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DESIGNING SUSTAINABLE SUPPLY CHAINS

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Abstract

A supply chain is a complex and dynamic supply and demand network of agents, activities, resources, technology and information involved in moving products or services from supplier to customer. The suitability of supply chains can be measured by multiple criteria, such as environmental, social, economic, and others. Finding an equilibrium between the interests of members of a sustainable supply chain is a very important problem.

The main objective of the paper is to analyze the design of sustainable supply chains and to create a comprehensive model and solution methods for designing sustainable supply chains. Multiple criteria analysis and game theory is a natural choice to effectively analyze and model decision making in such multiple agent situation with multiple criteria where the outcome depends on the choice made by every agent. Multiple criteria analysis is useful for assessing sustainability of supply chains. The De Novo approach focusses on designing optimal systems. Game theory has become a useful instrument in the analysis of supply chains with multiple agents. Games are used for behavior modeling of supply chains; they focus on the allocation of resources, capacities, costs, revenues and profits. The co-opetition concept combines the advantages of both competition and cooperation into new dynamics, which can be used to not only generate more profits, but also to change the nature of the business environment for the benefit of users.

Keywords: supply chain, sustainability, multiple criteria, De Novo approach, game theory, biform games.

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1 Introduction

Supply chain management is a philosophy that provides the tools and techniques enabling organizations to develop strategic focus and achieve sustainable competitive advantage (Simchi-Levi et al., 2008). This philosophy presents management with a new focus and way of thinking about the existence and workings of the organization in a wider business environment. Supply chain management is now seen as a governing element in strategy and as an effective way of creating value for customers.

The evolution of supply chain management recognized that a business process consists of several decentralized firms and that decisions of these different units impact each other's performance, and thus the performance of the whole supply chain. Each unit attempts to optimize his own preference. Behavior that is locally efficient can be inefficient from a global point of view. Sustainability in supply chain management has become a highly relevant topic for researchers and practitioners (Brandenburg et al., 2014; Carter and Rogers, 2008; Seuring, 2013). The objective of supply chain sustainability is to create, protect and grow long-term environmental, social and economic value for all stakeholders involved in bringing products and services to market.

The main objective of the paper is to analyze the design of sustainable supply chains and to create a comprehensive model and solution methods for designing sustainable supply chains. Multicriteria analysis and game theory tools are a natural choice for modeling and effective analysis of decision making in a situation with multiple criteria and multiple agents, where the outcome depends on the choice of each agent. Multiple criteria analysis is useful for assessing sustainability of supply chains. Game theory has become a useful instrument in the analysis of supply chains with multiple agents, often with conflicting objectives.

Standard multiple criteria approaches focus on valuation of already given systems. The De Novo approach focusses on designing optimal systems (Zelený, 2010). The approach is based on reformulation of the problem by given prices of resources and the given budget. Searching for a better portfolio of resources leads to a continual reconfiguration and reshaping of systems boundaries. The De Novo approach was adapted for supply chain design. Current business conditions are changing rapidly. New products are evolving faster. Technological innovations bring improvements to the criteria and a better utilization of available resources. This dynamics must be included in the new models. These changes can lead beyond trade-off-free solutions.

The search for equilibrium in supply chains is a very important problem. Games are used for behavior modeling of supply chains; they focus on allocation of resources, capacities, costs, revenues and profits (Kreps, 1991; Cachon and Netessine, 2004). There are numerous opportunities to create hybrid models that combine competitive and cooperative behavior. The co-opetition concept combines the advantages of both competition and cooperation into new dynamics, which can be used to not only generate more profits, but also to change the nature of the business environment for the benefit of users (Brandenburger and Nalebuff, 2011). Searching for relationships with complementors (competitors whose products add value to other agents) brings ever new opportunities that bring added values. The co-opetition is based on the biform game theory (Okura and Carfi, 2014). Biform games combine non-cooperative and cooperative approaches of the traditional game theory and are promising for modeling behavior of the agents in supply chains (Brandenburger and Stuart, 2007). The authors propose to divide the biform games into so-called sequential and simultaneous shapes. The proposed procedure captures these concepts; it is flexible and open to other concepts and procedures for designing sustainable supply chains.

