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ORIGINAL RESEARCH

Mathematical programming-based methodology for the evaluation of supply chain collaborative planning scenarios

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Abstract

Nowadays, supply chain (SC) decentralised decision making is the most usual situation in SC operations planning. In this context, different companies can collaboratively plan to achieve a certain level of individual and SC performance. However in many cases, there is reluctance to collaborate because it is not known a priori which benefits will be reported. This paper aims to develop a mathematical programming-based methodology for the evaluation of different supply chain collaborative planning scenarios (MPM-SC-CP). It is assumed that different SC decision centres (DCs) make decisions based on mixed and integer linear programming models. Two main inputs feed the proposed MPM-SC-CP, a framework and associated methodology that support the integrated conceptual and analytical modeling of the SC-CP process in which several DCs make decisions according to spatio-temporal integration. Finally, an application to a real ceramic SC was conducted.

Keywords Collaborative planning · Methodology · Mathematical models · Scenarios evaluation · Ceramic sector

1 Introduction

The relevance of supply chain (SC) management (SCM) for the firms in our globalised world has been introduced and described at length in the literature (Lambert & Cooper, 2000; Min & Zhou, 2002). This relevance is highlighted when disruptions occur, such as port strikes, natural disasters, product safety problems, supplier bankruptcy, terrorist attacks or today's

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pandemic situation. This reveals the critical importance of SCM nowadays (Craighead et al., 2020).

SCM includes strategic, tactical and operational decisions, all of which are relevant for the organisations that participate in the chain and, consequently, for their final customers. These SCM decisions comprise many business processes (from the purchase of raw materials to the final consumption of products) that deal with diverse and complex contexts for different purposes. The Supply Chain Council proposed a reference model that includes six distinct major processes (plan, source, make, deliver, return, enable) in the Supply Chain Operations Reference (SCOR) model (ASCM, 2022).

This paper focuses on the major process 'plan', and specifically on the collaborative perspective in operations planning. A new scenario has arisen in this century in which the processes, particularly SC operations planning, traditionally undertaken in an enterprise are being adapted to be collaboratively designed and executed by different firms operating in the same network or SC (Lejeune & Yakova, 2005). Collaborative planning can be defined as a joint decision-making process for aligning individual SC members' plans to achieve a certain degree of coordination (Stadler, 2009).

This collaborative process has been studied in the last two decades as a consequence of an increasing need to adapt operations planning processes to collaborative contexts, in which different geographically dispersed entities with their own characteristics and objectives, which are sometimes reluctant to share certain information, are willing to collaboratively plan to make more profits.

Many works have addressed the importance of its modelling by highlighting its decision flows and shared information (Alarcón et al., 2007; de Freitas, de Oliveira and Alcantara 2019; Hernández et al., 2014b; Stadler, 2009). Of these models, analytical ones based on mathematical programming have been especially relevant as a tool to optimise the performance of not only each individual entity, but also of the whole collaborative process.

Although it is true that mathematical programming models have been used mainly for centralised decision making in the SC operations planning context (Bernin et al. 2002; Timpe & Kallrath, 2000; Bajgiran et al., 2016a, 2016b), more research works about decentralized models have been published in the last decade. Nowadays, SC decentralised decision making, where different decision units have to be tactically and operationally coordinated to achieve a desired SC performance level, is the most common situation (Acar & Atadeniz, 2015; Ouhimmoua et al. 2008; Rius-Sorolla et al., 2020; Thomas, et al., 2015a, 2015b; Zoghlami et al., 2016).

Nevertheless, the literature review shows that works addressing methodologies to facilitate the integrated modeling of the SC-CP process are lacking, particularly when based on mathematical programming. In most cases, only isolated monolithic models with centralised approaches are applied to cover a wide range of SC configurations but, as no methodology justifies this centralised modelling, they are often far-removed from reality. The SC organisational structure, made up of different entities where decisions and information are difficult to centralise, is ignored. In other cases, more realistic decentralised models are used and address the coordination mechanisms between different SC decision entities, but mostly lack the complexity that the business reality requires. Studies that address spatio-temporal integration for any decision scenario (centralised or decentralised/distributed) are lacking, and the few existing ones are valid only for specific situations, and do not cover the necessary and simultaneous integration that may emerge during the SC-CP process.

As detailed in below, three shortcomings derive from above and justify this paper.

Firstly, works that precisely link the coordination mechanisms of the SC collaborative process with its mathematical-based programming modeling are lacking. This means that these mathematical models do not fully capture the real complexity. In the majority of quantitative papers, the analysis process prior to model formulation is omitted, which makes the understanding of these models difficult.

Secondly, but closely linked, the spatio-temporal interactions of these mechanisms are not clearly identified and are not simultaneously addressed in most cases.

Finally, the flexibility of these coordination mechanisms required to deal with changes in the collaborative scheme is not sufficiently approached because the way mathematical models are constructed makes their transferability difficult to other collaborative schemes if some changes occur. Hence their evaluation is not anf easy task.

The above, plus many companies' reluctance to collaboratively plan due to the uncertain benefits (i.e., collaboration) that they will gain and how these benefits will be shared all justify this paper, which proposes a mathematical programming-based methodology to evaluate SC collaborative planning scenarios (MPM-SC-CP).

The remainder of this paper is arranged as follows. The literature review is presented in Sect. 2. Section 3 proposes an MPM-SC-CP and describes its main inputs. Section 4 presents an MPM-SC-CP application to a real case of a ceramic SC. Section 5 includes the discussion of the results. Finally, Sect. 6 draws some conclusions and offers future research lines.

2 Literature review

Nowadays, SC collaboration: (i) is applied to different industrial sectors (i.e., ceramic SC (Alemany et al., 2011), soft drinks SC (Ramanathan, 2012) Petrolium, (Fernandes 2016), agribusiness SC (Bo et al., 2020), mining (Shi and Erh, 2019) or construction (Elmughrabi, 2020); (ii) comprises various approaches (i.e., QR—Quick Response- (Choi & Sethi, 2010), VMI – Vendor-Managed Inventory (Nimmy et al., 2019), CPFR—Collaborative Planning, Forecasting and Replenishment (Hollman et al. 2015; Panahifar, 2015), or is based on mathematical models with shared information (Pibernik, 2011; Nimmy et al., 2019); (iii) focuses on one or more specific business processes in the set of processes developed in the SC (i.e., sales forecast (Önkal et al., 2012), lot-sizing problems (Eslikizi et al., 2015; Taghipour & Frayret, 2013), transportation (Fernandes et al., 2016) or for the I4.0 context (Ivanov et al., 2021).

Some of the benefits of SC collaboration are: effective resources allocation due to the improved visibility of global capacity (Acar & Atadeniz, 2015), benefits sharing (Pibernik et al., 2011), the fairness of revenue sharing (Taghipour & Frayret, 2013), more profits compared to those made from a non-collaborative perspective (Hernandez et al., 2014c), a higher end-customer service level (Hernandez et al., 2014a; Acar & Atadeniz, 2015) or a minimised bullwhip effect (Nimmy et al., 2019).

But SC collaboration implies the definition of some coordination mechanisms which not only include joint decision making, but also information sharing, information technology and contracts (Kanda & Deshmukh, 2008).

Collaboration is achieved by exchanging relevant information (Almeida et al., 2012). Sharing this information among SC members is the key issue in the collaborative planning process (Hernandez, 2014a) which is, in turn, collected in a centralised repository (centralised decision models) to store and extract knowledge information to facilitate the decision-making process (Kuik & Diong, 2019), or each node manages its own information repository from a decentralised perspective (Hernandez, 2104b).

The role of information technology is fundamental for collaborative planning. Ivanov et al. (2021) presents interactions of production planning and control with technologies classified as infrastructure, engineering technology, data technology and communication technology. Here consolidated technologies are used, such as EDI, ERP or RFID (Choi & Sethi, 2010), as well as emerging information technologies, such as the Internet of Things (IoT), cloud computing, web services, big data, artificial intelligence, or sensor and tabs for I4.0 contexts, that offer real-time information to gain practical insights and to assist in decision making (Bueno et al., 2020; Kuik & Diong, 2019).

SC members also coordinate by using contracts to better manage supplier–buyer relationships and risk management. Contracts specify the parameters of relationships, such as price, quantity, time and quality (Kanda & Deshmukh, 2008), but also a framework for collaborative decision consequences like revenue-sharing contracts (Yang et al., 2011). These SC contracts do not entail complicated contracting mechanisms according to Belavina and Girotra (2012), but some proposals consider the contract to be an essential element for other coordination mechanisms; for example, transfer information of contracts to decision models (Bajgiran et al., 2016a, 2016b; Wenzel et al., 2016a). This latter approach is not widely used, and very few papers in the field of mathematical programming for collaborative SCs include such contracts as a remarkable element.

However, the components of coordination mechanisms are not coincident in the different proposals. Parahifar et al. (2015) defines implementation enablers for successful collaboration schemes and includes a high level of trust and the importance of information. Hollman et al. (2015) identifies four propositions: trust, information sharing, ICT (information and communication technologies) and contextual variables. Alemany et al. (2010) defines the structural elements to characterise coordination mechanisms in a collaborative process. These elements are the number of decision makers, the collaboration level, interdependence relationships' nature, interdependence relationships' type, number of coordination mechanisms, exchanged information, information processing, decision sequence characteristics and the stopping criteria of the coordination mechanism. Lehoux et al. (2014) focuses on information sharing, collaborative approaches and negotiation processes as a means to synchronise activities between partners.

The coordination mechanisms in the collaborative planning process include the previously indicated components. However, implementing these mechanisms is not trivial and many factors must be taken into account by all the collaborative SC members. Cuenca et al. (2013) proposes a maturity model as a tool to gain a better understanding of organisations' situation by helping them to find the best way for change toward a collaborative context. Hernandez et al. (2009) and Pérez-Perales et al. (2016) present a methodology that supports a collaborative planning process, although it is limited to a multi-agent system and the decision view, respectively.

An extense literature about coordination mechanisms using mathematical programming exist. A brief summary is given based on the works of Alemany et al. (2011) and Rius et al. (2020).

Two types of coordination may be distinguished. First, that one which implies the coordination of decisions across different decision-making levels (strategic, tactical and operational), also known as temporal integration. Secondly, that one regarding the coordination of decision making across the company's various functions (e.g., purchasing, manufacturing, distribution and sales), or across various geographically distributed organisations (e.g., suppliers, plants and retailers), also known as spatial integration.

Two different visions for temporal integration are used: the hierarchical planning of the levels and their simultaneous planning.

The hierarchical vision splits the problem into two subproblems (e.g., tactical and operational). One of the main advantages concerns to the compatibility with the organizational structure of the company and consistency among various planning activities in the different levels of organization's hierarchy. Infeasibility and suboptimality among the decisions made at the different hierarchical levels are among the main obstacles.

Although there is a large number of research works that report single company hierarchical applications (Hax & Meal, 2009; Bitran et al., 1981; Erscheler et al. 1986) not many report the hierarchical approach in supply chain contexts (Ozdamar & Yazgac, 1999; Vicens et al., 2001).

On the other hand planning models that deal with all decisions simultaneously. They use to be complex models whose optimality is just guaranteed in a few practical cases and with excessively high computational times. Besides, these models do not respond to the hierarchical structure of many companies, since their monolithic approach does not allow the interactions between those responsibles of each level of the hierarchy (Bitran & Tirupati, 1993; Gupta & Magnusson, 2005; Kovacs et al. 2009).

Regarding the spatial integration, two different visions are also used: the centralized and the decentralised (distributed).

Centralised mathematical programming models have extensively been proposed in the literature for coordinating the materials flow at both the tactical (planning) and the operational levels (scheduling). Special relevance to those models based on mixed and integer linear programming (MILP) applied to different SC physical configurations, ranging from two-stages (Lavoie & Abdul-Nour, 2003; Timpe & Kallrath, 2000) to multi-stage (Kreipl & Pinedo, 2004; Lin & Chen, 2004; Spitter et al., 2005). At the same time, most of them include production and distribution functions and consider various members in one or all the stages.

The decentralized/distributed approach focuses on how to ensure the coordination or alignment of different entities in a supply chain that are not fully controlled under a single authority. Each independent entity has its own objective function which is subject to its constraints and is not willing to reveal its own confidential information to others. To manage these interdependence relationships, it is necessary to define mechanisms that are capable of coordinating the decisions made about the production, inventory and transport as well as the exchanged information.

Although literature about decentralised/distributed decision-making is less extensive compared with the centralized, different problem scenarios with specific assumptions have been addressed as well as mathematical programming models and solution techniques.

According to Rius et al. (2020), some main characteristics determine the type of decentralized/distributed scenario:

First, the type of mathematical programming model used to coordinate. A significant quantity of models are based on MILP (Walter et al. 2008; Thomas et al., 2015a, 2015b; Zoghlami et al., 2016). Other types of models, such as linear programming (Lu et al., 2012), quadratic programming (Wenzel et al., 2016a) or non-linear programming (Zhou et al., 2022) have not been used as much in comparison with MILP´s.

Secondly, the type of relationship and objectives of the coordination mechanism. It stablishes how trustful is the relationship as well as the purpose of the coordination mechanism.

Regarding trust, in most of the works, team behaviour, where the information is not used opportunistically, is assumed (Albretch and Stadtler, 2015; Wenzel et al., 2016b). There are few studies on the consequences of a possible opportunistic behaviour (Pittman et al., 2007).

Regarding the purpose of the coordination, in some cases it is just sought to improve non-coordinated scenarios by achieving a better alignment of materials flows. This is typical in hierarchical systems where no compensations or renegotiations exist (Reiss & Buer, 2014). In other cases, the mechanisms seek to get closer to the optimal global results, knowing that although some of the entities can obtain worse results they will be rewarded or compensated. (Qu et al., 2015). Finally, some coordination mechanisms just aim to obtain a fair solution, sometimes far from the global optimum (Tang et al., 2016).

Third, the type of exchange information. It refers to what information is shared to reach the collaboration and which one is not disclosed.

At a tactical level, most of the studies assume that decentralized entities share insensitive information such as order proposals jointly with internal prices (Dudek and Stadtler, 2007; Lehoux et al., 2010; Bajgiran et al., 2016a, 2016b) as well as incentive schemes that align the decentralized objectives with the system-wide objective. This decentralized scheme allows the different entities to be coordinated and generate new improved proposals. On the other hand, sensitive information, such as local costs (Homberger et al., 2015) or to a lesser extent local capacity (Lau et al., 2011), at a detailed level, is usually hidden.

The last characteristic regards to the type of coordination mechanisms used. Many of the works have used the Lagrange multiplier (Wenzel et al., 2016b) or some of its extensions such as Dantzing-Wolf (Mason & Villalobos, 2015) or Benders methods (Behnamian, 2014). These methods tend to the optimal solution of the system.

Others coordination mechanisms are based on meta-heuristics, such as variable neighbourhood search (Homberger et al., 2015), ant colony, or simulated annealing (Eslikizi et al., 2015) that achieve better coordination according to some pre-defined rules but generating suboptimal solutions in most of the cases.

Hierarchical based coordination mechanisms are also extensively reported in the literature. This simple method gives better results than non-coordination, where suppliers must make forecasts of demand according to historical or other data. The hierarchical coordination mechanism can be initiated by upstream or downstream proposals (Simpson & Erenguc, 2001), with counter-proposals (Gaudreault et al., 2010), and with negotiations (Barbarosoglu & Ozgur, 1999). Anticipated information plays in important role in all these cases (Schneeweiss et al., 2004) as well as the consideration of compensations or discounts between the different entities (Kovács et al., 2013) in order to reach better global solutions.

Finally it is important to remark that many of the studies assume the presence of a central independent authority or mediator, specially in those contexts where the coordinated entities do not belong to the same organization and are not willing to disclose relevant information (Zaman et al., 2017). This mediator will collect the necessary information from the individual entities to ensure some synchronization through the supply chain previous to the negotiation phases.

From the above review, it can be said that the conditions and justification for using the centralised approach is not explicitly described in most of these works. It is taken for granted that several independent organizations agree in reaching a global objective and are willing to disclose their own confidential information with others.

