



Methodological elements of supply chain design

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Complete List of Authors:	Corominas, Albert; Universitat Politècnica de Catalunya, Institute of Industrial and Control Engineering Mateo, Manel; Universitat Politècnica de Catalunya, Department of Management Ribas, Imma; Univeratitat Politecnica de Catalunya. BarcelonaTech ,

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Albert Corominas^{1,2}, Manel Mateo², Imma Ribas²¹, Sergio Rubio³

¹Institute of Industrial and Control Engineering, Universitat Politècnica de Catalunya,
Spain

²Department of Management, Universitat Politècnica de Catalunya, Spain

³Department of Business Management & Sociology, Universidad de Extremadura,
Spain

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¹ Corresponding author: Imma Ribas

Avda. Diagonal 647, H7 08028 Barcelona

Phone: +34 93 401 65 87

Fax: +34 93 401 60 54

E-mail address: imma.ribas@upc.edu (I. Ribas)

albert.corominas@upc.edu (A. Corominas)

manel.mateo@upc.edu (M. Mateo)

srubio@unex.es (S. Rubio)

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Methodological Elements of Supply Chain Design

Abstract: After a discussion of the methodological proposals for supply chain design published so far, we describe a hierarchical method consisting of five stages, as well as related concepts and tools. The aim of this method, named SCOP (Supply Chain Outline Process), is to provide a frame for the decision-making about the supply chain configuration. The approach is applicable to all types of supply chains.

Keywords: Supply chain design, supply chain network.

1. Introduction

In recent years, the concept of supply chain has gained momentum both in academia and in business (Stock and Boyer, 2009; Corominas, 2013). The supply chain (hereinafter, SC) is a network whose nodes are entities that cooperate to provide customers and users with products, whether goods or services, and, where appropriate, to recover, treat and maybe reuse products fully or partially. The word "network" is key because it means that most SCs have a more complex structure than a chain, and that flows between entities are an inseparable part of the SC. The management of SCs poses new problems that require their own methods and tools.

The view of SC as a set of agents that cooperate to achieve shared goals optimally may lead us to forget that, in fact, in each SC there is a leading entity (company, public institution, NGO, association, club, foundation, etc.) that sets the objectives of *its* SC and, to a certain extent, has the authority to decide who forms part of it and who does not (of course, the leading entity has the power to decide its suppliers, but it might not have that of deciding the suppliers of its suppliers; in this case, the suppliers' suppliers, although contributing to the SC, may be considered outside its frontiers). In fact, the leadership is considered the third building block in the house of SCM (Stadtler, 2002), and according to Stadtler and Kilger (2005) there can exist a 'natural' leader or a steering committee. The leading entity (also called dominating unit –Chandra and Grabis, 2007– or focal firm –Wagner and Neshat, 2010–) is the SC nucleus, driver or leader. It is significant that most works on SC refer to its objectives as a whole and do not highlight the critical role of the leading organisation.

SC design is a strategic problem, whose solution strongly influences the performance of the SC, that comprises the decisions regarding the number and location of production facilities, the amount of capacity at each facility, the assignment of each market region to one or more locations, and supplier selection for sub-assemblies, components and materials (Chopra and Meindl, 2012). Chandra and Grabis (2007) define SC configuration as the determination of the size and location of the units to be included in the SC and the links among them), what coincides substantially with the definition of SC design by Chopra and Meindl (2012). The complexity of the SC design is illustrated in Klibi *et al.* (2010), where some strategic questions to be answered in the design process are formulated: Which markets should we target? What delivery time should we provide in different product markets and at what price? How many production and distribution centres should be implemented and where should they be located? Which activities should be externalized? Which partners should we select? What production, storage and handling technologies should we adopt and how much capacity should we have? Which products should be produced / stocked in each location? Which factory / DC [distribution centre] / demand zones should be supplied by each supplier/ factory/ DC? What means of transportation should be used? In the same paper it is pointed out that the activities of concern include those of recovery and revalorisation.

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4 Although most early research on SC focused on the management of a given
5 configuration, current literature on SC design has many significant contributions. Some
6 of these works discuss general concepts of design approaches but most propose
7 mathematical programming models, sometimes of great complexity and considerable
8 size. However, the SC design problem cannot be reduced to the formulation and
9 solution of a model since no model can incorporate the multitude of qualitative and
10 quantitative decisions necessary to determine a SC configuration. Even in the simplest
11 cases, there are previous and subsequent decisions to the use of the model.
12

13 Given that SC design is usually a complex, lengthy process, it is advisable to follow a
14 method, understood as a series of ordered steps with guidelines and tools to facilitate
15 their implementation (Chandra and Grabis, 2007).
16

17 The contribution of this paper is to propose a methodology for the supply chain design
18 that formalises the decisions that should be taken during the design process. The
19 methodology leads to a hierarchical top-down decision process in order to consider all
20 relevant aspects of the SC design. An example involving a real-life problem illustrates
21 the use of the method.
22

23 The remainder of this paper is organised as follows. Section 2 summarises the
24 published methodological contributions most relevant to our view on SC design. In
25 section 3 we outline the proposed method. An illustrative example is shown in section
26 4. Finally, section 5 contains the conclusions and proposes future lines of research.
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29 **2. A summary of the methodological contributions in the SC design literature**

30

31 Although numerous publications deal with SC design, few refer more or less explicitly
32 to the methodology.
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34 One of the first approaches is to consider the relation between the type of product and
35 the type of its SC. Fisher (1997) proposes the distinction between efficient and
36 responsive SCs, reintroduced, with a change in the terminology, and extended by
37 Vonderembse *et al.* (2006). Other contributions about the relations between product
38 design and SC design can be found in Appelqvist *et al.* (2004), Lamothe *et al.* (2006),
39 Seuring (2009), Chiu and Okudan (2011) and Marsillac and Roh (2014).
40