2 Sustainable supply chain

A supply chain is a complex and dynamic supply and demand network of agents, activities, resources, technology, and information involved in moving a product or service from the initial supplier to the ultimate customer (Tayur, Ganeshan and Magazine, eds., 2012; Snyder and Shen, 2011; Harrison, Lee and Neale, 2003). A supply chain consists of several decentralized firms; decisions of these different units impact each other's performance, and thus the performance of the whole supply chain.

A supply chain is defined as a network system that consists of clusters with:

- suppliers,
- manufacturers,
- distributors,
- retailers,
- customers,

where:

- material,
- financial,
- information,
- decision

flows connect participants in both directions. Decision flows are sequences of decisions among agents (see Fiala, 2005).

Supply chain management can be divided into four phases:
- design,
- control,
- performance evaluation,
- performance improvement.

These phases are repeated during the dynamic evolution of the environment and the supply chain. The design phase of supply chains plays an important role in supply chain management. This paper focuses on modeling this design phase.

The proposed approach promotes sustainability of supply chains through the following instruments:
- multiple criteria,
- De Novo optimization,
- technology development,
- biform games,
- the concept of co-opetition.

Sustainability of supply chains is evaluated by multiple criteria:
- environmental,
- social,
- economic,
- and others.

The model contains not only three basic aspects; other criteria can be used (technological, legal, etc.). Two models were used for multiple criteria evaluation of sustainable supply chains. Multi-objective linear programming (MOLP) is a model of optimizing a given system by multiple objectives (Steuer, 1986). Multi-objective De Novo linear programming (MODNLP) is a problem for designing an optimal system by reshaping the feasible set (Zelený, 2010). This approach seeks to find a trade-off-free solution and uses only the necessary resources for this solution, limited only by budget. The technological innovations included in the model bring improvements to the desired criteria and a better utilization of available resources.

The proposed biform game models provide suitable tools for finding an equilibrium in the agent-system by combining non-cooperative and cooperative approaches. The inclusion of the concept of co-opetition enriches the model with other aspects, including considering the influence of other agents such as competitors and complementors (Min, Feiqi and Sai, 2008). The search for equilibrium in a sustainable supply chain is based on a negotiation approach. Information exchange by negotiations reduces inefficiencies and material flows and leads to reduced environmental pollution and costs.

3 Multiple criteria analysis

The first component of the proposed procedure is multiple criteria analysis (Greco, Figueira and Ehrgott, 2016). A standard approach can be used to optimize the given system and the De Novo approach to design an optimal system. Both procedures will be described. The advantages of the De Novo approach will be explained.

3.1 Optimizing given systems

In MOLP problems, it is usually impossible to optimize all objectives together in a given system. Trade-off means that one cannot increase the level of satisfaction for an objective without decreasing it for another objective. Multi--objective linear programming (MOLP) problem can be described as follows:

$$\text{“Max” } \mathbf{z} = \mathbf{Cx}$$
$$\text{s.t.} \quad \mathbf{Ax} \leq \mathbf{b},\ \mathbf{x} \geq \mathbf{0} \tag{1}$$

where **C** is a $(\bar{k}, \bar{n})$ matrix of objective coefficients, **A** is an $(\bar{m}, \bar{n})$ matrix of structural coefficients, **b** is an $\bar{m}$-vector of known resource restrictions, **x** is an $\bar{n}$-vector of decision variables. The “Max” operator is used for vector optimization. For multi-objective programming problems, the concept of efficient solutions is used (e.g. Steuer, 1986). A compromise solution is selected from the set of efficient solutions. Many methods are proposed for solving the problem. Most of the methods are based on trade-offs between objective values.

Multiple criteria supply chain model

In the next part, a multiple criteria supply chain design problem is formulated. The mathematical program determines the ideal locations for each facility and allocates the activity at each facility so that the multiple objectives are taken into account and the constraints of meeting the customer demand and the facility capacity are satisfied. The presented model of a supply chain consists of four layers with m suppliers: $S_1, S_2, \dots, S_m$, n potential producers: $P_1, P_2, \dots, P_n$, p potential distributors: $D_1, D_2, \dots, D_p$ and r customers: $C_1, C_2, \dots, C_r$.