Although decentralizated/distributed approaches cope with this previous assumption, the SCs addressed in the majority of the works do not represent the complexity of the business reality. Most of the reviewed models are developed at a specific planning level (tactical or operational) where the different entities aim to reach a global common goal (in the majority of the cases looking for a near global optimal solution) and where no oportunistic behaviour exists. Additionally, the vast majority has used mechanisms with the requirement of a mediator and have not been applied in rolling horizons. Besides, only a few SC mathematical programming models have simultaneously considered temporal and spatial integrations (Ozdamar & Yazgac, 1999; Schneeweiss et al., 2004).

In light of all this, a mathematical programming-based methodology for the evaluation of SC collaborative planning scenarios (MPM-SC-CP) is proposed.

Firstly, the MPM-SC-CP aims to facilitate and guide final users to develop the integrated mathematical programming modelling of the current SC-CP process in which several decision centers (DCs) make decisions under temporal and spatial integration. Secondly, it indicates how to execute it to evaluate its performance. Finally, and highly linked with the previous steps, MPM-SC-CP can be used for the evaluation of supply chain collaborative planning scenarios that will affect more or less profoundly the SC-CP process and hence the possibility of knowing in advance the profits or costs that can be derived.

At this point, it must be highlighted that although different mathematical modelling approaches could be used, mixed integer linear programming (MILP) has been chosen to assist the DCs in making their decisions. As described in this section, coordination within MILP models has been widely used in the literature for system analysis and optimization (Timpe & Kallrath, 2000; Lavoie & Abdul-Nour, 2003; Kreipl & Pinedo, 2004; Lin & Chen, 2004; Spitter et al., 2005; Walter et al. 2008; Thomas et al., 2015a, 2015b; Zoghlami et al., 2016) as it presents a flexible and powerful method for solving large, complex problems such as those derived from SC contexts, where linearity may be assumed. Likewise MILP models have been used in the last two decades in the industry in the form of Advance Planning Systems (APSs) incorporated to Enterprise Resources Planning (ERPs) systems. APSs have become essential to provide adequate coordination in SC where temporal and spatial hierarchies exist (Stadler, 2009).

Moreover these MILP models have proved to be relatively easy to be formulated and flexible to be adapted to the analytical reference model addressed in the next section, which is one of the main pillars of the proposed MPM-SC-CP.

In the next section, the steps of the proposed MPM-SC-CP are described after briefly reviewing the main inputs that feed it.

3 Mathematical programming-based methodology for the evaluation of supply chain collaborative planning scenarios

3.1 Baseline

The framework for the analytical modelling of the SC-CP-Process (Pérez-Perales & Alemany, 2015; Pérez-Perales, et al., 2012), and the methodology for the (conceptual) modelling of the SC-CP-Process (Pérez-Perales, Lario & Alemany, 2008; Pérez-Perales, et al., 2016), are the basis of this proposal.

The main objective of the framework is to help to facilitate and guide those responsible for the SC-CP process in the task of modelling specific situations. It provides the corresponding (conceptual and analytical) concepts in an organised manner so that all the important aspects that influence the planning process are taken into account during the modelling procedure. This framework integrates four different modelling views: physical, organisation, decision and information, as well as the relations among them. This facilitates the development of integrated models of the SC CP process, and leads to more realistic and versatile models that can be applied to any complex SC. It also addresses the definition of different decision centres (DCs) at two decision levels: tactical and operational. At each level, decision making may be centralised (one DC) or distributed (several DCs). These DCs are subject to two

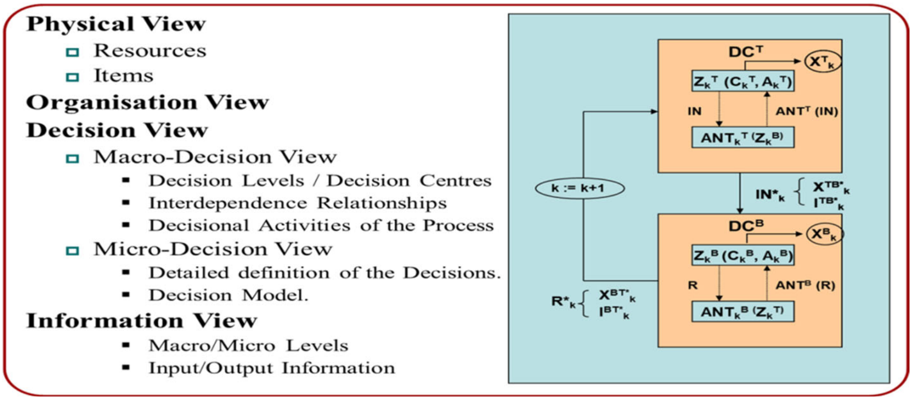


Fig. 1 Framework for the analytical modelling of the SC-CP-Process (adapted from Pérez-Perales et al., 2012)

interdependence relation types: temporal (between the DCs belonging to different decision levels) and spatial (between the DCs belonging to the same decision level).

Figure 1 shows the joint decision process (temporal or spatial) between two DCs where some interdependence interactions take place. DC^T, that is, the top DC that initialises the joint decision process, obtains a tactical or operational plan ($X_k{}^T$) and transmits an instruction (IN_k) to the bottom DC, that is, DC^B. This IN_k includes global variables ($X_k{}^{TB}$) and global information ($I_k{}^{TB}$). Then DC^B also obtains a tactical or operational plan ($X_k{}^B$) and transmits a reaction (R_k) to DC^T. In the most general case, several cycles (k) between DC^T and DC^B can occur until a plan is agreed. It is noteworthy that both DC^T and DC^B in collaborative planning scenarios can respectively anticipate (ANT) some relevant aspects of DC^B and DC^T to improve this joint decision process.

This framework leads to the definition of a reference analytical model (Fig. 2) for CP contexts for a generic DC^M. This $Z_k{}^M$ model includes not only local aspects, but also interdependence ones due to its relationships with other DCs. Hence this reference model comprises:

- A support structure composed of decision variables ($X_k{}^M$) and input information ($Ii_k.{}^M$)
- A main structure composed of the criterion ($C_k{}^M$) and a decision field ($A_k.{}^M$)

The solution of $Z_k{}^M$ aims to assign a value to $X_k{}^M$ that provides a certain accepted value of the $C_k{}^M$ subject to the different constraints expressed in $A_k{}^M$. Finally, after solving $Z_k{}^M$, some output information $Io_k{}^M$ is generated.

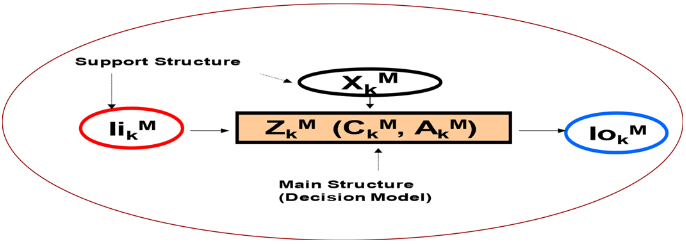


Fig. 2 Reference Analytical Model (adapted from Pérez-Perales et al., 2012)

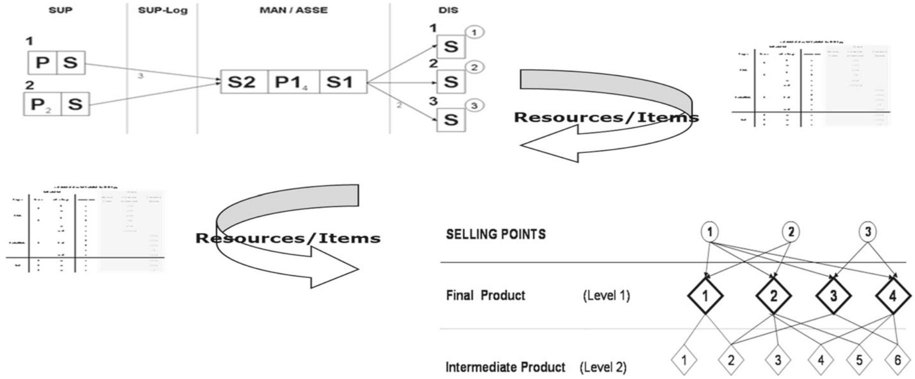


Fig. 3 SC physical view

The methodology for the (conceptual) modelling of the SC-CP-Process aims to indicate all the steps to follow to obtain an integrated model of the SC CP process in which all the decision activities (DA), execution order and exchanged information due to their relations are described.

This methodology comprises three blocks:

Firstly, the SC is characterised from a physical point of view by addressing the resources and items about which the collaborative planning process is undertaken, as well as their relations (Fig. 3).

SC resources include the nodes that belong to different stages: suppliers (SUP), suppliers-logistics: (SUP-Log), manufacturing/assembly (MAN/ASSE) and distribution (DIS). Moreover, some transformation activities are performed in the SC, with some in nodes (production-P and storage-S) and others in arches (transport). Finally, some points of sale (circles) are allocated. SC items include final products, whose demand is allocated to points of sale, and intermediate products that form part of its bill of materials (components, raw materials, etc.).

As pointed out later, the physical view (resources and items) is considered at a lesser or higher degree of aggregation depending on the decision level (tactical or operational).

Secondly, the organisation view is defined as an intermediate step between the physical and decision views. Resources may belong to different entrepreneurial organisations, and can strongly influence the decision view. Figure 4 depicts the decision view (at a macrolevel) and includes two decision levels (tactical and operational), where the different DCs that are responsible for the decision making of one transformation activity or several (production, storage, transport) are allocated.

Thirdly, and from the macrodecision view, an SC-CP model is obtained from the interdependent relations between the different DCs and a series of rules (Fig. 5). This SC-CP model is composed of a set of DA with a certain execution sequence, along with the information exchanged between them. DA are executed by the specific DCs placed at the tactical (TDL) and operational decision levels (ODL).

Finally, the information view (at a macrolevel) that integrates the other views and collects the necessary information to support the CP process is defined.

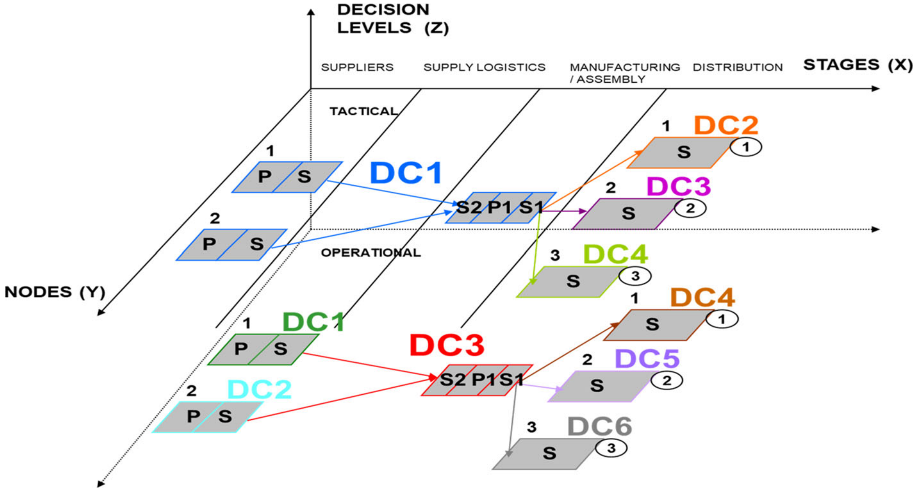


Fig. 4 SC decision view (at a macrolevel)

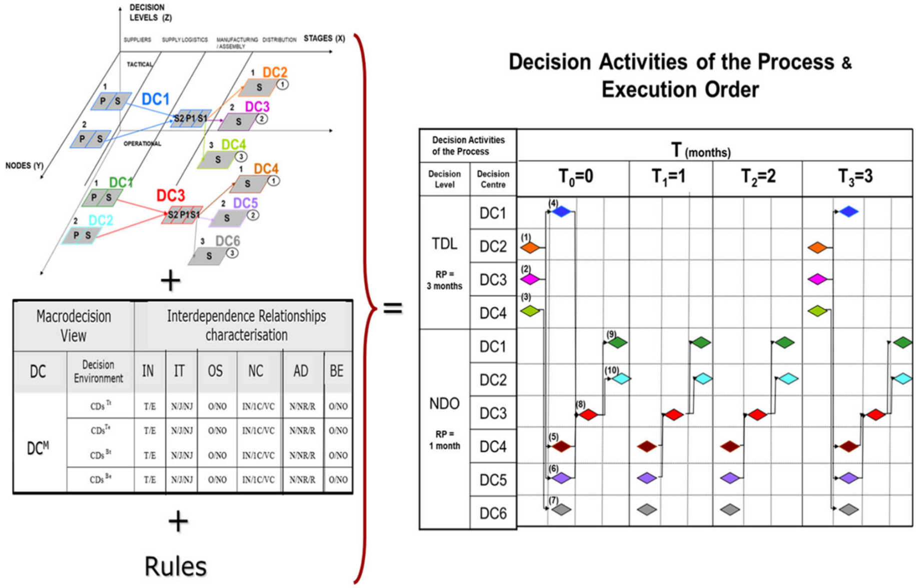


Fig. 5 Obtaining the SC-CP process

3.2 Methodology proposal

The MPM-SC-CP scenarios comprise two main blocks (Fig. 6):

1. MPM-SC-CP_Block 1: MILP Modelling the SC-CP process
2. MPM-SC-CP_Block 2: MILP Solution and Evaluation of the SC-CP process

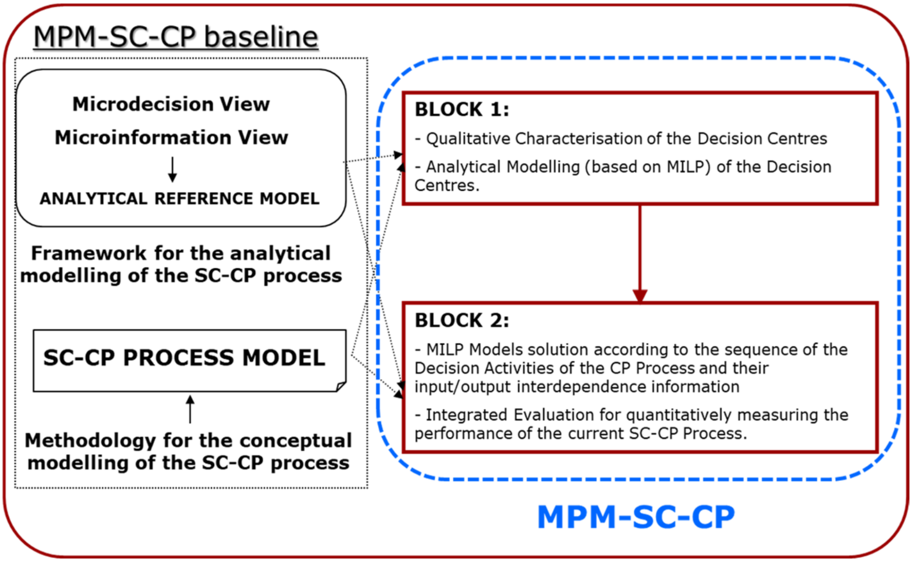


Fig. 6 A mathematical programming-based methodology for the evaluation of supply chain collaborative planning scenarios (MPM-SC-CP)

3.2.1 MPM-SC-CP_Block 1: MILP modelling the SC-CP process

Block 1 describes the steps to be followed by any generic DC associated with any of the DA previously identified in the modelling of the SC-CP Process to develop an MILP model.

The formulation of these MILP models relies on all the aspects addressed within the framework for the analytical modelling of the SC-CP process (physical, organisation, decision and information views) and, more particularly, the analytical reference model.

The top of Fig. 7 shows the analytical reference model of a generic DC^{M} subject to interdependence interactions with different DCs belonging to its decision environment. In the most general case, a generic DC can interact with top (T) or bottom (B) DCs due to temporal (t) or spatial (e) relationships (DC^{Tt}, DC^{Te}, DC^{Bt} and DC^{Be}). Its main structure, that is, model Z_k^{M} itself, is composed of C_k^{M} and A_k^{M}, and comprises either local (C_k^{MM} and A_k^{MM}) or interdependence components (C_k^{MTt}, C_k^{MTe}, C_k^{MBt}, C_k^{MBe}, A_k^{MTt}, A_k^{MTe}, A_k^{MBt}, A_k^{MBe}). The same occurs with the support structure; that is, X_k^{M} and Ii_k^{M}. For example, Ii_k^{M} encompasses the local (Ii_{lk}^{M}) and interdependence (Ii_{ik}^{M}) components, where the origin of the latter differs and comes from either DC^{T} (Ii_k^{TM}) or DC^{B} (Ii_k^{BM}) and, therefore, the types of interdependence interactions to be considered (IN, R or ANT). Analogously, some of the generated Io_k^{M}, that is, the final decisions (tactical or operational plan), are locally implemented and others are transmitted to DC^{B} or DC^{T} by an IN or R, respectively.