41 Other authors (Wang *et al.*, 2004; Sha and Che, 2006) focus on the supplier selection,
42 viewed as the central question in the SC design.
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45 However, most papers dealing with SC design tend to identify the design process with
46 the formulation and resolution of a mathematical programming model. Usually, the
47 structure of the SC is represented by means of a multistage graph (e.g., Balinski, 1965;
48 Geoffrion and Graves, 1974; Simchi-Levi *et al.*, 2008; and Chopra and Meindl, 2012) or
49 a network, i.e., a directed graph without any special structure (e.g., Melo *et al.*, 2005;
50 and Laínez *et al.*, 2009). This serves as a starting point to formulate a mathematical
51 programming model (usually a mixed integer linear program). The model can be static
52 or dynamic, deterministic or stochastic. It may admit the possibility of opening new
53 facilities only or closing existing ones as well. Revisions of the model-based literature
54 are found, e.g., in Beamon (1998), Goetschalckx *et al.* (2002), Meixell and Gargeya
55 (2005) and Shen (2007). Other works propose mathematical models for the SC design
56 on specific industries.
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3 Finally, a relatively reduced number of papers consider directly methodological
4 aspects.

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6 One of the most relevant is Lakhali *et al.* (1999), which focuses on the concept of
7 product-market chain (hereafter P-MC). Every product has its own P-MC, represented
8 by the graph of activities, in which specific symbols are used. According to Carle *et al.*
9 (2012), models based on the graph of activities were subsequently proposed by Vila *et al.*
10 (2006) and M'Barek *et al.* (2010). Four basic components must be defined for each
11 P-MC: elementary durable resources, elementary methods, elementary activities and
12 products (include the inputs, outputs and intermediary, and may be material or not, like
13 information, knowledge or services). "Elementary" means here that corresponds to the
14 highest level of detail required. Three types of activities are considered: time, which
15 consists in preserving something for some time; space, representing a change of
16 position in space; and form (assembly operations, order processing or decision
17 making). As the graph of a P-MC is a very detailed representation of the processes that
18 take place in it, its definition requires a deep analysis of these processes. Once the
19 graph of the P-MC, the attributes of the components, the functions associated with
20 each method and the objectives are defined, it is relatively straightforward to formulate
21 a mathematical program to optimise results. Lakhali *et al.* (1999) give only very general
22 indications to this respect; however, Lakhali *et al.* (2001) formulate a static model from
23 the graph of activities and propose a heuristic to solve it.

24
25 In Vila *et al.* (2006) the graph of activities is applied to the timber industry. The authors
26 present a complex dynamic model and its resolution by CPLEX and a list of five steps
27 in SC design, particularly interesting from a methodological point of view: definition of
28 the product-markets, sourcing context and planning horizon; definition of product
29 families and the elaboration of the manufacturing-storage activities process graph;
30 definition of potential network resources and technology dependent recipes for
31 production activities; definition of the revenues and costs associated to the network
32 design and activity decisions; optimal mapping of the process graph onto the potential
33 network resources.

34
35 Carle *et al.* (2012), also within the framework based on the graph of activities, propose
36 a dynamic model and a classification of activities somewhat different from that in
37 Lakhali *et al.* (1999): fabrication-assembly, warehousing-storage and consolidation-
38 transshipment. As in Lakhali *et al.* (1999), the decision whether an activity is internal or
39 external is not based on the model, but established a priori.

40
41 The approach proposed in Lakhali *et al.* (1999) and complemented by Vila *et al.* (2006)
42 and others provides a good methodological basis. However, in our view, it obliges to
43 consider all the details from the beginning. This might be appropriate for a very simple
44 SC, but probably not for most SCs. We believe that a hierarchical top-down process is
45 more suitable to address the complexity of network design. The consideration of details
46 without the context of an overview tends to inhibit the generation of alternative
47 proposals, and probably leads to the unnecessary consideration of too many elements
48 in an explicit way. Certainly, the discussed approach seems to favour premature
49 decision making, such as separation of external and internal activities or location of
50 activities. Note that transport is carried out between activity points and transport from
51 one activity to another can only be quantified if their respective locations have been
52 previously determined.

53
54 For their part, Talluri and Baker (2002) propose a mathematical programming approach
55 in which two phases (identification of business processes types and potential
56 candidates; evaluation and selection of the units) precedes the formulation and
57 resolution of the model. The methodology described in Dotoli *et al.* (2005) consists of
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three phases (candidate selection, network design –using a mathematical programming model– and evaluation and validation).

Chandra and Grabis (2007) offer a literature review about SC configuration, including ninety-one papers published up to 2006. The authors themselves propose a methodology that includes eleven steps, embracing all the decision processes from the initiation of the configuration initiative to the evaluation of the configuration decisions, with an emphasis on the information requirements (the step that is more specific to the SC design is the third one, “Information modeling”).

Another approach is the Supply Chain Operations Reference (SCOR) model, developed by an independent non-profit organization, the Supply Chain Council (SCC). It is a reference model as a diagnostic tool for the SCM, but without possibilities to do dynamic analysis (Long, 2014). However, its objective is not specifically the process of designing a SC and the complete information about SCOR is available only to the SCC members.