The following notation is used:
a_i = annual supply capacity of supplier i, b_j = annual potential capacity of producer j,
w_k = annual potential capacity of distributor k, d_l = annual demand of customer l,
f_j^P = fixed cost of potential producer j, f_k^D = fixed cost of potential distributor k,

c_{ij}^S = unit transportation cost from S_i to P_j, c_{jk}^P = unit transportation cost from P_j to D_k,
c_{kl}^D = unit transportation cost from D_k to C_l, e_{ij}^S = unit pollution from S_i to P_j,
e_{jk}^P = unit pollution from P_j to D_k, e_{kl}^D = unit environmental pollution from D_k to C_l,
x_{ij}^S = number of units transported from S_i to P_j, x_{jk}^P = number of units transported from P_j to D_k, x_{kl}^D = number of units transported from D_k to C_l,
y_j^P = binary variable for build-up of the fixed capacity of producer j,
y_k^D = binary variable for build-up of the fixed capacity of distributor k.

With the above notations, the problem can be formulated as follows:

The model has two objectives: The first one expresses minimizing total costs; the second one expresses minimizing total environmental pollution.

Minimize two objectives:

$$z_1 = \sum_{j=1}^{n} f_j^P y_j^P + \sum_{k=1}^{p} f_k^D y_k^D + \sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}^S x_{ij}^S + \sum_{j=1}^{n}\sum_{k=1}^{p} c_{jk}^P x_{jk}^P + \sum_{k=1}^{p}\sum_{l=1}^{r} c_{kl}^D x_{kl}^D$$

$$z_2 = \sum_{i=1}^{m}\sum_{j=1}^{n} e_{ij}^S x_{ij}^S + \sum_{j=1}^{n}\sum_{k=1}^{p} e_{jk}^P x_{jk}^P + \sum_{k=1}^{p}\sum_{l=1}^{r} e_{kl}^D x_{kl}^D$$

subject to the following constraints:
the amount sent from the supplier to producers cannot exceed the supplier capacity:

$$\sum_{j=1}^{n} x_{ij}^S \le a_i\,, \quad i = 1, 2, ..., m$$

the amount produced by the producer cannot exceed the producer capacity:

$$\sum_{k=1}^{p} x_{jk}^P \le b_j y_j^P\,, \quad j = 1, 2, \dots, n$$

the amount shipped from the distributor should not exceed the distributor capacity:

$$\sum_{l=1}^{r} x_{kl}^D \le w_k y_k^D\,, \quad k = 1, 2, \dots, p$$

the amount shipped to the customer must equal the customer demand:

$$\sum_{k=1}^{p} x_{kl}^{D} = d_l \,, \; l = 1,2,\dots,r$$

the amount shipped out of producers cannot exceed the number of units received from suppliers:

$$\sum_{i=1}^{m} x_{ij}^{S} - \sum_{k=1}^{p} x_{jk}^{P} \geq 0, \; j = 1,2,\dots,n$$

the amount shipped out of distributors cannot exceed the quantity received from producers:

$$\sum_{j=1}^{n} x_{jk}^{P} - \sum_{l=1}^{r} x_{kl}^{D} \geq 0 \,, \; k = 1,2,\dots,p$$

binary and non-negativity constraints:

$y_j^P, y_k^D \in \{0,1\},$

$x_{ij}^S, x_{jk}^P, x_{kl}^D \geq 0, \; i = 1,2,\dots,m, \; j = 1,2,\dots,n, \; k = 1,2,\dots,p, \; l = 1,2,\dots,r$

The formulated model is a multi-objective linear programming problem (MOLP). The problem can be solved using MOLP methods.

3.2 Designing optimal systems

By using given prices of resources and the given budget the MOLP problem (1) is reformulated into the following MODNLP problem (2):

$$\text{“Max”} \quad \mathbf{z} = \mathbf{Cx}$$
$$\text{s.t.} \quad \mathbf{Ax} - \mathbf{b} \leq \mathbf{0}, \; \mathbf{pb} \leq B, \; \mathbf{x} \geq \mathbf{0} \qquad (2)$$

where **b** is an $\overline{m}$-vector of unknown resource restrictions, **p** is an $\overline{m}$-vector of resource prices, and B is the given total available budget.

From (2) follows that:

$$\mathbf{pAx} \leq \mathbf{pb} \leq B$$

Defining an n-vector of unit costs $\mathbf{v} = \mathbf{pA}$, we can rewrite the problem (2) as:

$$\text{“Max”} \quad \mathbf{z} = \mathbf{Cx}$$
$$\text{s.t.} \quad \mathbf{vx} \leq B, \; \mathbf{x} \geq \boldsymbol{0} \qquad (3)$$

Solving single objective problems:

$$\text{Max} \;\; z^{i} = \mathbf{c}^{i}\mathbf{x}, \quad i = 1,2,\dots,\overline{k}$$

$$\text{s.t.} \quad \mathbf{vx} \leq B, \mathbf{x} \geq 0 \qquad (4)$$

$\mathbf{z}^*$ is a $\bar{k}$-vector of objective values for the ideal system, concerning budget B, where the elements of the vector are values z^i obtained by solving the set of problems (4).