At the bottom of Fig. 7 a mathematical programming model (based on MILP) is developed for each DC that is, in turn, responsible for executing each decision activity identified in the SC-CP process. All the aspects collected in the different framework views, and more particularly the above analytical reference model, will determine this MILP model.

The following premises are assumed in Block 1:

- The analytical models defined for each DC are deterministic and based on MILP

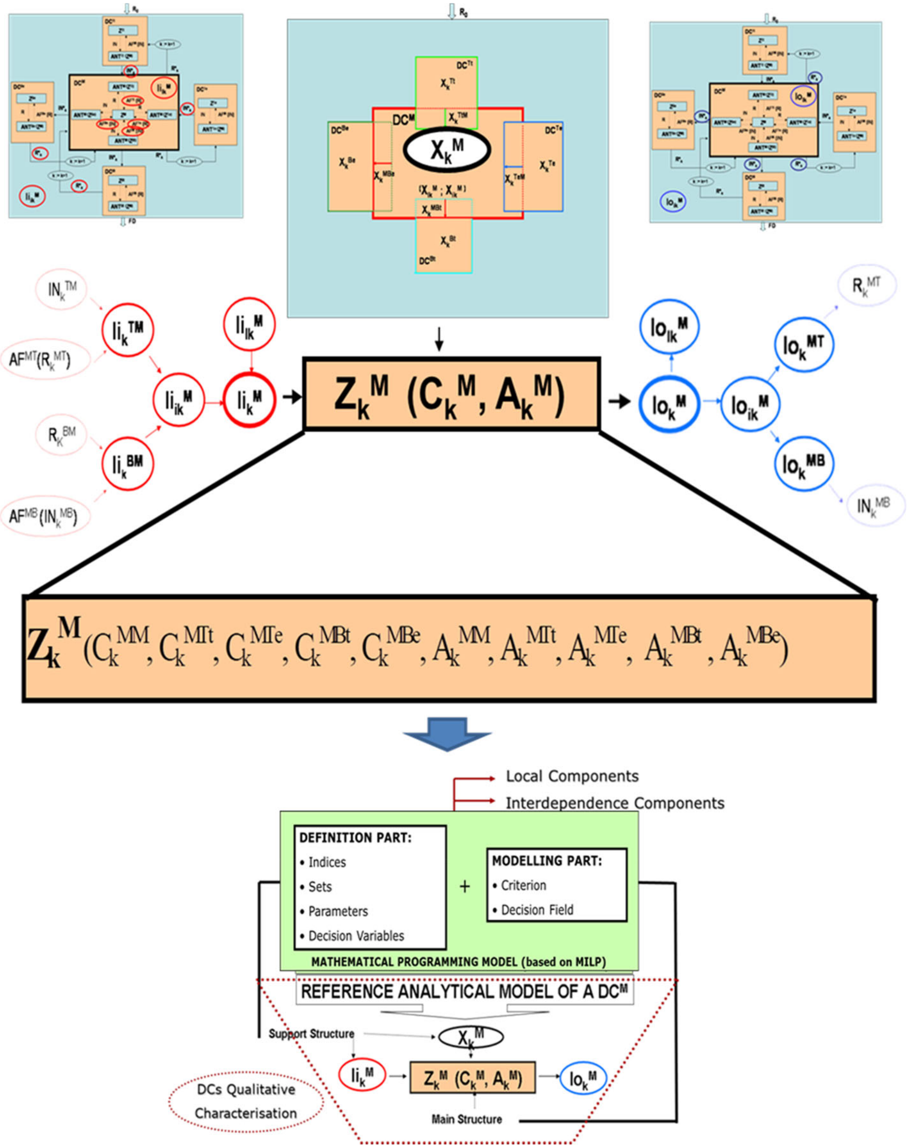


Fig. 7 MPM-SC-CP_block 1: MILP modelling of the SC-CP

- An organisational context is assumed; that is, the collaborative decision process aims to reach a global common goal between the different DCs via coordination mechanisms. No oportunistic behaviour exists
- A hierarchical context (temporal or/and spatial) is considered with only one cycle instruction (IN)—reaction (R). Thus, henceforth, the MILP model is represented by Z^M (C^M, $A.^M$)

Block 1 is made up of two steps:

In the first step, the qualitative characterisation of each individual DC and the information exchanged between them must be performed. This is done based on the subsequent MILP modelling. Thus all the information is structured according to the aforementioned decision reference model within the framework. This fact can lead to suggest some changes as to how DCs perform their tactical and/or perational plans.

So for each T/O DL – DCno (DC placed at the tactical-T or operational-O decision level-DL and with an assigned number, no.), the characteristics identified in the microdecision view of the framework must be addressed. These local characteristics encompass the horizon, planning and replanning periods of the tactical/operational plans, type of decisions (decision variables), objectives (criterion), constraints (decision field) and input information (input parameters).

These local characteristics must be complemented with the others collected in the macrodecision view in relation to the interdependence relationships between the different DCs which, in our case, are due to (ANTs) and instructions (IN). Although both are addressed in the process modelling, they must be explicitly defined at this point.

Firstly, only the interdependence component due to ANT (made by DC^M in relation to DC^B) is considered for the qualitative characterisation of each DC^M because it regards all the aspects that are known independently of executing DC^T. Therefore, the local definitions of decision variables, criterion and decision field are extended by taking into account the ANT information of other DCs with which some interdependencies exist (Table 1).

Secondly, the interdependence component due to IN (transmitted from DC^T to DC^M) is also considered. As previously mentioned, in the most general case this IN entails global variables (decisions made by DC^T and transmitted to DC^M) and global information (parameters that may improve the joint decision process). For example, a DC^T (DC of origin) can exchange some information at the operational decision level (temporal interdependence type) in the form of an IN, which comprises a global decision (purchasing quantities) and some global information (cost deviations on these purchasing quantities and lower/higher bounds of these deviations) to a DC^B (DC of destination). Finally, both the global decision or the global information results in input interdependence parameters from the DC^B side (Table 2).

Once the DC qualitative characterisation and the information exchanged between DCs are performed, the MILP models for each individual DC are developed in the second step.

Table 1 Qualitative characterisation of each DC

T/O DL – DCno: Qualitative Characterisation		
Temporal characteristics (local)		Horizon / Planning Period / Replanning Period
Decision Variables	Local	
	Interdependence (due to ANT)	Temporal
		Spatial
Criterion	Local	
	Interdependence (due to ANT)	Temporal
		Spatial
Decision Field	Local	
	Interdependence (due to ANT)	Temporal
		Spatial

Table 2 Information exchanged between DC

Information exchanged between DCs				
DC of Origin (DC^{T})	Interdependence Type	Instructions (IN)	DC of Destination (DC^{B})	Input Information (Interdependence Parameters—IN)
		Global Decisions	Global Information	

The algebraic formulation of the MILP models comprises the definition and modeling parts. These parts use the reference analytical model described within the framework for the analytical modelling of the SC-CP process (Sect. 3.1).

The definition part is the equivalent to the support structure described in the reference analytical model, which includes two components: decision variables (X^{M}) and input information Ii^{M} (input parameters). In addition, two more components collected from the different views from the framework must be previously defined because they are indices and sets.

The modelling part is the equivalent to the main structure described in the reference analytical model: the criterion and a decision field.

Let Z^{M} be the decision model of DC^{M} so that $Z^{M} = Z^{M}$ (C^{M}, A^{M}), where C^{M} is the criterion and A^{M} is the decision field of DC^{M}. The solution of Z^{M} aims to assign a value to X^{M}, which provides the best value of C^{M} and is subject to the different constraints expressed in A^{M}.

The MILP formulation of X^{M}, C^{M} and A^{M} is explicitly described below.

Decision Variables: X^{M} represents an unknown characteristic of an index or set, whose value is determined once the Z^{M} corresponding to a generic DC^{M} is solved. Collaborative contexts lead to define different types of X^{M}: local decision variables $X_{l}{}^{M}$ (or local variables) and interdependence variables $X_{i}{}^{M}$ (or interdependence variables).

The X^{M} MILP formulation encompasses two stages:

- Stage 1: X^{M} are formulated in each transformation activity (TA: production-P, storage-S and transport), that belong to the scope of DC^{M} and in each interconnection activity (IA: purchase-PU and sales-SA) that belong to the border of DC^{M}. The scope may extend to different SC stages/substages depending on how centralised or decentralised decision making is. The specific decisions variables (SDV) concerning these TA and IA are made at a tactical and/or operational decision level. In general, the decisions linked with the capacity and the execution planning of the different TA will be local for those DCs placed at the tactical and operational decision levels, respectively (Fig. 8).
- Stage 2: all the SDV defined at any TA make sense because they respond to 'what', 'where' and 'when'. Similarly, those defined in any of the IA respond to 'what', 'where', 'whom' and 'when'. For this purpose, some basic indices previously addressed in the definition are considered. These indices correspond to the categories 'general items', 'resources' and 'planning periods' respectively.

Tables 3 and 4 describe the formulation of decision variables X^{M}. These X^{M} belong to the scope of DC^{M}. Different SDV can be formulated in each TA performed in the different SC stages. These SDV regard either capacity or execution planning issues. Besides, the aggregation level of these SDV (expressed by the aforementioned categories/indices) varies depending on the decision level (tactical or operational). These X^{M} belong to the border

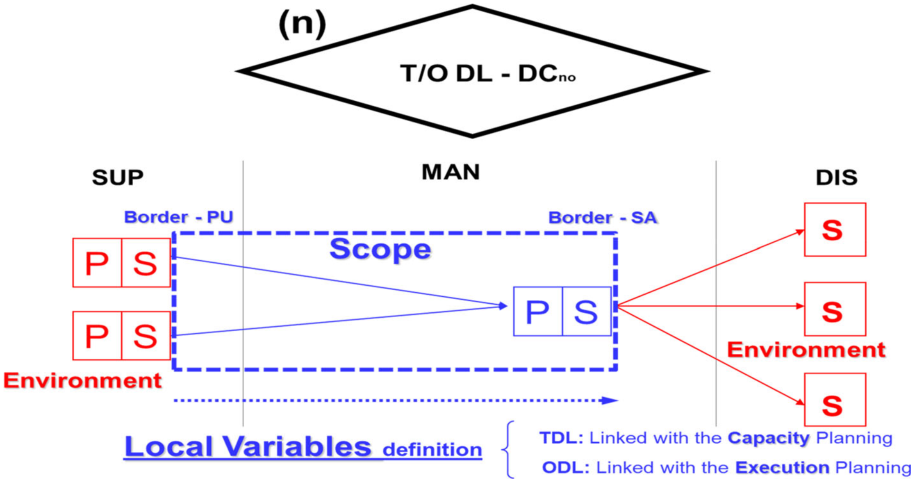


Fig. 8 Local Variables definition

Table 3 Formulation of the decision variables belonging to the DC Scope

DC scope	AGGREGATION – Basic Indices		
SC-Stage (TA – SDV)	What? General Items	Where? Resources	When? Planning Period
Production (P)	Items Groups of Items	Alternative	Daily
Storage (S)		Stage (intranode)	Weekly
Transport ()		Node	Monthly
		Points of sale	– -
		Groups of Nodes/Arches	– -
		Groups of Selling Points	– -
		Decision Centres	Annual

of DC^{M}. Similarly, different SDV can be formulated in each IA with different aggregation levels. A glossary with these SDV is found in the baseline (Section 3.1).

Once X^{M} are formulated, interdependence variables X_i^{M} are identified. These X_i^{M} depend on the temporal and spatial interdependences between DC^{M} and those belonging to its decision environment (DC^{MTt}, DC^{MTe}, DC^{MBt} and DC^{MBe}).

In practice, X_i^{M} correspond to those that connect with the global variables transmitted by an instruction from DC^{MT} and, if this were the case, also with the possible deviations. Another type is defined if DC^{M} anticipates some local variables X_l^{B} from DC^{MB}. The remaining ones are identified as local variables X_l^{M}.

Table 4 Formulation of the decision variables belonging to the DC Border

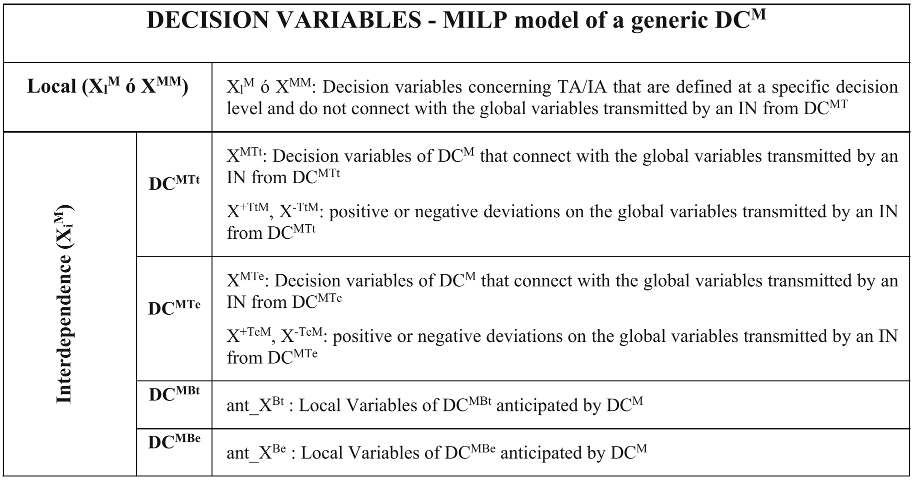
DC BORDER SC-Stage (IA – SDV)	AGGREGATION – Basic indices			
	What? General items	Where? Resources (I)	To Whom? Resources (II)	When? Planning Period
Purchase (PU)	Items	Stage (intranode)	Points of sale	Daily
Sales (SA)	Groups of Items	Node	Groups of Selling Points	Weekly
		Groups of Nodes	Decision Centres	Monthly
				– -
				– -
				– -
				Annual

It is noteworthy that for those DC^{M} placed at the tactical level, the ANT $X_l{}^{B}$ regarding DC^{MB} corresponds to the execution planning issues of the different TA.

Figure 9 summarises the different types of X^{M} to formulate an MILP model of a generic DC^{M}.

Criterion: $C_l{}^{M}$ is composed of the incomes and/or costs related to the different decision variables X^{M}. Two parts are distinguished in C^{M}: the local criterion ($C_l{}^{M}$ or C^{MM}) and the interdependence criterion ($C_i{}^{M}$).