In the process of designing a SC it is to be taken into account that, because of their complexity, SCs have a strong propensity to be disturbed by various natural or non-natural factors. Therefore, a distinction between uncertainty and risk is necessary (Klibi *et al.*, 2010; Klibi and Martel, 2012). We associate uncertainty with the possibility of realisation of one or another scenario (e.g., relative to demand), and risk with the disruptions caused by quality or delivery terms failures in the supply of raw materials or components, natural disasters, attacks, inclement weather, or traffic accidents among others. Scenarios have been extensively studied; therefore, there is abundant literature available (e.g., Santoso *et al.*, 2005 and Klibi and Martel, 2012). For a deeper consideration of risk in the SC: Tang and Musa (2011), a literature survey on SC Risk Management (SCRM); Micheli *et al.* (2014), about the selection of mitigation measures and Araújo *et al.* (2014), a proposal of classifying SC risks. In Klibi *et al.* (2010), several definitions of robustness, responsiveness and resilience are reviewed and the importance of these concepts in SC design is discussed. Vlajic *et al.* (2012) associate robustness with the ability to resist disruptions and resilience with the capacity to recover after disruptions, classify possible disturbances and propose redesign principles and strategies for robust behaviour of food SC

Summing up, although valuable methodological elements can be found in the literature, our analysis reveals that there is no sufficiently detailed, complete proposal of a method to guide the design of a SC.

3. An outline of the method: SCOP (Supply Chain Outline Process)

Leukel and Sugumaran (2013) point out the two main difficulties faced by SC design. The first one is that “the design space contains a vast number of alternatives, which makes it hard for designers to evaluate and select the best alternative”. The second is that “requires sharing and understanding design information by various parties”. Our purpose is to contribute to mitigate these difficulties with a method that we call SCOP (Supply Chain Outline Process). SCOP may help throughout the design process, avoiding the premature discarding of some options and sparing the detailed consideration of others as well. Moreover, SCOP facilitates the communication and is a starting point to develop a terminology and a grammar (Leukel and Sugumaran, 2013) in order to avoid ambiguities and make easier checking the correctness of the models. The main characteristics of SCOP are the following:

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3 a.- Hierarchical top-down approach, avoiding the consideration from the outset
4 of unnecessary details and the premature adoption of decisions. Particularly,
5 the decisions about the activities are considered before those concerning the
6 actors, what may reduce significantly the analysis of alternatives.

7
8 b.- The structure of the SC is not supposed to be a priori a tiered one. Any kind
9 of relations between the actors may be considered.

10
11 c.- Reverse logistics is considered from the first stage of the method.

12
13 d.- A list of alternatives, with indications about the circumstances in which it
14 would be advisable to adopt each one of them, is provided for every step of the
15 decision process.

16
17 e.- The activities are classified according to the diverse types and modes of
18 relations between inputs and outputs, so a pair type-mode is assigned to each
19 activity.

20
21 f.- The possibility that a significant delay may exist between the beginning of an
22 activity and the availability of its outputs is taken into account explicitly.

23
24 g.- In case the decision maker retains more than one option for one or more
25 activities, the method can lead to different solutions to be analysed considering
26 the adopted criteria.

27
28 h.- The proposed graphs are tools to represent in a precise way the relations
29 between activities and between actors. Moreover, they may make easier the
30 formulation of the mathematical models.

31
32 i.- SCOP is an open frame, which can be deepened (for instance, enlarging the
33 number of distribution options) without changing its basic structure.

34
35 Some of these characteristics are present in other methodological proposals
36 concerning SC design. However, to the best of our knowledge none offers all them
37 together.

38
39 In Figure 1 an overview of the proposed method is given (stages are described below).
40 The term "product" is used to refer to a single product or family of products, without
41 consideration of the peculiarities of each case. The whole method can be seen as a
42 help to answer the questions formulated in Klibi *et al.* (2010), synthesised in Section 2.
43 As in any hierarchical decision process, decisions taken at a particular level can force
44 or make desirable to review previous decisions taken at higher levels.

45
46
47 Figure 1. General layout of SCOP

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49 Although a chain is represented in Figure 1 (each link is a stage in the process), this
50 reflects only the case in which a unique alternative is retained at every stage.
51 Otherwise, the right representation would be a directed tree. The decision maker can
52 retain several alternatives for the macrostructure and each one may generate diverse
53 mesostructure configurations (however, most likely, one microstructure will derive from
54 a given mesostructure).

55
56 According to Figure 1, one or more graphs (with the corresponding vertexes and the
57 links between them) should be defined in stages 2, 3 and 4 of the method. However,

we do not claim that it is always necessary to *draw* the graphs, although we think that the graphical representations will frequently be useful to show concisely the corresponding structures and as a communication tool within the design team.

3.1. Stage 1: definition of the object, analysis of the environment and determination of the objectives

The design process must obviously start with the definition of the SC object. "Object" seems more appropriate than "product" or "mission". For instance, the objects of a SC relating to potatoes for consumption may be to grow and sell potatoes to large food retail chains; buy them from large producers and sell them to large retail chains... The definition of the object must include a definition of the product, but this is not enough. Potatoes may be for consumption or for seed potatoes. To give another example, decisions on the distribution types (via retailers or the Internet) can radically affect the nature of businesses and candidate markets.

The definition of the object of the SC ought often to include a characterization of the potential markets for the product. This delimitation of the potential markets may have significant implications on some treats of the SC (e.g., on the distribution options or pricing policies).

The definition of the SC object usually has a strong influence on its design, including the elimination of many a priori options. For example, the Internet sale of audiovisual materials as SC object excludes other ways of distribution.

Once defined the object of the SC, one can proceed to analyse the SC environment (SC Ecosystem, Viswanadham and Kameshwaran, 2013; the influencers, Melnyk *et al.*, 2014). In fact, this analysis may interact with the definition of the object of the SC. A particularly relevant derivation is the definition of the scenarios to be considered (in very complex settings, the use of simulation can help to define the most relevant scenarios).

Generally, objectives are subordinated to the SC object and may include, among others, maximisation of the stock market value of shares, profit, reliability, robustness and resilience; cost or response time minimisation; or covering a set of markets as soon as possible. At this stage, a set of objectives must be established and their relationships, if possible (otherwise, at later stages). The planning horizon should be included.

