material 0 from supplier 0 to site 6 in period 0 : 2
   Flow on vehicles 0 of material 1 from supplier 0 to site 6 in period 0 : 2
   Flow on vehicles 0 of material 0 from supplier 0 to site 6 in period 1 : 2
   Flow on vehicles 0 of material 1 from supplier 0 to site 6 in period 1 : 2
   Flow on vehicles 2 of material 2 from supplier 0 to site 6 in period 0 : 2
   Flow on vehicles 2 of material 2 from supplier 0 to site 6 in period 1 : 2
   Flow on vehicles 0 of material 0 from supplier 0 to site 7 in period 0 : 2
   Flow on vehicles 0 of material 1 from supplier 0 to site 7 in period 0 : 2
   Flow on vehicles 0 of material 0 from supplier 0 to site 7 in period 1 : 2
```

Figure 57 Example of the written output for the Basic Inventory vs Transport Problem

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10 Conclusions

In this Deliverable we defined tools to optimize the construction logistics supply chain in urban areas. These tools will be used in *Task 4.3 Solution Test and Simulation*.

We firstly described the construction logistics supply chain in urban areas as a two-echelon supply chain, which means that the supply chain can be considered made of two networks, one for the urban area, where the construction sites are located, and one for the outskirts, where suppliers and dumpsites are located.

Afterwards, we performed a deep literature review that ended into a detailed survey on the two-echelon optimization problems. This survey contains an improved notation with respect to the present notation of the two-echelon optimization problems. Indeed, it accounts for most of the characteristics that are considered into each of the works proposed in the literature. Thanks to this study we could detect what are the main methods used to solve the two-echelon optimization problems, and what are the novelties and features that are missing in the literature. For instance, we detected that many features such as multi product, multi period, multi vehicle, inventory, direct shipping, reverse logistics, and stochastic information had not had been studied yet all together. This has been of great help during the consequent modeling phase.

The study of the state of the art also paved the way to the determination of the SUCCESS urban construction logistics supply chain and the definition of its characteristics. As we said, we represented it as a two-echelon structure, including, among all, the following features:

- Multiple depots: more than one supplier and/or dump site;
- Multiple commodities: several materials are considered;
- Multiple periods;
- Different types of vehicles;
- Direct shipping allowed for some materials;
- Reverse logistics;
- Inventory;
- Multiple routes;
- Stochastic information;

These features have been included into the optimization problems we defined and detected to represent, simulate, and optimize the SUCCESS urban construction logistics supply chain. The optimization problems we decided to solve are part of the following classes:

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- Two-echelon (stochastic) facility location problems: that consider strategical problem of the introduction of CCCs into the supply chain and define their best location and size.
- Two-echelon allocation problems: that consider the tactical problem of defining the possible allocation of suppliers and construction sites to the CCCs.
- Vehicle routing problems: these problems are related to the operational day by day routing problems defined by the need of supply and collection of materials. These problems are defined to solve the optimization operational problems in both a two-echelon supply chain, linked to the introduction of CCCs, and in a one-echelon supply chain without CCCs.
- Inventory vs Transport problems: these problems consider a simplified supply chain where the problems can be conducted to an inventory versus transportation problem.

These problems are linked to the simulation scenarios proposed in *Task 4.2 Solution Design*. To ease its comprehension we provided and explanation of the link between the optimization problems and the simulation scenarios.

After the proposition of the problems, for each of them we proposed a set of Mixed Integer Linear Programming models taking into account the multiple features we described above. For all the presented models we provided a mathematical notation and a deep explanation of their meaning and usefulness.

We then described the defined tools prototype: these tools are made of the used algorithms, the input files required, and the output provided by the algorithms. For different models we used different solution methods, that are:

- Direct used of optimization solvers that make use of exact algorithms;
- Use of L-shaped Method type of algorithms for the problem with stochastic information;
- Heuristic algorithms for more complex problems such as the vehicle routing.

For each problem, the description of the needed input files is detailed and each needed component explained. On the other hand, the output of each model has been thought in two ways: a graphical output and a detailed written one. In the latter, the information of the obtained solution are reported in a clear and detailed way; in the graphical output only the most important information is reported to provide a fast response to the decision maker. For some models we made use of the graphical tools provided by the optimization solver, in other cases we made use of a more complex and detailed use of Google maps and QGis.

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These tools consider the main problems of a urban construction supply chain in both cases: we consider the introduction of CCCs or not. The provided models represents an improvement of the literature; but, most important, we believe that the provided tools can be used to determine good solutions to feed to *WP5 Evaluations and Validation*. We also believe that these tools, now in their porotype form, can be a good starting point for a possible development of a decision support system that can help stakeholders such as construction companies, suppliers, dumpsites, transporters, and local authorities in an improved decision making process.

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