The formulation of each income or cost in $C_l{}^{M}$ implies a local parameter $c_l{}^{M}{}_{i,,r,t}$ multiplied by a local variable $X_l{}^{M}{}_{i,,r,t}$. This multiplication takes place according to a summation that makes sense only for the different values taken by the local indices with which $c_l{}^{M}{}_{i,,r,t}$ and $X_l{}^{M}{}_{i,,r,t}$ are defined (Fig. 10–(1)). In this summation, the local indices whose domain is linked with the simple local set that they automatically originate and those whose domain is linked with a relational local set are distinguished. The values of these local indices correspond to



DECISION VARIABLES - MILP model of a generic DC^{M}		
Local ($X_l{}^{M}$ ó X^{MM})		$X_l{}^{M}$ ó X^{MM}: Decision variables concerning TA/IA that are defined at a specific decision level and do not connect with the global variables transmitted by an IN from DC^{MT}
Interdependence ($X_i{}^{M}$)	**DC^{MTt}**	X^{MTt}: Decision variables of DC^{M} that connect with the global variables transmitted by an IN from DC^{MTt} X^{+TtM}, X^{-TtM}: positive or negative deviations on the global variables transmitted by an IN from DC^{MTt}
	DC^{MTe}	X^{MTe}: Decision variables of DC^{M} that connect with the global variables transmitted by an IN from DC^{MTe} X^{+TeM}, X^{-TeM}: positive or negative deviations on the global variables transmitted by an IN from DC^{MTe}
	DC^{MBt}	ant_X^{Bt} : Local Variables of DC^{MBt} anticipated by DC^{M}
	DC^{MBe}	ant_X^{Be} : Local Variables of DC^{MBe} anticipated by DC^{M}

Fig. 9 Types of X^{M} in an MILP model of a generic DC^{M}

CRITERION – MILP Model of a generic DC^{M}			
Local (C$_l^{M}$ or C^{MM})		$(\sum_{i}\sum_{r}\sum_{t}\sum_{i\in I(i)}\sum_{r\in R(r)}\sum_{t\in T(t)}\sum_{i\in I(r)}\sum_{i\in I(t)}\sum_{r\in R(t)} c_l{}^{M}{}_{i,r,t} * X_l{}^{M}{}_{i,r,t})$	(1)
Interdependence **(C$_i^{M}$)**	**DC^{Tt} (C^{MTt})** **DC^{Te} (C^{MTe})** **DC^{Bt} (C^{MBt})** **DC^{Be} (C^{MBe})**	$(\sum_{i}\sum_{r}\sum_{t}\sum_{i\in I(i)}\sum_{r\in R(r)}\sum_{t\in T(t)}\sum_{i\in I(r)}\sum_{i\in I(t)}\sum_{r\in R(t)} c_i{}^{M}{}_{i,r,t} * X_i{}^{M}{}_{i,r,t})$	(2)

Fig. 10 Types of C^{M} in an MILP model of a generic DC^{M}

either their entire domain, such as i € I, r € R, t € T., or the domain of the relational local set, such as i € I(i), r € R(r), t € T(t), i € I(r), i € I(t) and r € R(t).

C$_i^{M}$ is composed of those incomes or costs that derive from the DC^{M} decision interactions. Nevertheless, these decision interactions do not necessarily imply the existance of C$_i^{M}$ because they can only affect some constraints formulated in the interdependence decision field A$_i^{M}$ as explained later.The formulation of each C$_i^{M}$ issue implies an interdependence parameter c$_i{}^{M}{}_{i,,r,t}$ (deviation costs in relation to the global variables transmitted from DC^{MT} or ANT costs in relation to some local variables from DC^{MB}), which is multiplied by an interdependence variable X$_i{}^{M}{}_{i,,r,t}$. This multiplication takes place according to a summation that makes sense only for the different values taken by the local and interdependence indices with which c$_i{}^{M}{}_{i,,r,t}$ and X$_i{}^{M}$ $_{i,,r,t}$ are defined (Fig. 10 – (2)). In this summation, the indices whose domain is linked with the simple local set that they automatically originate and those whose domain is linked with an interdependence set are distinguished.

Decision Field: A^{M} is the decision field of DC^{M}. A^{M} is represented by a series of constraints expressed by functions that restrict the X^{M} values. Two parts are also distinguished in A^{M}.

The local decision field (A$_l^{M}$ ó A^{MM}) is composed of all those restrictions that are within the scope/on the border of DC^{M} that exist regardless of the degree of interdependence of DC^{M} with another DC.

The A$_l^{M}$ restrictions are grouped into three large groups: materials limitations, resources-based and policies. In turn, each group addresses a set of specific constraints whose formulation depends on which TA/IA belonging to the scope/border are considered as well as the decisional level. A glossary with these specific decisions is found in the baseline (Sect. 3.1).

A$_l^{M}$ is made up of the restricted functions represented by a local parameter a$_l^{M}$ multiplied by a local variable X$_l^{M}$. A summation over the local indices with which a$_l^{M}$ and X$_l^{M}$ are defined also exists, in this case over simple and relational local sets (Fig. 11 – (3)). Unlike C$_l^{M}$, here the summation over the local indices is defined for each fixed value that the other different indices not contemplated in this summation may take. Besides, operator '∀' is used to express with which values of the local indices it would make sense to formulate the previous summations. In this case, simple and relational local sets are also defined.

The interdependence decision field (A$_i^{M}$) deals with those restrictions that reflect the interdependence relationships of DC^{M} to the other DCs that belong to its decision environment. Depending on the type of interdependence relationship, these restrictions reflect the

DECISION FIELD – MILP Model of a generic DC^{M}			
Local **(A$_{l}^{M}$ or A^{MM})**		$\min_{l}{}^{M}{}_{i,r,t} \le (\sum_{i}\sum_{r}\sum_{t}\sum_{i\in I(i)}\sum_{r\in R(r)}\sum_{t\in T(t)}\sum_{i\in I(r)}\sum_{i\in I(t)}\sum_{r\in R(t)} a_{l}{}^{M}{}_{i,r,t} * X_{l}{}^{M}{}_{i,r,t}) \le \max_{l}{}^{M}{}_{i,r,t}$ $\forall$ i, r ,t, i € I(i), r € R(r), t € T(t), i € I(r), I € I(t), r € R(t)	(3)
Interdependence (A$_{i}^{M}$)	**DC^{Tt}** **(A^{MTt})**	$x_{F}{}^{MTt}{}_{i,r,t}(\min) \le (\sum_{i}\sum_{r}\sum_{t}\sum_{i\in I(i)}\sum_{r\in R(r)}\sum_{t\in T(t)}\sum_{i\in I(r)}\sum_{i\in I(t)}\sum_{r\in R(t)} a^{MTt}{}_{i,r,t} * X^{MTt}{}_{i,r,t}) \le x_{F}{}^{MTt}{}_{i,r,t}(\max)$ $\forall$ i, r ,t, i € I(i), r € R(r), t € T(t), i € I(r), I € I(t), r € R(t)	(4.1)
		$(\sum_{i}\sum_{r}\sum_{t}\sum_{i\in I(i)}\sum_{r\in R(r)}\sum_{t\in T(t)}\sum_{i\in I(r)}\sum_{i\in I(t)}\sum_{r\in R(t)} a^{MTt}{}_{i,r,t} * X^{MTt}{}_{i,r,t} + X^{-MTt}{}_{i,r,t} - X^{+MTt}{}_{i,r,t} = x_{NF}{}^{MTt}{}_{i,r,t}$ $\forall$ i, r ,t, i € I(i), r € R(r), t € T(t), i € I(r), I € I(t), r € R(t)	(4.2)
	DC^{Te} **(A^{MTe})**	$\sum_{i'}\sum_{r'}\sum_{t'}\sum_{i'\in I'(i')}\sum_{r'\in R'(r')}\sum_{t'\in T'(t')}\sum_{i'\in \acute{I}'(r')}\sum_{i'\in \acute{I}'(t')}\sum_{r'\in R'(t')} x_{F}{}^{MTe}{}_{i',r',t'}(\min) \le$ $(\sum_{i}\sum_{r}\sum_{t}\sum_{i\in I(i)}\sum_{r\in R(r)}\sum_{t\in T(t)}\sum_{i\in I(r)}\sum_{i\in I(t)}\sum_{r\in R(t)} a^{MTe}{}_{i,r,t} * X^{MTe}{}_{i,r,t}) \le$ $\sum_{i'}\sum_{r'}\sum_{t'}\sum_{i'\in I'(i')}\sum_{r'\in R'(r')}\sum_{t'\in T'(t')}\sum_{i'\in I'(r')}\sum_{i'\in I'(t')}\sum_{r'\in R'(t')} x_{F}{}^{MTe}{}_{i',r',t'}(\max)$ $\forall$ i, r ,t, i € I(i), r € R(r), t € T(t), i € I(r), I € I(t), r € R(t) $\forall$ i′, r′ ,t′, i′ € I′(i′), r′ € R′(r′), t′ € T′(t′), i′ € I′(r′), I′ € I′(t′), r′ € R′(t′)	(5.1)
		$(\sum_{i}\sum_{r}\sum_{t}\sum_{i\in I(i)}\sum_{r\in R(r)}\sum_{t\in T(t)}\sum_{i\in I(r)}\sum_{i\in I(t)}\sum_{r\in R(t)} a^{MTe}{}_{i,r,t} * X^{MTe}{}_{i,r,t}) + X^{-MTe}{}_{i,i'r,r',t,t'} - X^{+MTe}{}_{i,i'r,r't,t'} =$ $\sum_{i'}\sum_{r'}\sum_{t'}\sum_{i'\in I'(i')}\sum_{r'\in R'(r')}\sum_{t'\in T'(t')}\sum_{i'\in I'(r')}\sum_{i'\in I'(t')}\sum_{r'\in R'(t')} x_{NF}{}^{MTe}{}_{i',r',t'}$ $\forall$ i, r ,t, i € I(i), r € R(r), t € T(t), i € I(r), I € I(t), r € R(t) $\forall$ i′, r′ ,t′, i′ € I′(i′), r′ € R′(r′), t′ € T′(t′), i′ € I′(r′), I′ € I′(t′), r′ € R′(t′)	(5.2)
	DC^{Bt} **(A^{MBt})**	$\sum_{i}\sum_{r}\sum_{t}\sum_{i\in I(i)}\sum_{r\in R(r)}\sum_{t\in T(t)}\sum_{i\in I(r)}\sum_{i\in I(t)}\sum_{r\in R(t)} ant\_\min{}^{MBt}{}_{i,r,t} \le$ $a^{MBt}{}_{i,r,t} * X^{MBt}{}_{i,r,t} \le$ $\sum_{i}\sum_{r}\sum_{t}\sum_{i\in I(i)}\sum_{r\in R(r)}\sum_{t\in T(t)}\sum_{i\in I(r)}\sum_{i\in I(t)}\sum_{r\in R(t)} ant\_\max{}^{MBt}{}_{i,r,t}$ $\forall$ i, r ,t, i € I(i), r € R(r), t € T(t), i € I(r), I € I(t), r € R(t)	(6)
	DC^{Be} **(A^{MBe})**	$\sum_{i'}\sum_{r'}\sum_{t'}\sum_{i'\in I'(i')}\sum_{r'\in R'(r')}\sum_{t'\in T'(t')}\sum_{i'\in \acute{I}'(r')}\sum_{i'\in \acute{I}'(t')}\sum_{r'\in R'(t')} ant\_\min{}^{MBe}{}_{i',r',t'} \le$ $(\sum_{i}\sum_{r}\sum_{t}\sum_{i\in I(i)}\sum_{r\in R(r)}\sum_{t\in T(t)}\sum_{i\in I(r)}\sum_{i\in I(t)}\sum_{r\in R(t)} a^{MBe}{}_{i,r,t} * X^{MBe}{}_{i,r,t}) \le$ $\sum_{i'}\sum_{r'}\sum_{t'}\sum_{i'\in I'(i')}\sum_{r'\in R'(r')}\sum_{t'\in T'(t')}\sum_{i'\in I'(r')}\sum_{i'\in I'(t')}\sum_{r'\in R'(t')} ant\_\max{}^{MBe}{}_{i',r',t'}$ $\forall$ i, r ,t, i € I(i), r € R(r), t € T(t), i € I(r), I € I(t), r € R(t) $\forall$ i′, r′ ,t′, i′ € I′(i′), r′ € R′(r′), t′ € T′(t′), i′ € I′(r′), I′ € I′(t′), r′ € R′(t′)	(7)
Logical (A$_{lo}^{M}$)		$\min_{g}^{M}(X^{M}) \le F_{g}(X^{M}) \le \max_{g}^{M}(X^{M})$	(8)
Technical (A$_{te}^{M}$)		$\min_{c}^{M}(X^{M}) \le X^{M} \le \max_{c}^{M}(X^{M})$	(9)

Fig. 11 Types of A^{M} in an MILP model of a generic DC^{M}

coherence, consistency, synchronization and flexibility given by the upper level DC^{MT} to the lower level DC^{M}, as well as the way in which DC^{M}, in turn, takes into account its lower level DC^{MB} by anticipating it to a greater or lesser extent. Below $A_i{}^{M}$ is specified depending on which DC is considered from its decision environment.

Regarding DC^{MTt}:

- Some A^{MTt} restrictions are based on the final global variables transmitted by an IN from DC^{MTt}, and are considered by DC^{M} to be interdependence parameters, and more particularly those that restrict the lower (min), higher (max) or equal function defined by DC^{M} (Fig. 11–(4.1)). The use of summations allows DC^{M} to adjust the dimensions (indices) with which decisions are made about DC^{MTt}, in this case by disaggregating them. These final global variables definitively affect the DC^{M} decision field because they correspond to the decisions previously implemented by DC^{MTt}.
- Some A^{MTt} restrictions are based on the non-final global variables transmitted by an IN from DC^{MTt}, and are considered by DC^{M} to be interdependence parameters, although their value can be changed in this case (Fig. 11–(4.2)). So these non-final global variables do not definitively affect the DC^{M} decision field because they are not implemented by DC^{MTt} and minor variations are permitted to obtain consistent disaggregation.

Regarding DC^{MTe}:

- Some A^{MTe} restrictions are based on the final global variables transmitted by an IN from DC^{MTe}, and are considered by DC^{M} to be interdependence parameters, and more particularly those that restrict a lower (min), higher (max) or equal function defined by DC^{M} (Fig. 11–(5.1)). The use of summations in not only the restricted function, but also at the lower and higher bounds, is because DC^{M} may have to adjust its decisions dimensions in relation to DC^{MTe}, although in this case, and unlike DC^{MTt}, some aggregation might take place. However, in most cases, no disaggregation or aggregation, and only a matching process, exists. Finally, it is worth noting that if one of the summations uses a certain category (index) dimension, the another must omit it and vice versa. This is because aggregated decisions (in relation to a dimension) are always made up of one DC, and never at once. That is why the different categories (indices) of a summation may or may not be formulated with a prime (for example r or r').
- Some A^{MTe} restrictions are based on the non-final global variables transmitted by an IN from DC^{MTe}, and are considered by DC^{M} to be interdependence parameters, although their value can be changed in this case (Fig. 11–(5.2)). So these non-final global variables do not definitively affect the DC^{M} decision field and minor variations are permitted so that consistent disaggregation/aggregation/matching may take place.

Regarding DC^{MBt}:

- A^{MBt} restrictions are based on the ANT parameters of DC^{MBt} (interdependence parameters) that can affect $X_i{}^{M}$ in relation to DC^{MBt} (Fig. 11 – (6)). The use of summations for ANT parameters (ant_min^{MBt} and ant_max^{MBt}) is because DC^{M} may have to adjust (in advance) its decision dimensions (indices) in reltion to DC^{MBt} by disaggregating them in this case.

Regarding DC^{MBe}:

- A^{MBe} restrictions are based on the ANT parameters of DC^{MBe} (interdependence parameters) that can affect $X_i{}^{M}$ in respect to DC^{MBe} (Fig. 11 – (7)). The use of summations for not only ANT parameters (ant_min^{MBe} and ant_max^{MBe}), but also for the restricted function is because DC^M may have to adjust (in advance) its decision dimensions (indices) in relation to DC^{MBe}. In this case, and unlike DC^{Bt}, by also having to aggregate or simply match them.

Additionally to the local ($A_l{}^M$) and interdependence ($A_i{}^M$) decision fields, two more groups of constraints must be formulated in the MILP model: logical ($A_{lo}{}^M$) and technical ($A_{te}{}^M$) decision fields. $A_{lo}{}^M$ restrictions represent relations, which are sometimes artificially formulated, to ensure the model's coherency (Fig. 11–(8)), while $A_{te}{}^M$ restrictions reflect the decision variables' nature (Fig. 11–(9)).

3.2.2 MPM-SC-CP_ Block II: MILP solution and evaluation of the SC-CP

Block II indicates the steps for the MILP solution of the whole SC-CP process, and places a special emphasis on how the individual DC models previously developed for each DA 'interact' so that the performance of such collaboration can be quantitatively evaluated from the integrated solution of these models.

Previously, some information obtained by applying the methodology to model the SC-CP process (Sect. 3.1) is collected, especially that regarding the sequence to execute the different DCs and their shared information.

This Block 2 is also made up of two steps:

In the first step, MILP models are solved according to the SC-CP process sequence. All the input information, which may be either local or due to interdependences, is firstly collected (Fig. 12).