3.2. Stage 2: definition of the SC macrostructure

At this point, the presence of large blocks as part of the SC and the relationships between them are defined. The result may be represented in the called *M-graph*.

All SC activities involve procurement, production and distribution, and a set of users (often properly called markets or customers). Some of these activities can be insignificant, but they are always somehow present. Thus, we will always have a procurement-production-distribution block, P, and a block representing all users. The simplest SC macrostructure is therefore represented by the M-graph A in Figure 2 and corresponds to a SC without reverse logistics. Waste generated by procurement, production and distribution activities might be sent to what we call depots (block D), which may be landfills, waste treatment plants, sorting centres for further processing or charitable organisations (M-graph B, Figure 2).

Figure 2. Examples of M-graphs

It is difficult to find examples of SC without the more or less important presence of reverse logistics. Sometimes the management of returns requires a significant logistics effort. The SC may include collection of obsolete products from some collection points (block C); therefore, either block D and/or a set of remanufacturing or recycling activities (block R) must be in the SC. Block S (for secondary markets) is for remanufactured products sold in specific markets. Without any claim to completeness, these blocks in different SC macrostructure configurations are shown in the M-graph C (Figure 2).

The main consideration in reverse logistics network design is the choice between an independent network for the collection of end of use (EoU) products and a network integrated into the forward SC, resulting in a closed-loop supply chain (CLSC). Akçali, *et al.* (2009) note that network design (ND) for reverse supply chain “is concerned with establishing an infrastructure to manage the reverse channel *only*” and in ND for CLSC there is “an infrastructure to manage *both* the forward and reverse channels in a *coordinated* manner”. In any case, both are set around two critical activities: (i) collection of EoU products and (ii) recovery of their economic value (remanufacturing, reusing and recycling). In the literature on reverse logistics most of the authors propose a four-step reverse logistics system (Lambert *et al.*, 2011): gatekeeping, collection, sorting and disposal. In our case, collection and reprocessing (usually including sorting) are described as a part of the SC mesostructure, meanwhile disposal is a block belonging to the macrostructure previously defined.

3.3. Stage 3: definition of the SC mesostructure

The definition of mesostructure requires a sufficiently defined product structure (modules or subassemblies) and production process.

SC mesostructure corresponds to the relations between the *classes* of elements contained in each vertex of the M-graph, where a *class* is the set of elements (which are not necessarily and probably not identified at this stage) capable of executing a particular *recipe*, i.e., a transformation of inputs into outputs. The mesostructure is represented by the called *m-graph*, where each class corresponds to a vertex or *cluster* of vertices connected with other classes, inputs and outputs of the class in question being outputs and inputs of those classes.

The m-graph is a tool to represent in a compact, precise way the set of activities to be performed in the SC and their relations. The μ -graph (see 3.4.1), which derives from the m-graph, includes all the information required to formulate, if necessary, a mathematical programming model.

The consideration of recipe depends on the point of view, since a recipe can often be decomposed into smaller recipes. As a general orientation, it may be considered as a recipe the whole transformation processes in the same facility.

Generally, the transformation of an M-graph vertex into the corresponding set of m-graph vertices may have diverse variants, some of which are incompatible. Some can be ruled out by what we call strategic decisions; others must be evaluated separately.

From the knowledge about the product and process, one must decide which *options* to consider in detail regarding:

- Procurement and production
- Distribution
- Collection
- Reprocessing

The literature has addressed these *groups* of activities in several levels of detail (see Subsection 3.3.1). In each group, classes may be of various *types*, according to the relationship between inputs and outputs.

3.3.1. On the options

Procurement and production options

The most important alternative for each recipe is to buy or make, i.e., entrusting an external entity with its execution or executing it in-house. Since the former admits variants, the options to consider are:

- P1 Make.
- P2 Buy from a single supplier with a long-term contractual relationship.
- P3 Buy from a set of suppliers without long-term contractual relationships.
- P4 Buy from one or more suppliers over time (e.g., when setting up a new plant and closing an old one, the least expensive suppliers may be different).
- P5 Buy in the market (the module or component is continuously available, with standard quality and a price determined by its market).

“Make” (P1) must be chosen when the recipe requires the leading entity’s expertise that gives a specific character to the product and the company does not want to take risks regarding the dissemination of such knowledge. At the other end, an always-available component of consistent quality will be purchased in the market (P5).

Decisions about in-between options are more complex. Long-term commitment with a single supplier (P2) offers a cost reduction for both parties, but implies the risk of failure of the supplier and a somewhat difficult situation (Inman and Blumenfeld, 2014). P3 involves a lower cost reduction in exchange for an increase in reliability.

Shortly, the selection criteria for the option for each recipe are confidentiality, reliability (concerning quality and delivery time) and cost.

The degree of product modularity and the selection of options in this group are interdependent. According to Ülkü and Schmidt (2011), product architecture is the key to move from option P1 (integrated chain) to the rest, i.e. decentralised chain.

The choice among the five options depends heavily on the degree of modularity of the product. The decomposition into parts reduces design complexity. In production, common modules and a manufacturing process with a hierarchy of assembly steps simplifies the flows, provides flexibility against uncertainty in demand and reduces inventories (Langlois and Robertson, 1992; Ulrich, 1995). Finally, modularity facilitates product configuration, updating and maintenance by the user (Ramachandran and Krishnan, 2008).

Distribution options

An extensive and excellent discussion of distribution network design for manufactured products can be found in Chopra and Meindl (2012).

They consider options D1 to D6 in the following list, to which we add D7.

- D1 Manufacturer storage with direct shipping to customer.
- D2 Manufacturer storage with direct shipping and in-transit merge of components of the order in intermediary facilities.
- D3 Distributor storage and home delivery by a logistic operator.
- D4 Distributor storage and home delivery with last-mile delivery.
- D5 Manufacturer or distributor storage with customer pickup.
- D6 Retail storage with customer pickup.
- D7 Centralised storage with customer pickup at a retailer under previous order.