The problems (4) are continuous "knapsack" problems, with the solutions:

$$x_j^i = \begin{cases} 0, j \neq j_i \\ B/v_{j_i}, j = j_i \end{cases}, \text{ where } \ j_i \in \left\{ j \in (1,\ldots,n) \middle| \max_j \,(c_j^i/v_j) \right\}$$

The meta-optimum problem can be formulated as follows:

$$\begin{aligned} \text{Min} \quad & f = \mathbf{vx} \\ \text{s.t.} \quad & \mathbf{Cx} \geq \mathbf{z}^*, \mathbf{x} \geq \mathbf{0} \end{aligned} \qquad (5)$$

Solving the problem (5) provides the solution: $\mathbf{x}^*$, $B^* = \mathbf{vx}^*$, $\mathbf{b}^* = \mathbf{Ax}^*$.

The value B^* identifies the minimum budget to achieve $\mathbf{z}^*$ through solutions $\mathbf{x}^*$ and $\mathbf{b}^*$, with the given budget level $B \leq B^*$. The optimum-path ratio for achieving the best performance for a given budget B is defined as:

$$r_1 = \frac{B}{B^*}$$

The optimum-path ratio provides an effective and fast tool for the efficient optimal redesign of large-scale linear systems. The optimal system design for the budget B:

$$\mathbf{x} = r_1 \mathbf{x}^*, \ \mathbf{b} = r_1 \mathbf{b}^*, \ \mathbf{z} = r_1 \mathbf{z}^*$$

Multi-objective De Novo supply chain model

The De Novo approach can be useful in the design of the multi-criteria supply chain. Only a partial relaxation of constraints is adopted. Producer and distributor capacities are relaxed. Unit costs for capacity build-up are computed:

$p_j^P = \frac{f_j^P}{b_j}$ = cost of the unit capacity of potential producer j,

$p_k^D = \frac{f_k^D}{w_k}$ = cost of the unit capacity of potential distributor k.

Variables for build-up capacities are introduced:

u_j^P = variable for the flexible capacity of producer j,

u_k^D = variable for the flexible capacity of producer k.

The constraints for non-exceeding the producer and distributor fixed capacities are replaced by the flexible capacity constraints and the budget constraint:

$$\sum_{k=1}^{p} x_{jk} - u_j^P \leq 0, \; j = 1,2,\dots,n$$

$$\sum_{l=1}^{r} x_{kl} - u_k^D \leq 0, \; k = 1,2,\dots,p$$

$$\sum_{j=1}^{n} p_j^P u_j^P + \sum_{k=1}^{p} p_k^D u_k^D \leq B$$

The multi-objective optimization can be then seen as a dynamic process. Technological innovations bring improvements to the objectives and the better utilization of available resources. The technological innovation matrix $T = (t_{ij})$ is introduced. The elements in the structural matrix A should be reduced by technological progress.

The problem (2) is reformulated into the innovation MODNLP problem (6):

$$\text{“Max”} \quad \mathbf{z} = \mathbf{Cx}$$
$$\text{s.t.} \quad \mathbf{TAx} - \mathbf{b} \leq \mathbf{0}, \; \mathbf{pb} \leq B, \; \mathbf{x} \geq \mathbf{0} \qquad (6)$$

The De Novo approach provides a better solution with respect to multiple objectives and also with lower budget thanks to flexible capacity constraints. The capacity of supply chain members has been optimized as regards flows in the supply chain and budget.

3.3 An illustrative example

The De Novo approach was tested on a case study. A supply chain is proposed with three potential suppliers, three potential manufacturers, three potential distributors, and three customers. The chain is evaluated according to two criteria: the first one aimed at minimizing total costs and the second one, at minimizing overall environmental pollution.