Then as the MILP models are solved, the decision variables and the criterion value of each one are obtained by distinguishing between the local and interdependence components. As indicated in the step 1 of Block 1, each generic DC^M associated with a DA generates certain output information due to interdependencies once its MILP model is solved. This interdependence output information comprises either IN or R, which is transmitted to DC^B (DC^{Bt}, DC^{Be}) and DC^T (DC^{Tt}, DC^{Te}), respectively (Fig. 13). It is worth remarking that only IN (global variables x^{MB} and global information i^{MB}) are considered because only hierarchical contexts are addressed in the proposed MPM-SC-CP with only one cycle instruction-reaction (IN-R). This means that although several Rs may exist, they do not affect the established execution sequence of the several DCs that form part of the SC-CP process because they are executed just once. Only the interdependence criterion is affected if these Rs exist.

In the second step of Block 2, the integrated evaluation of the performance of the whole SC-CP process is made (Fig. 14).

Three performance indicators are proposed to evaluate global SC performance:

1. Total criterion (C^{total}): as a measure of a global objective.
2. Total solution time (T^{total}): as a measure of the global decision-making time.
3. Total consistency (CO^{total}): as a measure of the degree of compliance of DC^B in relation to the global decisions transmitted from DC^T.

To calculate the total criterion (C^{total}), only the local criterion and the criterion due to the interdependencies with DC^T are computed. In this case, the interdependence criterion in respect to DC^B is not considered because this value is the consequence of an ANT. So its true value is given when these are subsequently solved by DC^B. The ANT of the DC^B decision models, particularly of their individual criterion, enables the joint criterion to improve, and can even result in the deterioration of which that anticipates them. If a criterion is due to interdependencies with DC^T, it means that some of the global variables transmitted as IN

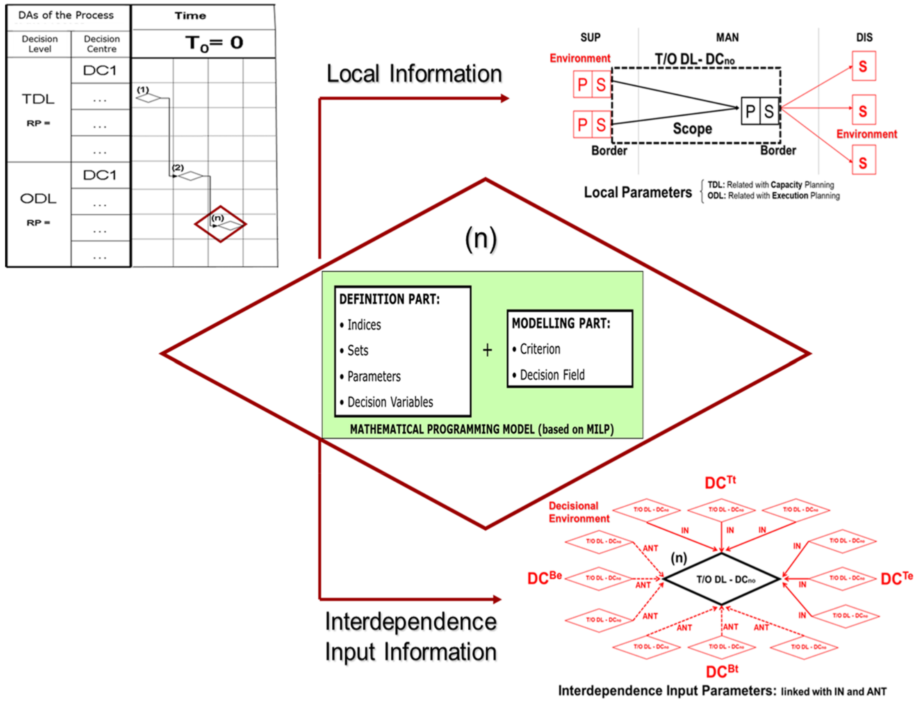
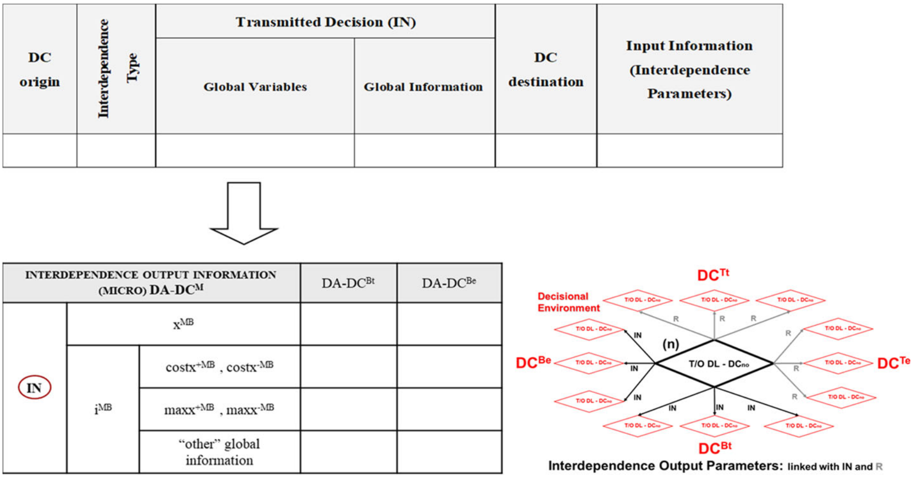


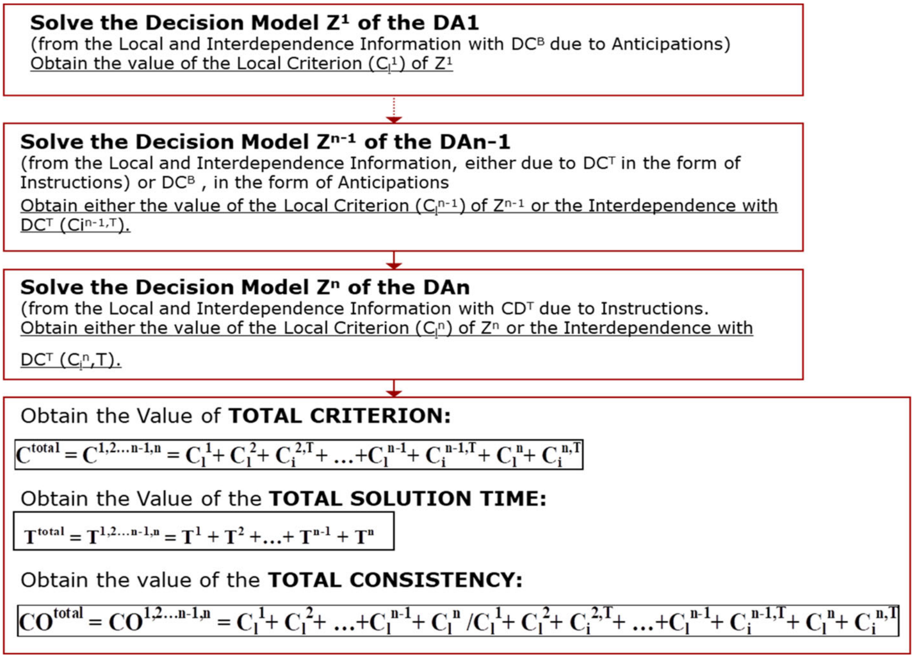
Fig. 12 Input information of a decision activity



DC origin	Interdependence Type	Transmitted Decision (IN)		DC destination	Input Information (Interdependence Parameters)
		Global Variables	Global Information		

INTERDEPENDENCE OUTPUT INFORMATION (MICRO) DA-DC^{M}			DA-DC^{Bt}	DA-DC^{Be}
IN	x^{MB}			
	i^{MB}	costx^{+MB} , costx^{-MB}		
		maxx^{+MB} , maxx^{-MB}		
		"other" global information		

Fig. 13 Output information generated by a decision activity



Solve the Decision Model Z^1 of the DA1

(from the Local and Interdependence Information with DC^B due to Anticipations)

Obtain the value of the Local Criterion (C_l^1) of Z^1

Solve the Decision Model Z^{n-1} of the DAn-1

(from the Local and Interdependence Information, either due to DC^T in the form of Instructions) or DC^B , in the form of Anticipations

Obtain either the value of the Local Criterion (C_l^{n-1}) of Z^{n-1} or the Interdependence with DC^T ($Ci^{n-1,T}$).

Solve the Decision Model Z^n of the DAn

(from the Local and Interdependence Information with CD^T due to Instructions.

Obtain either the value of the Local Criterion (C_l^n) of Z^n or the Interdependence with

DC^T (C_l^n,T).

Obtain the Value of **TOTAL CRITERION:**

$$C^{total} = C^{1,2\ldots n-1,n} = C_l^1 + C_l^2 + C_i^{2,T} + \ldots + C_l^{n-1} + C_i^{n-1,T} + C_l^n + C_i^{n,T}$$

Obtain the Value of the **TOTAL SOLUTION TIME:**

$$T^{total} = T^{1,2\ldots n-1,n} = T^1 + T^2 + \ldots + T^{n-1} + T^n$$

Obtain the value of the **TOTAL CONSISTENCY:**

$$CO^{total} = CO^{1,2\ldots n-1,n} = C_l^1 + C_l^2 + \ldots + C_l^{n-1} + C_l^n / C_l^1 + C_l^2 + C_i^{2,T} + \ldots + C_l^{n-1} + C_i^{n-1,T} + C_l^n + C_i^{n,T}$$

Fig. 14 Integrated evaluation of the performance of the SC-CP process

have altered; that is, there is an R that entails a cost. However, the process continues to be executed/solved because the cost of ‘managing’ such alterations (with different nuances depending on whether it is temporal or spatial interdependence) is precisely the criterion due to the interdependencies with DC^T which have, on the other hand, made it possible to improve the joint criterion. It must be stated that, as previously mentioned, only hierarchical contexts with just one cycle IN-R are considered.

The total solution time (T^{total}) is defined as the sum of the solution time of the individual DC models developed for each DA of the SC-CP process.

Total consistency (CO^{total}) is defined as ‘the weight of the sum of the criterion due to interdependences with DC^T compared to the sum of the local criterion’. This performance measure evaluates the degree of compliance in relation to the global variables transmitted as IN from DC^T or, instead, how it affects the fact that DC^T admits (in order to optimise the joint criterion) that DC^B can have reactions, normally bounded by some coordination mechanisms, as in the case of global information, which is also transmitted from DC^T as the maximum and minimum permitted deviations and a cost derives from them.

All this makes it possible to not only evaluate the current situation, but for it to also be used as a ‘simulator’ of different collaborative planning scenarios. These changes can be more or less profound; for example, when changing the interdependence relationships between the DC or varying the execution sequence of different DA, by redefining fewer DCs at a certain decision level to make the centralisation in decision making greater.

4 Application of MPM-SC-CP to a ceramic supply chain

The proposed MPM-SC-CP was applied to a real case in a ceramic SC, which involves a Spanish Industrial Group (IG) that designs, manufactures, markets and distributes different ceramic products.

Figure 15 shows the physical characterisation of this SC from the resources point of view. In the production stage (MAN), there are several production plants (M1-M2-M3) that belong to the IG, and manufacture a wide-ranging catalogue of finished goods, some of which are subcontracted (lower-value ones) to an independent plant (M4). Each production plant follows a make-to-stock strategy and can be classified as a hybrid flow shop comprising several stages, of which the presses-glazing lines and kilns are the most critical ones from the planning point of view. These production plants are supplied with various raw materials from different suppliers (SUP: S1-S2-S3), some of which also belong to the IG. Inthe distribution stage, the finished goods from the production plants to end customers are distributed in several substages by some distribution centres. The flow from the central warehouses (DIS^1) is divided among the independent distributors (50% to exports, 25% to the national market), the logistics centres (10%, only the national market), and full orders are sent directly to construction firms (15%). Some flow occurs from the central warehouses to the end customers, but it is minimal. Logistics centres (DIS^2) supply finished goods to the shops (demand) that have been previously assigned to them. These shops, with no storage capacity, attend to end customers' demands and some small orders from constructions firms. Some independent shops are also supplied by independent distributors that are not hererin considered.

Figure 16 shows a physical characterisation of this SC from the items point of view. Eight points of sale are allocated in the two central warehouses and the six shops where 214 final products are marketed. These final products are grouped into four families thatare manufactured on each production line and in all the kilns in the plants. These product families are, in turn, composed of six different raw materials that are grouped into three types: white clay, red clay and glaze.

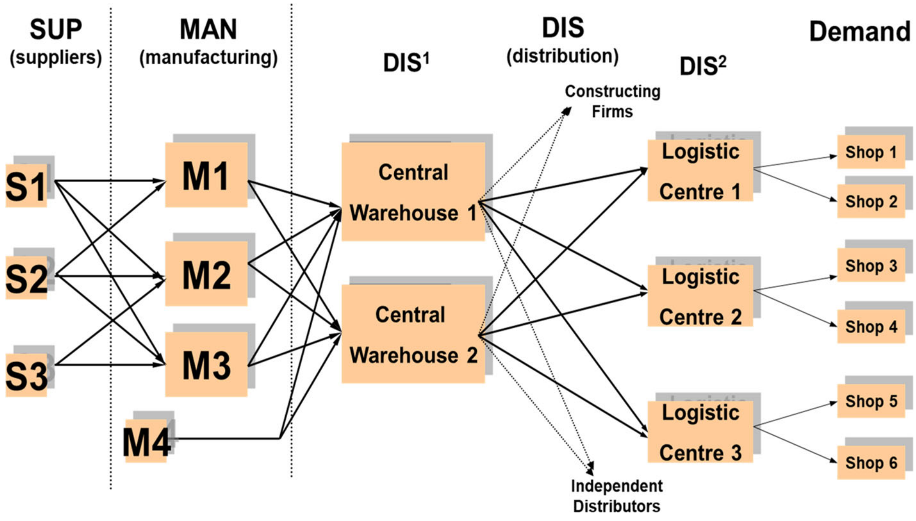


Fig. 15 Ceramic SC physical characterisation (resources)

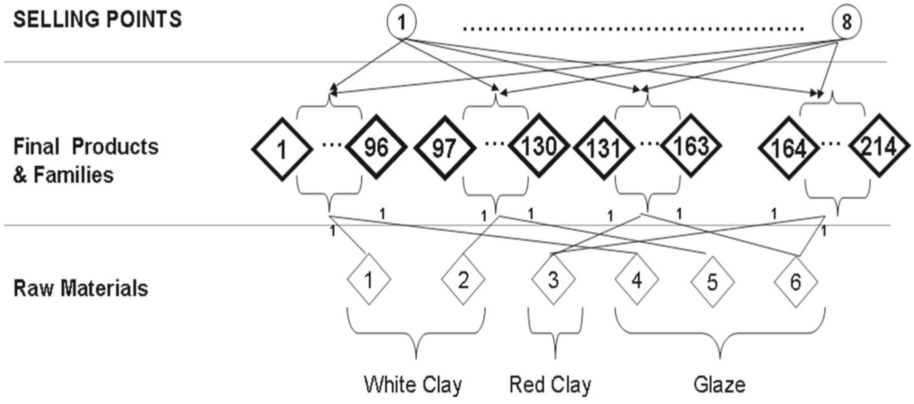


Fig. 16 Ceramic SC physical characterisation (items)

As stated in Sect. 3.1, the MPM-SC-CP application lies in, on the one hand, obtaining the ceramic SC-CP process model and, on the other hand, all the aspects and concepts developed within the framework for the analytical modelling of the SC-CP process.

To gain a better understanding of the MPM-SC-CP application, some steps to obtain the SC-CP process model are presented.

One important intermediate step concerns the identification of the DCs at the tactical and operational decision levels, as depicted in Figs. 17 and 18, respectively. As these figures depict, the decisions made throughout the SC cover three different transformation activities (TA): production (P), transport (arches) and storage (S). A DC can make decisions in one of these TA or more. Depending on which decision level DCs are placed (tactical or operational), these decisions will be related more to planning the capacity of or executing the TA, respectively. Finally, points of sale are also represented by circles at both the decision levels.