D5 and D6 differ in that in the former customers must travel to product storage facilities, but in D6 most customers can find a store within walking distance from their homes. The choice between D1 and D7 depends on the characteristics of the product and the density of the pickup retailer network in D7.

Chopra and Meindl (2012) describe in detail, illustrate with examples, assess options D1 to D6 against cost and service criteria and draw conclusions about the suitability of each option to different product features.

Collection options

Alumur *et al.* (2012) highlight that reverse logistics network configuration is a complex problem that requires the determination of optimal localisations and capacities of collection centres, sorting centres, remanufacturing facilities and/or recycling plants.

The return process for EoU products begins with their collection, for which the following options are considered:

- C1 Directly by manufacturer or remanufacturer
- C2 Through a network of distributors and retailers
- C3 Through third-party logistics providers (3PL)

The residual value of the EoU products and their marginal value of time (MVT; Blackburn *et al.*, 2004) can be considered as the selection criteria for the most appropriate collection option. Option C1 with a pick-up system is generally used to collect EoU products with high residual value and high MVT (e.g., computers); C2 with a drop-off system is suitable for products with high residual value and low MVT (white brand appliances); C3 is used under a drop-off regime to collect EoU products with low residual value and low MVT (e.g., tyres).

Reprocessing options

The reprocessing stage is the central element of a reverse logistics network, as it is the phase where the economic value of EoU products is recovered using one of the following options:

- R1 Reuse
- R2 Remanufacturing
- R3 Recycling

This classification of reprocessing options can help to establish a relationship with the collection options (C1, C2, C3), providing an integrated perspective of the reverse flow of the SC. Option R1 implies very simple reconditioning operations of EoU products and their reintroduction in the market in similar conditions to those of new products. R2 requires additional work to provide EoU products with similar technical and quality characteristics to their original counterparts. R3 is aimed at recovering the economic value of raw materials of EoU products.

In general, it is impossible to establish a univocal correspondence between collection and reprocessing options, although in most cases recycling (R3) is associated with collection systems through 3PL or the so-called collective management systems, e.g. packaging material. R2 can be related to several collection options (Savaskan *et al.*, 2004). Thus, EoU products can be collected directly by the manufacturer (C1), as in the case of companies such as Xerox or Samsung, through retailers (C2) as in the case of single-use cameras or mobile phones, or using 3PL (C3) for certain EoU products in the automobile industry. Regarding R1, different collection options are usually employed.

3.2.2 Vertices and types of vertices in the m-graph

The representation of a class must identify its inputs and outputs, as well as all resources relevant to SC design.

As mentioned previously, these classes may be of different *types*, according to the relationships between inputs and outputs. For some types, quantitative relationships between inputs and outputs will be required.

Figure 3 shows suggested representations for all types of classes.

Figure 3. Types of vertices in the m-graph

Type T_α has just one output, which may be the input of one or more recipes, and no incoming arcs. There is at least one T_α in every m-graph.

Type T_ω , symmetrical to T_α , has inputs that come from one or more recipes but no outgoing arcs. The vertices of this type may correspond to blocks U and D of the M-graph.

Therefore, all the other types of vertices, designated here as T_g , have inputs and outputs. A recipe may receive one or more inputs, which may come from one or more recipes. It can also provide one or more outputs, and each can be the input of one or more recipes.

In order to avoid ambiguities, the use of auxiliary vertices is recommended. These auxiliary vertices gather inputs from different recipes and distribute outputs among several recipes (Figure 3).

In every recipe, we can consider a main vertex that has some information (maybe not perfectly quantified) about the relationship between inputs and outputs. This relationship can correspond to one of the following *modes*:

M_c (convergence)	A number of units belonging to the elements of a set of components generate one unit of final or intermediate product.
M_x	Many products are obtained by mixing different raw

(flexible mix)	materials. When its composition is defined by intervals or the recipe ingredients can be selected from a set of alternative raw materials or both, we assign this recipe to mode Mx.
Md (divergence)	A unit of input provides certain quantities of several outputs.
Mm (many to many)	Some quantities from several inputs provide some quantities of several outputs.
Ms (sum)	There is no transformation process. The same input coming from different recipes becomes output. Except for losses, the quantity of output is the total sum of the inputs considered.
Me (evolution)	A certain proportion of an input becomes an output of a different nature or condition requiring a significant amount of time, either deterministic or random.

If there are alternative recipes for one activity of the process, they may be included in the same m-graph, inscribing them in a common rectangle. However, this will complicate the formulation of the corresponding mathematical model (see 3.4). If there are many steps with alternative recipes or, even more, completely alternative processes, it will be better to formulate a model for each alternative.

3.4. Stage 4: definition of SC microstructure

The definition of SC microstructure is aimed at determining the facilities where recipes will be developed, the volume of outcoming and incoming flows between facilities, and the respective transportation means.

The tools for defining the microstructure are the μ -graph(s) and the mathematical programming model(s) based on them. Every m-graph defined at stage 3 generates a μ -graph that provides a particular SC configuration, probably with the help of a mathematical programming or simulation model.

Note where is the place of the mathematical programming models in our approach. When formulating a mathematical programming model, some options are assumed and others are discarded. However, it should be avoided to do this without careful consideration. Moreover, in spite of algorithmic and software developments, it must not be lost of sight that the mixed integer programming problem is NP-hard and this implies that the complexity these models can deal with is bounded.

3.4.1 The μ -graph

The μ -graph is based on the m-graph. Every cluster of vertices belonging to a recipe in the m-graph must be replaced with a set of clusters, whose elements are referred to an existing or potential facility where recipes are to be developed.

Once a list of facilities is established, it is advisable to evaluate each one with the aim of retaining only those fulfilling a set of predefined conditions. So, the complexity of the design process is kept within reasonable limits.