Inputs for the model are as follows:
Capacities $a_i = 100$, $i = 1, 2, 3$; $b_j = 100$, $j = 1, 2, 3$;
$w_k = 100$, $k = 1, 2, 3$; $d_l = 50$, $l = 1, 2, 3$.
Fixed costs $f_1^P = 110$, $f_2^P = 100$, $f_3^P = 120$, $f_1^D = 120$,
$f_2^D = 110$, $f_3^D = 150$.

Unit transportation costs and unit pollution are shown in Table 1 and Table 2.

Table 1: Unit transportation costs

c_{ij}^S	1	2	3	c_{jk}^P	1	2	3	c_{kl}^D	1	2	3
1	5	10	6	1	7	5	9	1	8	3	10
2	8	9	7	2	6	8	4	2	6	5	4
3	3	6	8	3	5	7	9	3	7	3	5

Source: Authors.

Table 2: Unit pollution

e_{ij}^S	1	2	3	e_{jk}^P	1	2	3	e_{kl}^D	1	2	3
1	4	3	8	1	8	7	9	1	8	6	2
2	8	9	2	2	6	8	4	2	8	9	8
3	7	6	8	3	4	7	9	3	5	3	5

Source: Authors.

This model was solved by different approaches. The first two approaches minimize each criterion separately. The compromise solution is calculated by the traditional STEM interactive approach for multi-criteria problems using the De Novo approach. The following are non-zero values of the variables that express the number of units of the product shipped between each supply chain layer.

The following values are given for each problem-solving approach:

Min z_1: $x_{13}^S = 50$, $x_{31}^S = 100$, $x_{12}^P = 100$, $x_{31}^P = 50$, $x_{12}^D = 50$, $x_{21}^D = 50$, $x_{23}^D = 50$.
Min z_2: $x_{12}^S = 100$, $x_{23}^S = 50$, $x_{23}^P = 100$, $x_{31}^P = 50$, $x_{13}^D = 50$, $x_{31}^D = 50$, $x_{32}^D = 50$.
STEM: $x_{11}^S = 58.13$, $x_{23}^S = 91.87$, $x_{12}^P = 58.13$, $x_{31}^P = 91.87$, $x_{12}^D = 46.87$, $x_{13}^D =$
$= 45$, $x_{21}^D = 50$, $x_{22}^D = 3.12$, $x_{23}^D = 50$.
De Novo: $x_{23}^S = 62.86$, $x_{32}^S = 87.14$, $x_{21}^P = 10$, $x_{23}^P = 77.14$, $x_{31}^P = 62.86$, $x_{12}^D =$
$= 50$, $x_{13}^D = 22.86$, $x_{31}^D = 50$, $x_{33}^D = 27.14$.

Criteria values z_1, z_2 and budget B are compared according to these solutions. The De Novo solution is better in all values than the STEM solution. The De Novo approach provides better solutions with respect to both criteria and also with a lower budget due to flexible capacity constraints. The capacities of supply chain members have been optimized for flows in the supply chain and budget. The comparison of results is shown in Table 3.

Table 3: Comparison of solution results

	Min z_1	Min z_2	STEM	De Novo
z_1	2460	3490	3070	3000
z_2	3100	1800	2030	2000
B	460	490	460	365.71

Source: Authors.

4 Equilibrium searching by biform games

The second component of the proposed procedure is the search for equilibrium (Myerson, 1997). Most supply chains are composed of independent agents with individual interests and preferences. Biform games are used for searching for an equilibrium in sustainable supply chains. A biform game is a combination of non-cooperative and cooperative games for searching for an equilibrium. The authors propose to divide biform games into sequential and simultaneous forms.

4.1 Sequential biform games

A sequential biform game (Fiala, 2016a) is a two-stage game: in the first stage, players choose their strategies in a non-cooperative way, thus forming the second stage of the game, in which the players cooperate. First, suppliers make initial proposals and take decisions. This stage is analyzed using a non--cooperative game theory approach. The players search for the Nash equilibrium by solving the next problem.

An n-player non-cooperative game in the normal form is a collection

$$\{N = \{1,2, \dots, n\};\ X_1, X_2, \dots, X_n;\ \pi_1(x_1, x_2, \dots, x_n), \dots, \pi_n(x_1, x_2, \dots, x_n)\ \} \quad (7)$$

where N is a set of n players; X_i, $i = 1, 2, \dots, n$, is a set of strategies for player i; $\pi_i(x_1, x_2, \dots, x_n)$, $i = 1, 2, \dots, n$, is a pay-off function for player i, defined on a Cartesian product of n sets X_i, $i = 1, 2, \dots, n$.