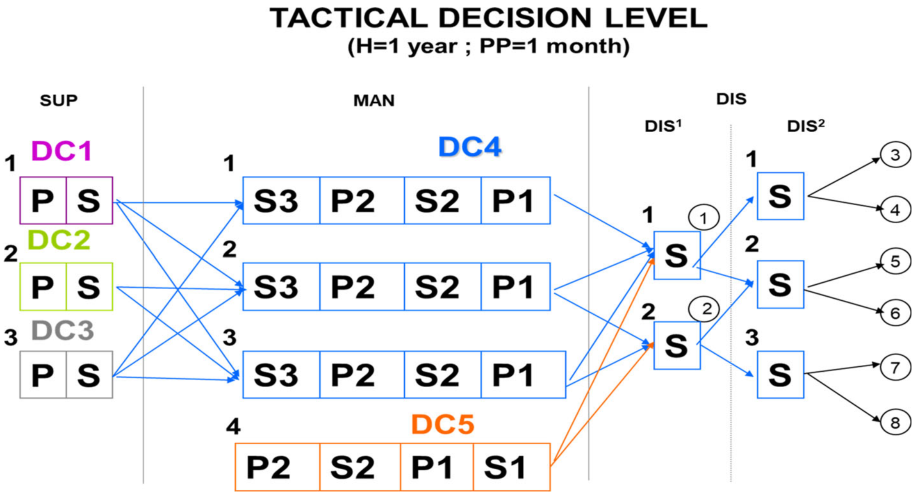


Fig. 17 Identifying the DCs at the tactical decision level

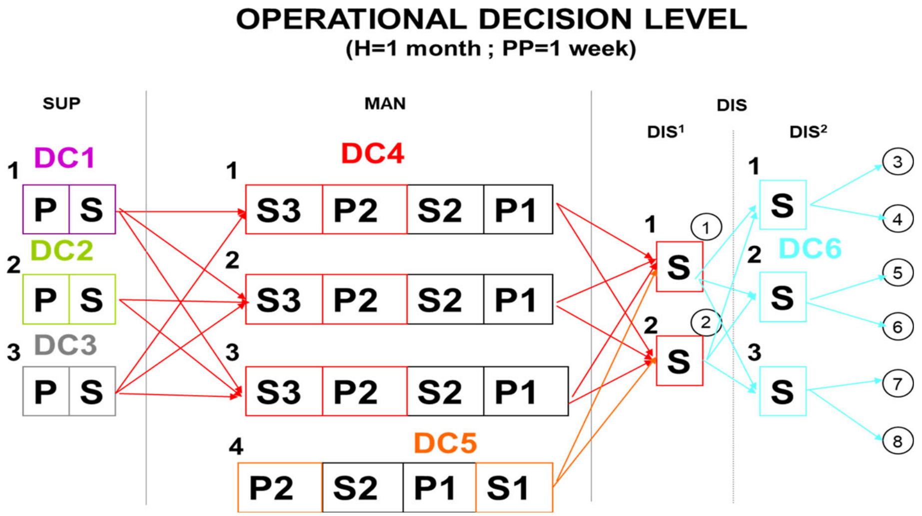


Fig. 18 Identifying the DCs at the operational decision level

Once the different DCs have been identified at each decision level, the ceramic SC-CP process is obtained based on a set of interdependence relationships and specific rules among the DCs placed at the same (spatial) and different (temporal) decision levels. This SC-CP process is made up of some DA with a certain sequence. The decisions in each DA are made by a DC that, in turn, can be placed at either the tactical decision level (TDL) or the operational decision level (ODL).

Only a subprocess of the initial ceramic SC-CP process is selected for the MPM-SC-CP application. This subprocess comprises the following DAs (Fig. 19):

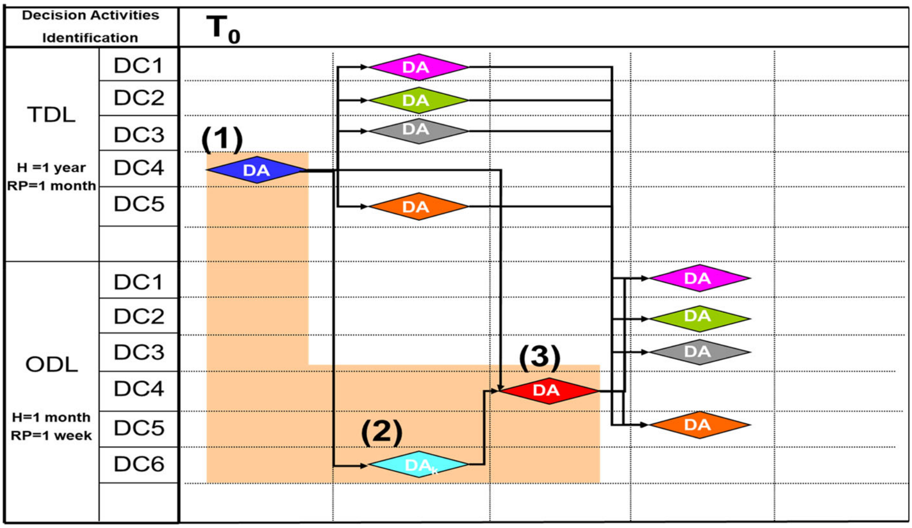


Fig. 19 Application scope of the ceramic SC-CP process

- DA (1) executed by TDL-DC4. Here the tactical decisions about production, transport and storage that affect plants, warehouses and logistic centres are made
- DA (2) executed by ODL-DC6. Here the operational decisions about transport and storage that affect logistic centres and shops are made
- DA (3) executed by ODL-DC4. Here operational decisions about the production, transport and storage that affect plants and warehouses are made

4.1 MPM-SC-CP application_Block 1

Block I of MPM-SC-CP indicates the steps to be followed by each DC to develop an MILP model. In this case, the selected DCs are TDL-DC4, ODL-DC6 and ODL-DC4; that is, those DCs in charge of decision making in the selected DA of the ceramic SC-CP process (Fig. 19).

4.2 Block 1: Step 1

In the first step, a qualitative characterisation of each DC and the information exchanged among them must be performed.

On the one hand, a qualitative characterisation comprising the microdecision view of each DC, complemented with those aspects anticipated from DC^{B} (Table 5, 6 and 7), is carried out. It must be noted that those DC with which some degree of integration exists, but are beyond the scope of the selected ceramic SC-CP subprocess, appear as '*italics*'.

A qualitative characterisation of the information exchanged between TDL-DC4, ODL-DC6 and ODL-DC4 must also be performed. Figure 20 and Table 8 show this information at the macro- and microlevel, respectively.

4.3 Block 1: Step 2

This second step corresponds to the formulation of the MILP models for each DC.

Given its length and to make reading the paper easier, only the methodological MILP formulation of ODL-DC6 (also represented as ODC6) is shown.

An MILP collaborative-model is developed to solve the planning problem of ODC6. It provides a deterministic model and collects either temporal or spatial interdependencies with DC^{Tt} (TDC4) and DC^{Be} (ODC4), respectively. In this case, no interdependence exists with either DC^{Te} (no IN is received from the other DC regarding 'purchase quantities') or DC^{Bt} (no decision level is considered below the operational one).

The indices, sets of indices, parameters, and decision variables are described in Tables 9, 10, 11 and 12 respectively. Local and interdependence components are differenciated.

The criterion (objective function) expresses the total net profit over the time periods and is calculated by substractingthe total costs from the total revenues. It is, in turn, made up of local and interdependence components.

Regarding the local components (Table 13–(1)), some costs and revenues are considered. Costs comprise the variable and fixed transport costs of the final products from warehouses to logistic centres, the inventory costs in logistic centres, the variable transport costs from logistic centres to shops, the purchase costs in warehouses and backorder costs in shops. Revenues comprise those produced by the sales made in shops.

Regarding the interdependence components (Table 13–(2)), only the cost due to the positive deviation in relation to the target capacity already decided in TDC4 is computed.

Table 5 Qualitative characterisation of TDL-DC4

TDL-DC4: Qualitative characterisation			
Temporal Characteristics	Horizon:1 year; Planning Period: 1 month; Replanning Period: 1 month		
Decision variables	Local	Production capacity (number of shifts on lines and activation/deactivation of kilns), transport capacity between warehouses and logistics centres (number of trucks)	
	Interdependence	Temporal	ODL-DC4: Anticipation of the quantity of each raw material to be purchased from each supplier, quantity to be subcontracted from each family in all the warehouses, quantity (kg) of each raw material to be transported from each supplier to each plant, inventory of each raw material in every plant, quantity to be produced for each family in lines and kilns, decisions about changeovers on lines and kilns, inventory of each family in all the plants (intermediate inventory between lines and kilns), quantity of each family to be transported from plants to warehouses, inventory of each family in all the warehouses, quantity to be sold and backordered of each family in each warehouse to construction firms and independent distributors
			ODL-DC6: Anticipation of the quantity of each family to be transported between warehouses and logistics centres, inventory of each family in all the logistic centres, quantity to be sold and backordered of each family in logistics centres to the set of shops assigned to them
Criterion	Local	*Minimise Costs:* Production capacity (number of shifts on lines and activation/deactivation of kilns), transport capacity between warehouses and logistics centres (number of trucks)	
	Interdependence	Temporal	ODL-DC4: *Maximise Profits (incomes—costs)*:

Table 5 (continued)

TDL-DC4: Qualitative characterisation			
			Incomes: Anticipation of sales of families in warehouses *Costs*: Anticipation of purchasing each raw material from every supplier by subcontracting each family in all the warehouses, transporting each raw material from each supplier to all the plants, storing each raw material in all the plants, changeovers of families in lines and kilns, storing each family in all the plants (intermediate storage between lines and kilns), transporting each family from plants to warehouses, inventory of families in warehouses, backorders of families in warehouses to construction firms and independent distributors ODL-DC6: *Maximise Profits (incomes—costs):* *Incomes*: Anticipation of sales of families in logistics centres to the set of stores assigned to them *Costs*: Anticipation of transporting each family between warehouses and logistics centres, inventory of each family in all the logistic centres, backorders of families in logistics centres to the set of stores assigned to them
Decision field	Local	Restrictions of the capacity flow control, the minimum number of periods and the maximum capacity on lines and kilns, the maximum number of trucks available for each route	

The former is subject to some restrictions that shape the decision field, which is made up of local (Table 14–(3–10)), interdependence (Table 15–(11–13)), logical (Table 16–(14–15)) and technical (Table 16–(16–17)) components.

Regarding the local components, the following restrictions are considered: the maximum quantities (weight) of the final products to be transported between warehouses and logistics centres (Table 14–(3)), the conservation flow of the final products in logistics centres (Table 14–(4)), the maximum quantities of the final products to be stored in logistics centres (Table 14–(5)), the safety stocks in logistics centres (Table 14–(6)), the final products transported from a certain warehouse to each logistic centre equals the purchased quantity (Table 14–(7)), the final products transported to a certain shop from each logistic centre equal

Table 5 (continued)

TDL-DC4: Qualitative characterisation			
	Interdependence	Temporal	ODL-DC4: Restrictions of anticipating the inventory balance of the raw material in plants, the maximum inventory of the raw material in plants, the minimum production batches of families on lines and kilns, the minimum and maximum consumption capacities of different families (related to the efficient use of lines and kilns and their capacity, respectively), changeovers control of the families on lines and in ilns, productive performance (different qualities and losses) of lines and kilns, inventory balance of the final products in warehouses, the maximum inventory of the families in warehouses, the maximum backorders of the families in warehouses to construction firms and independent distributors
			ODL-DC6: Restrictions of anticipating the maximum quantities (weight) of each family to be transported between warehouses and logistics centres, flow-conservation of the families in logistics centres, the maximum inventory of each family in logistics centres, the maximum backorders of the families in logistics centres to the set of stores assigned to each one
		Spatial	*TDL-DC1; TDL-DC2; TDL-DC3: Restrictions of anticipating the lower/higher bounds of the raw material/s to be purchased from suppliers*
			TDL-DC5: Restrictions of anticipating lower/higher bounds of subcontracted families

Table 6 Qualitative characterisation of ODL-DC6

ODL-DC6: Qualitative characterisation			
Temporal characteristics	Horizon:1 month; Planning Period: 1 week; Replanning Period: 1 week		
Decision Variables	Local	Quantity to of each final product be purchased in each warehouse, quantity of each final product to be transported between warehouses and logistics centres, inventory of each final product in every logistic centre, quantity of each final product to be transported between logistics centres and shops, quantity of each final product to be sold in all the shops, quantities of each final product to be backordered in all the shops	
Criterion	Local	*Maximizs Profits (incomes—costs):* *Incomes*: Sales of final products in stores *Costs*: Purchase of final products in warehouses, transporting final products between warehouses and logistics centres, fixed cost of transport due to the use of lorries, inventory of the final products in logistics centres, transporting the final products between logistics centres and shops, backordering the final products in shops	
Decision field	Local	Restrictions of the maximum quantities (weight) of the final products to be transported between warehouses and logistics centres, the conservation flow of the final products in logistics centres, the maximum inventory of the final products in logistics centres, the safety stocks in logistics centres, the maximum backordering quantities of the final products in shops	
	Interdependence	Spatial	ODL-DC4: Restrictions of anticipating lower bounds in relation to the quantity of the final products to be purchased in warehouses

the sales quantity (Table 14–(8)), the backorders that may exist in shops (Table 14–(9)), and the maximum quantities of the final products backordered in shops (Table 14–(10)).

Regarding the interdependence components, the following restrictions are considered:

As regards DC^{Tt}, and more particularly TDL-DC4, restrictions concern the disaggregation aspects elated to the target transport capacity (conditioned by the number of hired trucks) between warehouses and logistics centres (Table 15–(11)) and the maximum positive deviation in relation to that target transport capacity (Table 15–(12)).

As regards DC^{Be}, and more particularly ODL-DC4, restrictions concern anticipating lower bounds in relation to the quantity of final products to be purchased in warehouses (Table 15–(13)).

Table 7 Qualitative characterisation of ODL-DC4

ODL-DC4: Qualitative characterisation		
Temporal characteristics	Horizon:1 month; Planning Period: 1 week; Replanning Period: 1 week	
Decision variables	Local	Quantity of each raw material to be purchased from each supplier, quantity of each final product to be subcontracted in each warehouse, quantity (kg) of each raw material to be transported from each supplier to all the plants, inventory of each raw material in every plant, quantity of each final product to be produced on each line, overtime capacity to be assigned to each line, changeovers of the families and final products on lines, quantity of each final product to be transported from each plant to all the warehouses, inventory of each final product in all the warehouses, quantity of each final product to be sold in each warehouse to every logistic centre, construction firms and independent distributors, quantity to be backordered from each final product in all the warehouses to construction firms and independent distributors
Criterion	Local	*Maximise Profits (incomes—costs):* *Incomes*: Sales of final products to logistic centres, construction firms and independent distributors *Costs*: Purchase of raw materials, subcontracting final products, transporting raw materials from each supplier to every plant, inventory of the raw materials in each plant, production of the final products on lines, overtime capacity on lines, changeovers of the families and final products on lines, transporting final products from plants to warehouses, inventory of the final products in warehouses, backorders of final products to construction firms and independent distributors
Decision field	Local	Restrictions of the inventory balance of the raw materials in plants, safety stock of raw material, the maximum limit of the normal and overtime capacities on lines, changeovers control of families and products, productive performance of lines, the minimum production batches, inventory balance of the final products in warehouses, the maximum limit of backorders of final products to construction firms and independent distributors

Table 7 (continued)

ODL-DC4: Qualitative characterisation			
	Imterdependence	Spatial	*TDL-DC1; TDL-DC2; TDL-DC3: Restrictions of anticipating the maximum limits in respect to the quantity of raw material to be purchased from suppliers* *TDL-DC5: Restrictions of anticipating the maximum limits in relation to the quantity of final products to be subcontracted*

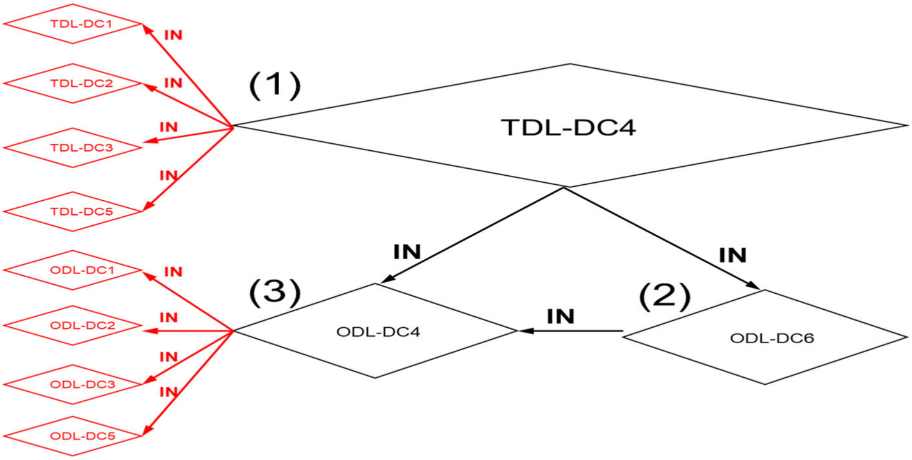


Fig. 20 Information exchanged between TDL-DC6, ODL-DC6 and ODL-DC4 (macrolevel)

Additionally, some logical restrictions are contemplated; for example, if a certain final product in a warehouse is purchased or not (Table 16–(14)), or if any final product is transported from a certain warehouse to a given logistic centre (Table 16–(15)). Finally, some technical restrictions, such as the non-negativity ones (Table 16–(16)) and the definition of binary variables (Table 16–(17)), are formulated .