The data concerning a facility in a vertex of the μ -graph, relevant for the design of the SC, are:

- location,
- ownership,
- availability (committed or potential) during the time horizon,
- quantified relationship between inputs and outputs,
- time lag between inputs and outputs,
- output unit cost,
- capacity,
- energy consumption and emissions,
- fixed costs per period,
- opening and closing costs.

Not all these data are required for any facility. For instance, if the owner is a supplier, the leading entity is not concerned with the possible opening or closing costs.

The ownership and the availability during the time horizon are especially important in order to check the consistency between the options adopted in stage 3 and the set of facilities taken into account in the μ -graph, and later to help formulating the mathematical programming model. To this end, it would be useful to assign to each facility a code indicating whether it is owned by the leading entity or by suppliers, when the facility will be open or may be open, and when it will be closed or may be closed.

For instance, if P1 is adopted for a vertex of the m-graph, all the corresponding facilities in the μ -graph must be owned by the leading entity and, at every period, the joint capacity of the available facilities has to be not less than the required one. On the other hand, if P2, P3 or P4 are adopted, all the corresponding facilities in the μ -graph must be owned by suppliers.

Regarding the clusters of block U in the M-graph, the term "facility" should be replaced with "market" and the capacity will be equivalent to the demand (a numerical value for each period).

If several recipes can be implemented in the same facility, the links between groups of vertices are the same as those in the m-graph. However, the links between groups of vertices related to different facilities generally require new vertices belonging to a new mode: Mt (transportation mode). Any Mt vertex represents a transportation means between two given locations.

For each Mt, we should know:

- delay between delivery and reception,
- fixed and unit transportation costs,
- capacity,
- energy consumption and emissions, and
- investment costs.

Therefore, Mt vertices can be found in the μ -graph but not in the m-graph.

3.4.2. The models

In order to optimise the decisions that configure the SC, a mathematical programming model can be derived from the μ -graph. The own structure of the graph and the associated information facilitate the formulation of the model. The decision variables represent flows between facilities or the opening or closing of facilities (concerning

these latter decisions, the code that is suggested in Section 3.4.1 would permit to determine immediately the sets of the corresponding binary variables). The constraints will define the flow balance in every vertex, capacity limitations and probably financial considerations. For long-lasting production or transportation processes, time differences between the reception of the inputs and the delivering of outputs require consideration.

If product prices are given and market demand can be forecast, a MILP model can be formulated and solved using commercial software or, depending on the complexity of the μ -graph, by using heuristic procedures.

It is worth noting that a model is useful not only in working out the optimal or good solutions, but also in evaluating its sensitivity in different scenarios.

3.5. Stage 5: Choosing a SC configuration and defining an incident protocol

The process results in the choice of a SC configuration, according to the established criteria and the adopted process of decision-making.

The final step consists in formulating a strategic plan to deal with incidents and disruptions in the SC effectively, including a description of means to detect incidents and of corrective actions (Tang, 2006; Klibi *et al.*, 2010; Vljajic *et al.*, 2012). Some metrics, such as the ones proposed by SCOR, can help to make the best suitable decisions.

4. Illustrative example

An example based on a real situation is described in order to provide insights about how the proposed approach works. This case represents the process of developing a SC for the manufacturing and distribution of an ecological product called ECOXY, an epoxy resin, employed in the repair and maintenance of many different materials, for example boats, surfboards, snowboards, skis, etc. In this case, a European entrepreneur was granted an exclusive license to manufacture and distribute ECOXY in Europe. To this aim, our entrepreneur created the company EUROXY located in a plant close to Barcelona. Now, s/he wants to plan the future configuration of EUROXY SC considering that good market conditions for this product are expected in the next years.

ECOXY consists of two components A and B that can be combined in different ways to obtain different properties and qualities. Component A is obtained as a result of a reaction of a concentrate and an additive. The concentrate is exclusively manufactured and supplied by the licensor in drums of 200 kg. The additive can be bought in the market. On the other hand, component B can be bought to the licensor or manufactured by EUROXY using materials that can be provided by local suppliers.

Stage 1. Object, environment and objectives

- Object: The first step is to decide between make to stock or customize the product. Taking into account that each one of the multiple applications of ECOXY requires ideally a different composition and that the customisation would give the product a unique character in front of the competitors, the

entrepreneur decides to customize the product. Therefore, EPOXY will be manufactured to order and marketed online via the Internet. The market includes manufacturers of the sportive equipments indicated above and, based on the ecological attributes of ECOXY, individuals practicing sports in contact with nature and concerned about environmental issues.

- Environment: A significant increase of demand for ECOXY is expected, so the entrepreneur has defined several scenarios for demand (i.e., the demand forecast for each one of the considered commercial areas) and economic conditions, including the evolution of the financial markets.
- Objectives: Since this is a novel product, in the introduction and growth phases, the goal is to settle in the market, as soon as possible, in order to avoid the entry of competitors while minimizing the risk of failure.

Stage 2. Definition of SC macrostructure

The product cannot be recovered. The drums containing the concentrate will not be returned to the licensor because of the high transportation costs. The packaging material will not be recovered after consumption due to its low residual value and the huge collection costs. However, customers close to the EUROXY's plant/s can return the containers and obtain a discount, if they pick the product up directly at EUROXY.

Therefore, besides the blocks P and U, the M-graph will include a block D in order to dispose of drums and other packaging materials and a block R corresponding to the return of the containers.