Decisions of players other than player i are summarized by the vector:

$$\mathbf{x}_{-i} = (x_1, \dots, x_{i-1}, x_{i+1} \dots, x_n) \quad (8)$$

A vector of decisions $(x_1^0, x_2^0, \dots, x_n^0)$ is the Nash equilibrium of the game if:

$$x_i^0(\mathbf{x}_{-i}^0) = \text{argmax}_{x_i}\, \pi_i(x_i, \mathbf{x}_{-i}) \forall i = 1,2, \dots, n \quad (9)$$

The Nash equilibrium is a set of decisions from which no player can improve the value of his pay-off function by unilaterally deviating from it.

Next, players negotiate among themselves. In this stage, a cooperative game theory is applied to characterize the outcome of negotiation among the players over how to distribute the total surplus. Each player's share of the total surplus is the product of its added value and its relative negotiation power. Distribution of the total surplus to players can be given by Shapley values (14).

The cooperative game theory looks at the set of possible outcomes, studies what the players can achieve, what coalitions they will form, how the coalitions that do form divide the outcome, and whether the outcomes are stable and robust.

The maximal combined output is achieved by solving the following problem:

$$\mathbf{x^0} = \text{argmax}_{\mathbf{x}} \sum_{i=1}^{n} \pi_i(x_i) \tag{10}$$

When modeling cooperative games it is advantageous to switch from the normal form to the characteristic function form. The characteristic function of the game with the set N of n players is a function $v(S)$ that is defined for all subsets $S \subseteq N$ (i.e. for all coalitions) and which assigns to each subset S a value $v(S)$ with the following characteristics:

$$v(\emptyset) = 0,\ v(S_1 \cup S_2) \geq v(S_1) + v(S_2) \tag{11}$$

where S_1, S_2 are disjoint subsets of N. The pair (N, v) is called a cooperative game of n players in the characteristic function form.

Allocation mechanisms are based on different approaches, such as Shapley values, contracts, auctions, negotiations, etc. A particular allocation policy, introduced by Shapley (1953), has been shown to possess the best properties in terms of balance and fairness (Mahjoub and Hennet, 2014). The so called Shapley vector is defined as:

$$\mathbf{h} = (h_1, h_2, \ldots, h_n) \tag{12}$$

where the individual components (Shapley values) indicate the mean marginal contribution of i-th player to all coalitions, of which she/he may be a member. Player contribution to the coalition S is calculated by the formula:

$$v(S) - v(S - \{i\}) \tag{13}$$

The Shapley value for the i-th player is calculated as a weighted sum of marginal contributions according to the formula:

$$h_i = \sum_S \left\{ \frac{(|S|-1)\,!\,(n-|S|)\,!}{n!} . [v(S) - v(S - \{i\})] \right\} \tag{14}$$

where the number of coalition members is denoted by $|S|$ and the summation runs over all coalitions $i \in S$.

4.2 Simultaneous biform games

The simultaneous biform game is a one-stage model where combinations of concepts for cooperative and non-cooperative games are applied. The combinations will be changed according to situations in problems. At this stage, multi-round negotiations take place. The first problem is a classification of situations. The situations are affected by:

- which players can cooperate,
- to what scope they can cooperate.

If all players can cooperate fully, a standard cooperative model (10) can be used with subsequent distribution of the result according to the Shapley values (14). If no one can cooperate even in a partial context, a standard non--cooperative model (9) is used.

The general simultaneous biform games are based on a negotiation process with multiple criteria (see Fiala, 1999). The negotiation concept is based on the assumption that each negotiating subject decides under pressure of objective context. The scope of cooperation is dynamic and changes over time. The effects of pressures are reflected in restrictive conditions.

Negotiation model

Suppose we have n negotiation participants. Denote by X the decision space for the negotiating process. The elements of this space are decisions $\mathbf{x} \in X$, which are vectors whose components represent the parameters of the decision. A consensus decision $\mathbf{x}^*$ should be chosen from the decision space X. The traditional game concepts assume a fixed structure and fixed sets of strategies. The sets of strategies are assumed to be dynamic $X_i(t)$, for players $i = 1, 2, \ldots, n$, depending on discrete time periods $t = 0, 1, 2, \ldots, T$. A dynamic evaluations of strategies will be also considered.