4.4 MPM-SC-CP application_Block 2

In Block 2 of MPM-SC-CP, an integrated solution and the evaluation of the whole SC-CP process are conducted (Fig. 21).

In the first step, MILP models are individually solved and validated according to the ceramic SC-CP process sequence. The sequence for the selected subprocess is TDL-DC4, ODL-DC6 and ODL-DC4, which was identified. Therefore ODL-OD6 is solved after TDL-CD4 and before ODL-DC4, as seen in Fig. 19.

Table 8 Information exchanged between TDL-DC6, ODL-DC6 and ODL-DC4 (microlevel)

Information exchanged between DCs

DC of origin	Interdependence Type	Instructions (IN)		DC of destination	Input Information (Interdependence Parameters—IN)
		Global Decisions	Global Information		
TDl-DC4	Temporal	Transport capacity between each warehouse / logistics centre for every month of the annual horizon	The maximum allowed deviation in relation to transport capacity Cost of deviation in relation to transport capacity	ODL-DC6	Transport capacity between each warehouse / logistics centre for every week of the monthly horizon The maximum allowed deviations and their costs
		Production capacity on each line for every month of the annual horizon 'Target' inventory of each family in each warehouse for each month of the annual horizon	The maximum and minimum allowed deviations in relation to the "targeted" inventory Cost of these deviations respect the "targeted" inventory	ODL-DC4	Production capacity on each line for every week of the monthly horizon The 'target' inventory of each final product in all the warehouses for every month of the annual horizon
	Spatial	Quantity of the raw material (approximate) to be purchased every month of the annual horizon		*TDL-DC1* *TDL-DC2* *TDL-DC3*	*Quantity of the raw material (approximate) to be sold every month of the annual horizon*

Firstly, all the input information (input parameters, and either local or due to interdependences) must be collected. Two types of interdependence parameters are considered: the IN transmitted from DC^T and the ANT of DC^B (Fig. 22). Some interdependence parameters exist as a result of the IN transmitted from DC^T, which is temporal in this case (TDL-DC4), as well as others related to the ANT of DC^B, which is spatial in this case (ODL-DC4).

In Table 17 the interdependence information due to the instructions transmitted from CD^T is explicitly shown at the microlevel.

Table 8 (continued)

Information exchanged between DCs

DC of origin	Interdependence Type	Instructions (IN)		DC of destination	Input Information (Interdependence Parameters—IN)
		Global Decisions	Global Information		
		Quantity of the families (approximate) that are intended to be subcontracted every month of the annual horizon		TDL-DC5	*Quantity of the families (approximate) to be subcontracted every month of the annual horizon*
ODL-DC6	Spatial	Quantity of the final products to be purchased every week of the monthly horizon		ODL-DC4	Quantity of the final products to be sold every week of the monthly horizon
ODL-DC4	Spatial	Quantity of the final products to be purchased every week of the onthly horizon		*ODL-DC1* *ODL-DC2* *ODL-DC3*	*Quantity of the final products to be sold every week of the monthly horizon*
		Quantity of the final products to be purchased every week of the monthly horizon		*ODL-DC5*	*Quantity of the final products to be sold every week of the monthly horizon*

In this case, a single instruction is received from TDL-DC4, which includes both the interdependence parameter corresponding to the transport capacity already established at the tactical level between warehouses and logistics centres $^{\circ}ctr_{d1,d2,t}$ (from the global variable $CTR_{d1,d2,t}$) and the global information (parameters) regarding an allowed positive deviation cost ($costctr_{d1,d2}$ +) and the maximum allowed deviation ($maxctr_{d1,d2}$ +).

Only five final products are considered, which approximately represent 10% of the total transport capacity. Thus the interdependence parameter that derives from the global variable $CTR_{d1,d2,t}$ is defined as $^{\circ}ctr_{d1,d2,t} * 0.1$.

Having collected all the input information due to the local and interdependence parameters, the MILP model of ODL-DC6 is solved, and the decision variable values and the criterion value are computed by distinguishing between local and due to interdependencies.

The decision variable values that optimise the ODL-DC6 MILP model are not shown in this work so that this paper is not too lengthy,and because the main purpose is the integrated

Table 9 Local and interdependence indices

Local Indices	
Items	
fp	Final products (fp = 1…fp)
Resources	
d2	Nodes from distribution stage 2 (logistic centres) (d2 = 1… d2)
sp	Selling points (sp = 1…sp)
Planification Periods	
t′	Weeks (t´ = 1…t´)
Interdependence Indices	
Items	
–	
Resources	
d1	Nodes from distribution stage 1 (warehouses) (d1 = 1… d1)
tdc	Tactical decision centres (tdc = 1…tdc)
odc	Operational decision centres (odc = 1…odc)
Planning periods	
t	Months (t = 1…t)

solution and evaluation of the ceramic SC-CP process. So only the final criterion value of ODL-DC6, plus TDL-DC4 and ODL-DC4, are shown.

The criterion aims to maximise the monthly benefits, which are calculated from incomes and costs. Tables 18 and 19 show the detailed breakdown of both the local and interdependence costs, respectively.

The values of the local and interdepence criterion are as follows:

The value of the local criterion C_l^{ODC6} of Z^{ODC6} is:

$C_l^{ODC6} = \text{Local Benefit}^{ODC6} = [\text{Local Incomes} - \text{Local Costs}]^{ODC6} = [38220.7140 - 35612.3518] = 2608.3622$ Euros/monthThe value of the interdependence criterion C_i^{ODC6} of Z^{ODC6} is:

$$\begin{aligned} C_i^{ODC6} = C_i^{ODC6,T} = C_i^{ODC6,Tt} = C_i^{ODC6,TDC4} &= \text{Interdependence Benefit}^{ODC6,TDC4} \\ &= \left[\text{Interdependence Incomes} - \text{Interdependence Costs}\right]^{ODC6,TDC4} \\ &= [0 - 102.5420] = -102.542 \text{ euros/month} \end{aligned}$$

Tables 20 and 21 show the total criterion value obtained for ODL-DC6 and the computating effort, respectively. It is noteworthy that the short solution time of ODL-DC6 is due to its simplicity compared to TDL-DC4 and ODL-DC4, which account for much more decision variables and restrictions because production activities take place. In any case, the main purpose of MPM-SC-CP described in this paper is covered.

Finally after solving the MILP model of ODL-DC6, a certain IN is transmitted to DC^B, which is spatial in this case (ODL-DC4). Figure 23 and Table 22 reflect the interdependence output information of ODL-DC6 at the micro- and the macrolevel, respectively.

Table 10 Local and interdependence sets

Local Sets	
Basic local sets	
Items	
FP	The set of final products
Resources	
D2	The set of logistic centres
SP	The set of selling points
Planification Periods	
T'	The set of weeks (operational horizon)
Relational local sets	
Items-Resources	
FP(d2)	The set of final products to transport to each logistic centre
FP(sp)	The set of final products to transport to each selling point
Resources-Resources	
SP (d2)	The set of selling points supplied by each logistic centre
D2 (sp)	The set of logistic centres that supply each selling point

Interdependence sets	
Basic interdependence sets	
Items	
–	
Resources	
D1	The set of warehouses
TDC	The set of tactical decision centres
ODC	The set of operational decision centres
Planning periods	
T'	The set of months (tactical horizon)
Relational interdependence sets	
Items-Resources	
D1 (fp)	The set of warehouses that supply each final product
Resources-Resources	
D1(d2)	The set of warehouses that supply each logistic centre
D2(d1)	The set of logistic centres supplied by each warehouse
D1(odc)	The set of warehouses that belong to the scope of each operational decision centre
Planning Periods-Planning Periods	
$T'(t)$	The set of weeks of each month

Table 11 Local and interdependence parameters

Local Parameters	
Scope stages / Processing Activities	
Distribution Stage 1	
Transport	
v_{fp}	The weight of each final product
costtr $_{fp,d1,d2}$	The transport cost of each final product from warehouses to logistic centers
costftr $_{d1,d2}$	The transport fixed cost
Distribution Stage 2	
Storage	
cin $_{d2}$	The storage capacity of each logistic centre
costin $_{fp,d2}$	The inventory cost of each final product in each logistic centre
ss $_{fp,d2}$	The safety stock of each final product in each logistic centre
in0 $_{fp,d2}$	The initial inventory of each final product in each logistic centre
Transport	
costtr $_{fp, d2,sp}$	The transport cost of each final product from logistic centres to selling points
Border / Interconnecting Activities	
Purchase	
ODC	
costpu $_{fp, d1, odc}$	The purchase cost of each final product in each warehouse that belongs to the scope of each operational decision center
Sales	
Selling Points (no *ODC*)	
dem $_{fp,sp,t'}$	The demand of each final product at each selling point every week
maxsa^{-} $_{fp,sp}$	The maximum backordered quantity of each final product at each selling point
costsa^{-} $_{fp,sp}$	The backorder cost of each final product at each selling point
inc $_{fp,sp}$	The incomes of each final product at each selling point

Interdependence parameters	
DC^{Tt}	
TDC4	
°ctr $_{d1,d2,t}$	The 'target' transport capacity between each warehouse and each logistic centres every month
°maxctr + $_{d1,d2}$	The maximum positive deviation on the 'target' transport capacity between each warehouse and each logistic centre in a week
°costctr + $_{d1,d2}$	The cost of the positive deviation on the 'target' transport capacity between each warehouse and each logistic centre in a week
DC^{Be}	
ODC	
ant_lminsa $_{fp,d1,odc}$	The anticipation of the minimum selling lot of each final product in each warehouse that belongs to the scope of each operational decision centre

Table 12 Local and interdependence variables

Local variables	
Scope stages / Processing Activities	
Distribution Stage 1	
Transport	
$TR_{fp,d1,d2,t'}$	The amount of each final product to transport between each warehouse and each logistic centre every week
$YTR_{d1,d2,t'}$	The binary variable with a value of 0 if transport between warehouses and logistic centres every week exists, and 0 otherwise
Distribution Stage 2	
Storage	
$IN_{fp,d2,t'}$	The inventory of each final product in each logistic centre every week
Transport	
$TR_{fp,d2,sp,t'}$	The amount of each final product to transport from each logistic centre to each selling point every week
Border / Interconnecting Activities	
Purchase	
ODC	
$PU_{fp,d1,odc,t'}$	The amount of each final product to purchase in each warehouse belonging to the scope of each operational decision centre every week
$YPU_{fp,d1,odc,t'}$	The binary variable with a value of 1 if a final product is purchased in a warehouse belonging to the scope of each operational decision centre every week, and 0 otherwise
Sales	
Selling Points	
$SA_{fp,sp,t'}$	The amount of each final product to sell at each selling point every week
$SA^{-}{}_{fp,sp,t'}$	The amount of each final product to backorder at each selling point every week
Interdependence variables	
DC^{Tt}	
TDC4	
$CTR_{d1,d2,t'}$	The consumed transport capacity between warehouses and logistic centre every week
$CTR^{+}{}_{d1d2,t'}$	Positive deviation on the 'target' transport capacity between each warehouse and each logistic centre every week
DC^{Be}	
ODC	
—	

As shown, ODL-DC6 transmits an IN to ODL-DC4 (DC^{Be}), which is made up of the global variable corresponding to the purchase quantity target of each final product in every warehouse ($PU_{pf,d^{1},t'}$). Although no global information exists in this case, previous ANT of ODL-DC6 exists in relation to ODL-DC4.

After solving and validating the MILP models of TDL-DC4, ODL-DC6 and ODL-DC4, an integrated evaluation of the performance of the whole ceramic SC-CP process is carried

Table 13 Local and interdependence criterion

Local criterion
Max [Z] =
Scope stages / Processing Activities
Distribution Stage 1
Transport
$-\sum_{t'}\sum_{d1}\sum_{d2\in D2(d1)}\sum_{fp\in FP(d2)} costtr_{fp,d1,d2} * TR_{fp,d1,d2,t'} -$
$\sum_{t'}\sum_{d1}\sum_{d2\in D2(d1)} costftr_{d1,d2} * YTR_{d1,d2,t'}$
Distribution Stage 2
Storage
$-\sum_{t'}\sum_{d2}\sum_{fp\in FP(d2)} costin_{fp,d2} * IN_{fp,d2,t'}$
Transport
$-\sum_{t'}\sum_{d2}\sum_{sp\in SP(d2)}\sum_{fp\in FP(sp)} costtr_{fp,d2,sp} * TR_{fp,d2,sp,t'}$
Border / Interconnecting Activities
Purchase
ODC
$-\sum_{t'}\sum_{odc}\sum_{d1\in D1(odc)}\sum_{fp\in FP(d2)} costpu_{fp,d1,odc} * PU_{fp,d1,odc,t'}$
Sales
Selling Points (no ODC)
$\sum_{t'}\sum_{sp}\sum_{fp\in FP(sp)} inc_{fp,sp} * SA_{fp,sp,t'} -$
$\sum_{t'}\sum_{sp}\sum_{fp\in FP(sp)} costsa^{-}_{fp,sp} * SA^{-}_{fp,sp,t'}(1)$
Interdependence Criterion
$\mathrm{DC}^{\mathrm{Tt}}$
TDC4
$-\sum_{t'}\sum_{d2}\sum_{d1\in D1(d2)} costctr^{+}_{d1,d2} * CTR^{+}_{d1,d2,t'}$
$\mathrm{DC}^{\mathrm{Be}}$
ODC4
– (2)

out in the second step. As indicated in MPM-SC-CP, three performance indicators evaluate its global performance: total criterion, solution time and consistency, as shown in Fig. 24.

On the results, it is noted that as performance indicator $\mathrm{CO}^{\mathrm{total}}$ is below 1, it means that while computing $\mathrm{C}^{\mathrm{total}}$ a certain component due to the interdependence criterion in relation to CD^{T} came into play, but it does not have much weight in relation to $\mathrm{C}^{\mathrm{total}}$ in this case. So the probability of the previously calculated/predicted $\mathrm{C}^{\mathrm{total}}$ is high, that is, 13,788.2934 euros/month.