Stage 3. Definition of the SC mesostructure

Structure and production process: The structure of the product has been described at the beginning of this section 4. Components A and B will be mixed by customer according to the required specifications; therefore, both components will be canned separately and then bundled together to be dispatched to the client

- Options: Concerning A, the concentrate must be bought to PRO (P2 option) and the additive will be bought in the market (P5). Given the conditions of the license, the only option for manufacturing A is P1 (i.e. it has to be manufactured by EUROXY). Component B could be purchased from PRO, but the cost would be greater than manufacturing costs at EUROXY plant/s; so, P1 will be the chosen option. Therefore, it will be necessary to select the suppliers of the corresponding ingredients (P3 option). The packaging materials will be purchased in the market (P5). Regarding the distribution to individual customers, couriers will deliver the product at home (D1). Companies can choose between receiving the product in their facilities (D1) or picking it up from EUROXY (D5), with a discount. Regarding the collection options, EUROXY collects the packaging materials from customers close to facilities (C1). The companies who fetch ECOXY at the EUROXY's warehouses and return the containers can be considered as a special case of C2; for the reprocessing options, the containers will be reused (R1).
- Specification of modes: The processes to obtain A and B correspond to a convergence mode (Mc). As both can be distributed in containers of different capacities, a divergence mode (Md) is considered for the packing. The final bundle is obtained following a convergence mode (Mc).

Stage 4. Definition of SC microstructure

- List of facilities: the entrepreneur must establish a list of possible locations for plants and can associate to each of them a set of suppliers for ingredients and packaging materials and a depot. Once the selected set of locations is obtained, one can pass from the vertices of the m-graph to vertices of the μ -graph.
- Sources of demand: they are the commercial areas used in the definition of the environment in stage 1.
- Means of transport: the use of ships to transport components of A is obliged, as the air transport is too expensive. Therefore, a long period of time is needed to move the materials from U.S. to European ports. At this stage, several alternatives of transportation are also considered and evaluated: from ports and suppliers to plants, from plants to customers.
- μ -graph: the vertices of this graph correspond to the selected potential locations of the plants, and to the means of transport from PRO to the plants and between the plants and the sources of demand.
- Mathematical model: as a result of the decisions that have been adopted throughout the design process, ultimately the decisions to be modelled are: where, when and with which capacity the plants are opened (or expanded), the allocation of each commercial area to each plant and the means of transport, over time, according to the objectives set in stage 1. The remaining decisions (suppliers and depots) will be taken accordingly.

Stage 5. Choose of SC configuration

The final configuration of the supply chain is given by the resolution of the model. The robustness of the SC must be ensured by means of inventory of the ingredients, giving especial consideration to the concentrate.

5. Conclusions and future lines of research

In order to systematise the process of SC design, a top-down hierarchical method called SCOP (Supply Chain Outline Process) has been proposed. The method consists of five stages, including lists of alternatives and guidelines for selecting them and terminology and tools to facilitate communication and coherence analysis.

SCOP is a holistic frame to drive the decision making process of designing the SC. The method forces to consider all the relevant decisions and at every stage only takes into account the pertinent decisions. Given that the elimination of an alternative at one stage implies generally that of many more ones at subsequent stages, the top-down approach simplifies the design process, reducing the number of alternatives to be analysed and requiring the data as they are becoming necessary. This avoids the gathering of data that at the end of the day reveal themselves superfluous.

Particularly, the layout of the method and its considerations show that, contrary to that is assumed, explicitly or not, in many publications, the use of a mathematical programming model is an important step in the process of SC design, but it has not to

be confused with the whole method. If this confusion prevails, it is very likely that many alternatives will be discarded from the outset, probably without due consideration.

Our prospects of future research include the application of SCOP to complex real SCs, which would help to develop the method itself.

However, the main line of work will be the definition of rules to formulate mathematical models from the information provided by the μ -graph. We think that the terminology and the conditions of coherence included in this paper are a suitable point of depart to tackle this task and that its result will be useful for academics (both for research and teaching) and practitioners as well.

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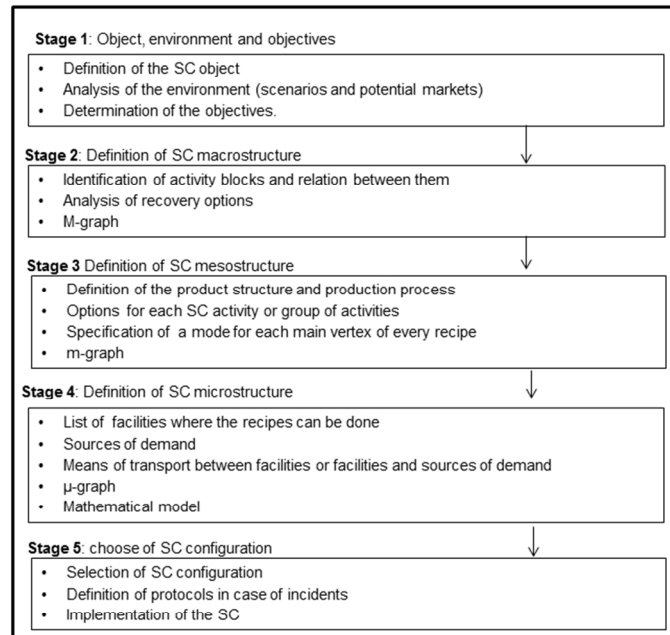
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26 Figure 1.General layout of SCOP

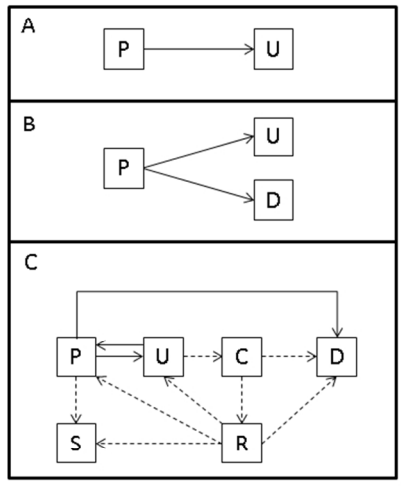
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28 Figure 2. Examples of M-graphs