Each participant evaluates decisions using multiple criteria and compares the decisions with the target values. Multiple criteria analysis from the first component of the proposed procedure is applied. The analysis is based on the De Novo approach. The criteria are in the form of criteria functions, and all participants want to optimize their values. Each participant in negotiations may have a different number of criteria. Denote by $\mathbf{f}^1(\mathbf{x}), \mathbf{f}^2(\mathbf{x}), \ldots, \mathbf{f}^n(\mathbf{x})$ the vector criteria functions that transform decision $\mathbf{x}$ into the vectors of target values $\mathbf{y}^1$, $\mathbf{y}^2, \ldots, \mathbf{y}^n$ of the target spaces of participants $Y^1, Y^2, \ldots, Y^n$. However, the participant tries to not reveal his interests and his strategy to all players. One's own negotiations and exchanges of information between the participants occur in the decision space.

The negotiation process can be represented by dynamic models. Individual time moments correspond to rounds of negotiation, in which the current joint problem representation shows the degree of consensus or conflict between the parties in the negotiations. The development of problem representations can be described as a search for consensus through the exchange of information between the participants. The negotiation process takes place at discrete time points $t = 0, 1, 2, \ldots, T$. At time T the process is completed by finding a trajectory to time horizon T. The negotiation process can be modeled as a gradual change over time of the negotiation space, which is a subset of the decision space containing acceptable decisions of participants in the negotiation time until a single-element negotiation space is reached.

For each participant, a set of acceptable decisions is formulated, which is a set of decisions that are permissible and acceptable in terms of the required aspiration levels of criteria functions. The aspiration levels $\mathbf{b}^i(t)$, $i = 1, 2, \ldots, n$, $t = 0, 1, 2, \ldots, T$, of criteria functions represent opportunities for added values. At the beginning of the negotiations it has the form:

$$X_i(0) = \{\mathbf{x}; \mathbf{x} \in X, \mathbf{f}^i(\mathbf{x}) \leq \mathbf{b}^i(0)\}, i = 1, 2, \ldots, n \tag{15}$$

Then the negotiation space is defined at the beginning of the negotiations as an intersection of sets of acceptable decisions of all participants in the negotiations:

$$X_0(0) = \bigcap_{i=1}^{r} X_i(0) \tag{16}$$

If the negotiation space $X_0(0)$ is a single-element set, the negotiation problem is trivial. This element is the consensus. The negotiation problem becomes interesting when the negotiation space is empty or contains more than one element. In the former case, the participants have to reduce some or all of the aspiration levels of criteria functions, but the participants are involved more in the reduction of certain criteria and less in the reduction of others. In the latter case, each element of the negotiation space is acceptable to all participants, but different elements are evaluated differently, because they meet the criteria of the participants on different levels. Further negotiations are conducted at time points $t = 1, 2, \ldots, T$, and should lead to a consensus decision, to achieve the single-element negotiation space $X_0(t)$.

5 Conclusion

This paper proposes and discusses a procedure for designing sustainable supply chains. This procedure takes into account multiple agents in the system and multiple evaluation criteria to solve the design problem. The procedure is flexible enough: it is, in general, open to other types of criteria and other types of agents. The De Novo approach is applied to the multiple-criteria supply chain design problem and provides a better solution than traditional approaches applied on fixed constraints. The approach is not oriented towards the optimization of some criteria, but seeks a trade-off-free solution by reformulating resource constraints only limited by the budget. The resources are saved by drawing only in the amount necessary to reach a balanced solution.

The multi-criteria approach is applied to the search for equilibrium for interested agents using biform game procedures. Biform games combine cooperative and non-cooperative approaches of game theory. The authors propose to divide biform games into sequential and simultaneous forms and to use a negotiation model for simultaneous games. The concept of co-opetition brings other aspects into design of sustainable supply chains, including other agents, such as competitors and complementors.

The procedure is open to be complemented by other concepts and approaches: for example, allocation mechanisms can be based on different approaches, such as Shapley values, contracts (Fiala, 2016a), auctions (Fiala, 2016b), and negotiations (Fiala, 1999). A combination of these concepts and approaches can be a powerful instrument for designing supply chains. The complex structure of the model can be captured using graph theory in a system consisting of an environment in which agents (nodes) create interactions (edges) and flows directed to meet the global demand. Some future research trends of sustainable supply chain management have been suggested. The proposed procedure tries to capture, at least partially, some of these trends.

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