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30 Figure 3.Types of vertices in the m-graph
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General layout of the SCD
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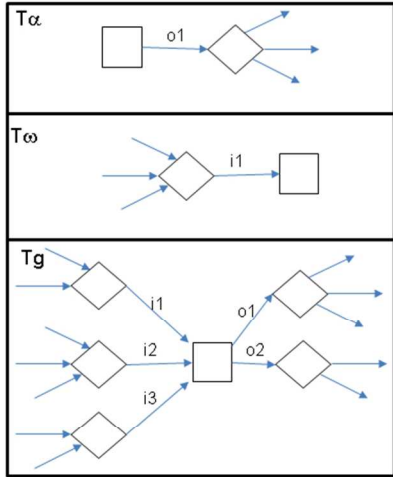
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Examples of M-graphs
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Types of vertices in the m-graph
254x190mm (96 x 96 DPI)

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Reviewer: 1

Thank you for your prompt and constructive review. According to it, we have prepared a revised version of the paper. The changes have been coloured in yellow.

Comments to the Author

The first half of the paper has improved significantly. However, there are major issues that have to be improved in the almost completely rewritten sections in the second half of the paper. Please note that I am referring to the manuscript pages and not to the PDF page numbering.

Minor issues:

Page 4 line 39-41: There is something wrong with the sentence:

"... our analysis reveals that there is not in it any sufficiently detailed, complete ..."

Maybe the authors mean: "... our analysis reveals that there is no sufficiently detailed, complete ..."

The sentence has been rewritten (page 4) according to your suggestion.

Page 4: Section 3 heading. The name of the method SCD is a bit too generic. Maybe the authors could find a more specific name for their approach. Otherwise, the reader could think that the characteristics mentioned refer to supply chain design in general and do not specifically refer to their approach.

We appreciate your suggestion. We have renamed our approach. SCD has been replaced with SCOP (Supply Chain Outline Process) in all the paper. The new denomination is introduced in page 4.

Page 5 point e: The bullets a. to d. are very clear to the reader and it is understandable why holistic SCD should satisfy those characteristics. Point e. is very specific and is not clearly formulated as a characteristic. I would propose to rephrase point e.

We agree with your comment. Point e has been rephrased (page 5).

Page 5 point i: This does not seem to be a characteristic but rather a remark. Otherwise, the authors should clarify this characteristic.

1
2
3 We also agree. Point i has been deleted, since the main idea of this point is
4 presented in other parts of the paper. Accordingly, the former point j is now point i
5 (page 5).
6

7
8 **Page 6: "It is not always necessary to draw the graphs (M-graph, m-graph
9 and μ -graph) mentioned." However, the names in the brackets are mentioned
10 for the first time. They should be defined beforehand. Moreover, in the
11 following pages the authors always refer to the end of section 3 where the
12 graphs are defined.
13**

14
15 This paragraph has been rewritten. Now, we mention it in Fig. 1, in which the
16 graphs appear for the first time in the paper.
17

18
19 **Page 14: The first half of the first sentence of section 4 does not seem to be
20 correct.
21**

22 Your observation has been taken into account when we have completely rewritten
23 section 4, according to your comment about it.
24

25
26 **_Major issues:_**
27

28 **Page 12-13 (Section 3.4.1): Why do the authors introduce a mathematical
29 notation if it is not used afterwards? The new formulated section does not
30 enhance the readability of the article and it does not help to understand the
31 meaning and purpose of this graph. Moreover, the authors have to improve
32 the language in this section.
33**

34
35 This section has been rewritten in order to reduce its length and to eliminate
36 superfluous details. In the previous version we have tried to illustrate the possibility
37 of defining a notation in the frame of the approach. However, most likely this can
38 be suggested, as we have tried to do in the new version, without introducing so
39 many details as in the previous one.
40

41
42 **Section 4 in general: This section presents the end result of the approach but
43 it does not show how each step itself is conducted. The example does not
44 clearly show the benefit(s) of the approach. I do not see that the decision
45 maker is supported by this approach. I still do not see the benefit of the
46 graphical representations of your different kinds of graphs. The authors have
47 to improve the language in this section.
48**

49
50 We have rewritten section 4 with the purpose of trying to show how the proposed
51 approach may help the decision maker both to not forget the consideration of any
52 relevant decision and to rule out progressively alternatives that a priori might seem
53 appropriate. To this aim, now the section begins depict the starting situation, to
54 proceed thereafter to describe synthetically the decisions adopted progressively in
55 the design process and how the approach really helps the entrepreneur. We hope
56 that the considerations concerning the role of the graphs and their graphical
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3 representation in the whole approach may also help to clarify their role in the
4 example.
5
6

7 **Section 5: The contribution of the paper is not clearly presented in section 5.**
8 **If I would summarize the contribution which the authors have expressed in**
9 **section 5, in simple terms, it would be the following: It seems that the**
10 **approach leads to a rough and quick but rather holistic picture of a supply**
11 **chain. Therefore, the approach neglects "unnecessary details" and does not**
12 **include a mathematical programming model. However, I am convinced that**
13 **this is not the author's intended contribution.**
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15

16 Really, we are sorry that section 5 in the previous version may be interpreted as
17 you point out. This, obviously, was not our intention. Accordingly, second and third
18 paragraphs of the section have been reformulated (page 15).
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Reviewer: 2

Thank you for your prompt and constructive review. In the new revised version the changes relative to the preceding one have been coloured in yellow.

Comments to the Author

My observations have been properly addressed, I have no further comment for the work other than consider a SCD simulation or system dynamics prior (probably in the same publication) to real SCs scenarios, that would feed the hypotheses generation and make the work process more interesting.

We have introduced in **page 6** a short comment about the use of simulation in the generation of scenarios.