Table 14 Local decision field

Local decision field
Scope stages / Processing Activities
Distribution Stage 1
Transport
$\sum_{fp\in FP(d1)}(TR_{fp,d1,d2,t'} * v_{fp}) \le CTR_{d1,d2,t'}, \forall d1, d2 \in D2(), t'(3)$
Storage
$\sum_{d1\in D1(d2)} TR_{fp,d2,t'} + IN_{fp,d2,t'-1} = \sum_{sp\in SP(d2)} TR_{fp,d2,sp,t} + IN_{fp,d2,t'}, \forall d2, fp \in FP(d2), t'(4)$
$\sum_{fp\in FP(d2)} IN_{fp,d2,t'} \le cin_{d2}, \forall d2, t'(5)$
$IN_{fp,d2,t'} \ge ss_{fp,d2}, \forall d2, fp \in FP(d2), t'(6)$
Transport
–
Border / Interconnecting Activities
Purchase
ODC
$PU_{fp,d1,odc,t'} = \sum_{d2\in D2(d1)} TR_{fp,d1,d2,t'}, \forall fp, d1 \in D1(fp), t'(7)$
Sales
Selling Points (no ODC)
$TR_{fp,d2,sp,t'} = SA_{fp,sp,t'}, \forall sp, d2 \in D2(sp), fp \in FP(sp), t'(8)$
$SA_{fp,sp,t} + SA^{-}_{fp,sp,t} = dem_{fp,sp,t} + SA^{-}_{fp,sp,t-1}, \forall fp, sp, t(9).$
$SA^{-}_{fp,sp,t} \le maxsa^{-}_{fp,sp} * dem_{fp,sp,t}, \forall fp, sp, t(10)$

Table 15 Interdependence decision field

Interdependence decision field
$\mathrm{DC}^{\mathrm{Tt}}$
TDC4
$CTR^{+}_{d1,d2,t'} \le^{\circ} maxctr^{+}_{d1,d2} * CTR_{d1,d2,t'}, \forall d1, d2, t'(12)$
$\mathrm{DC}^{\mathrm{Be}}$
ODC4
$PU_{fp,d1,odc,t} \ge ant\_lminsa_{.fp,d1,odc4} * YPU_{fp,d1,odc4,t'}, \forall fp, d1 \in D1(fp), t'(13)$

Table 16 Logical and technical decision field

Logical decision field
$PU_{fp,d1,odc4,t'} \geq M1 * YPU_{fp,d1,odc4,t'}, \forall fp, d1 \in D1(fp), t'(14)$
$\sum_{fp \in FP(d2)} TR_{fp,d1,d2,t'} \leq M2 * YTR_{d1,d2,t}, \forall d1 \in D1(fp), d2 \in D2(d1), t'(15)$
Technical decision field
$CO_{fp,d1,odc,t'}, TR_{fp,d1,d2,t'}, IN_{fp,d2,t'}, TR_{fp,d2,sp,t'}, SA_{fp,sp,t'}, SA^{-}_{fp,sp,t'} \geq 0(16)$
$CO_{fp,d1,odc,t'}, YTR_{d1,d2,t'} \geq 0(binary)(17)$

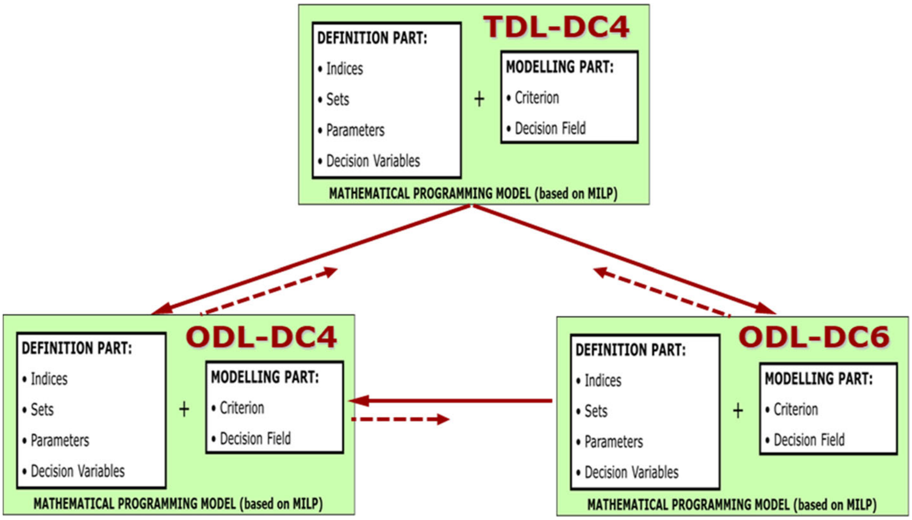


Fig. 21 Integrated solution and evaluation of the whole ceramic SC-CP process

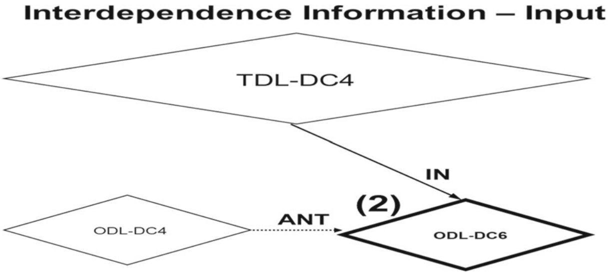


Fig. 22 Interdependence input information (macrolevel) of ODL-DC6

Table 17 Interdependence Input Information of ODL-DC6 (microlevel)

Input Information/micro DA/ODL-DC6	DA/DC^{Tt}		
	DA/TDL-DC4		
IN	xTDL-DC4,ODL-DC6	°ctr d1,d2,t * 0.1	
	iTDL-DC4,ODL-DC6	costx^{+}d1,d2,t	costctr^{+}d1,d2
		maxx^{+}d1,d2,t	maxctr^{+}d1,d2
		others	

Table 18 Solution of the ODL-DC6 MILP model: Local Costs

Local Cost of ODL-DC6				
Activity type	Stage/Substage	Specific PA/IA	Cost Items	Value (€)
Transformation Activities (TA):	DIS^{1}	Transport	Variable transport cost of the final products from warehouses to logistic centres	1982.2192
			Fixed transport cost from warehouses to logistic centres	5500
	DIS^{2}	Storage	Inventory cost of the final products in logistic centres	302.4275
		Transport	Variable transport cost of the final products from logistic centres to shops	452.0170
Interconnection Activities (IA):	Purchasing	Purchase cost of the final products (in warehouses)	27,248.0956	
	Sales	Backorder cost of the final products (in shops)	127.5926	
			Total cost	35,612.3519

Table 19 Solution of the ODL-DC6 MILP model: Interdependence Costs

DC^{T} Interdependence cost of ODL-DC6				
DC^{T}	T/ODL-DC no	Global variable	Deviation Cost ±	Value (€)
DC^{Tt}	TDL-DC4	Transport capacity of each route between warehouses and logistic centres	Positive deviation	102.542
Total cost	102.542			

Table 20 Solution of the ODL-DC6 MILP model: criterion Value

ODL-DC6 Criterion (Max. benefits)	Local criterion	Interdependence criterion	Total
	2608.362	– 102.542	2585.8201

Table 21 Solution of the ODL-DC6 MILP model: computing effort

Computating effort of ODL-DC6	
Iterations	396
Variables	636
Integers	64
Restrictions	676
Non-zeros	1635
Density	0.4
Solution time (in sec.)	0.08

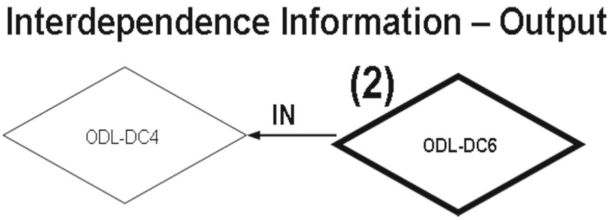


Fig. 23 Interdependence output information of ODL-DC6 (macrolevel)

Table 22 Interdependence output information of ODL-DC6 (microlevel)

Output information/micro DA/ODL-DC6	DA/DC^{Be}		
	DA/ODL-DC4		
IN	$_{x}$ODL-DC6,ODL-DC4	PUfp,d^{1},odc4,t´	
	$_{i}$ODL-DC6,ODL-DC4	costx^{+MB} costx^{-MB}	–
		maxx^{+MB} maxx^{-MB}	–
		others	–

In this paper, only the current ceramic SC-CP process performance was evaluated, although it can be used as a simulator of different collaborative planning scenarios.

Finally, a general overview of the MPM-SC-CP application to the ceramic SC is depicted in Fig. 25.

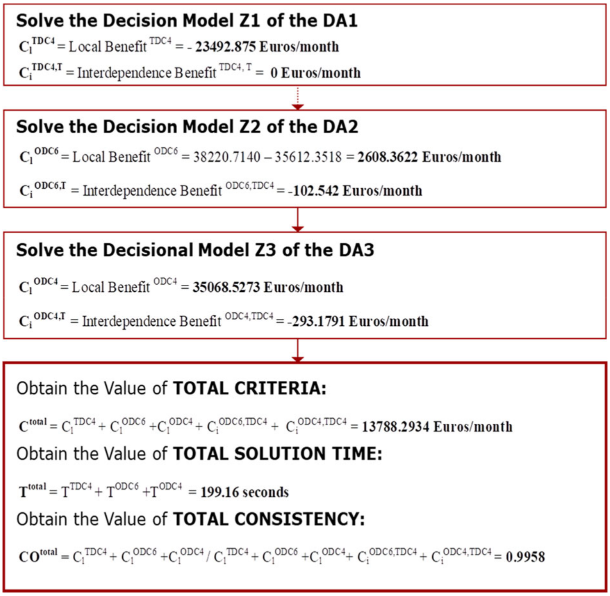


Fig. 24 Integrated evaluation of the performance of the ceramic SC-CP process

5 Results and discussion

As previously mentioned, given the very high magnitude of the analysed ceramic SC, only one part of its SC-CP process was the target for the MPM-SC-CP application.

This subprocess comprises three DA, which are performed by three of the most relevant decision centres. On the one hand, these DA give rise to a decision centre which, after some proposed ‘improvements’, is centralised at a tactical level the operations of manufacturers, warehouses and logistics centres (TDL-DC4); on the other hand, to two decision centres at an operational level (ODL-DC6 and ODL-DC4) with the same actors that depend on one another and also on the previous tactical one. Therefore, the selected subprocess includes both the temporal and spatial integrations, which is one of the main contributions of this paper.

The analysis of the microdecision view for the qualitative characterisation of these three selected DCs means making changes about how to make decisions. These changes improve the decision making in the collaborative contexts in which temporal and spatial interdependencies take place, and also because they made subsequent integrated mathematical modelling and solutions feasible.

The most relevant changes are the following:

- Modifying the temporal characteristics of TDL-DC4. Here it is advised to maintain the 1-year horizon, but with a monthly period (instead of an annual one) to allow more decision points and a closer approximation to reality. For example, the monthly planning period makes it possible to reflect more accurately on the changeovers of product families at a tactical level and to, therefore, better estimate the necessary capacity and costs

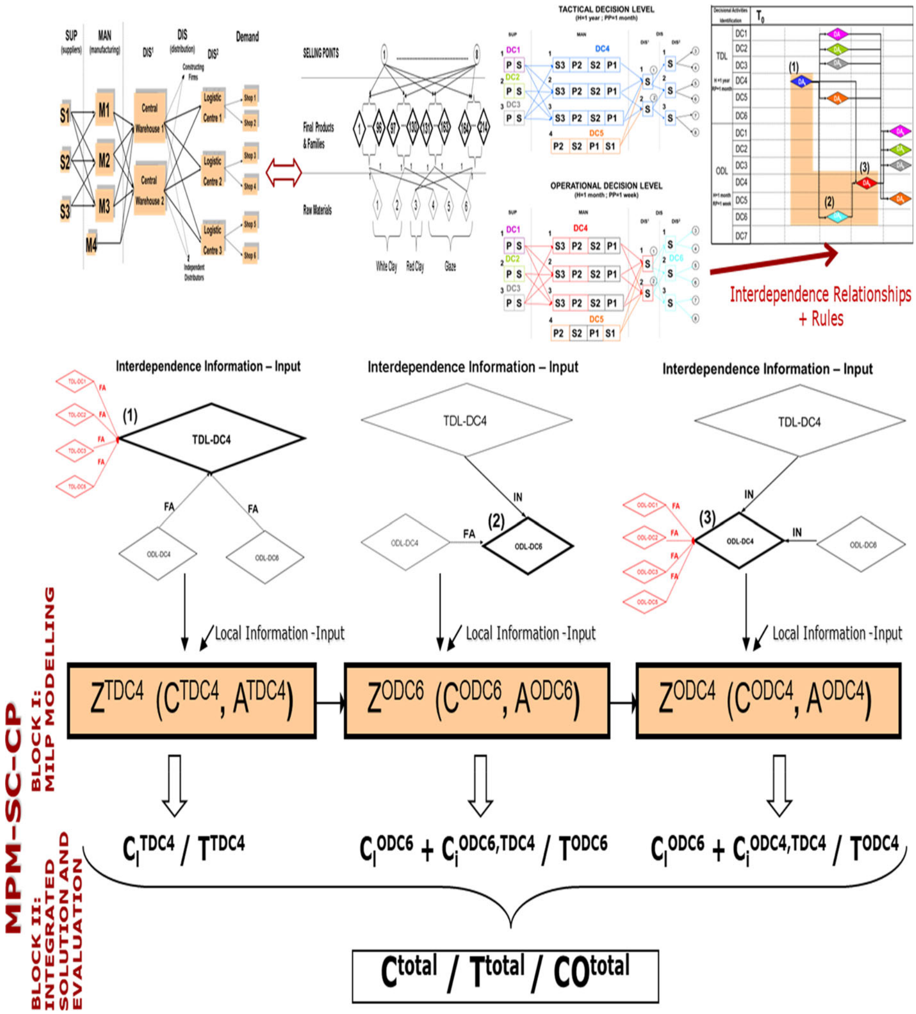


Fig. 25 Overview of the MPM-SC-CP application to a ceramic SC

- Obtaining TDL-DC4 about manufacturing or subcontracting through a single step of tactical decisions (dimensioning productive capacity). This is because these decisions are closely linked with one another and are not simultaneously taken
- Explicitly incorporating TDL-DC4 for decisions about capacity sizing, and more specifically the number of shifts and overtime per production line and decisions about the activation/deactivation of kilns. This dimensioning was previously done implicitly with the annual budget provided by senior management
- Adding for TDL-DC4 the decisions about the distribution stage because, at the tactical level, they are not taken by assuming that its capacity is infinite However, costs were considered low when this stage was also contemplated. It is not difficult to make this change because, although the plants and logistics centres belong to different entrepreneurial entities, they form part of the same business group

- Explicitly modelling coordination mechanisms with raw material and final product suppliers through ‘interdependence’ restrictions
- Making a one-step definition of the decisions by ODL-DC4 (similarly to TDL-DC4), which enbles the simultaneous durationation of the production capacity restrictions on different lines imposed by TDL-DC4 and to maximise profits benefits
- Explicily modelling the changeovers of the final products on lines to optimise costs and capacity consumption

It must also be noted that for the solution/validation of the MILP models of the three selected DCs, some simplifications are necessary. They affect ODL-DC6 and ODL-DC4 because the amount of data that they manage is substantially bigger than TDL-DC4 for being in a lower aggregation state.

This is specifically reflected in the number of final products considered for ODL-DC6 and ODL-DC4 because they only account for approximately 10% of the total of each family. The approximate figure of 10% is taken as representative when determining what percentage of final products are to be selected at the operational level (ODL-DC6 and ODL-DC4) over the amount of final products considered at the tactical level (TDL-DC4). This fact influences the capacity restrictions that are considered when solving the MILP models of ODL-DC6 and ODL-DC4 because they are calculated at the tactical level by TDL-DC4 for all the initial 214 final products.

In any case, these simplifications are consistent with the proposed MPM-SC-CP because the integrated solution and evaluation of the current ceramic SC’s collaborative performance is the main objective, along with the inclusion of all the transmitted decisions between the different DCs and their shared information.

6 Conclusions

Nowadays, SC decentralised decision making is the most usual situation in SC operations planning. Different companies collaboratively plan to achieve a certain level of individual and SC performance while maintaining a good customer service level.

In parallel, optimisation methods, and more particularly those based on mathematical programming, are becoming increasingly more necessary in these collaborative contexts, in which good SC efficiency must be achieved to survive in the competitive arena.

In this paper, a mathematical programming-based methodology for evaluating the performance of supply chain collaborative planning scenarios is proposed (MPM-SC-CP). Two main inputs feed the proposed MPM-SC-CP: a framework and an associated methodology. They support the integrated conceptual and analytical modelling of the SC-CP process.

Although it is true that the use of mathematical programming for collaborative planning has been conducted in many research works in the last decade, no explicit methodology that capture the complexity of reality is described, which leads to sub-optimal results. Additionally, reluctance to collaborate exists because potential benefits are not known.

For all the above reasons, the main contributions of MPM-SC-CP are: firstly, it strongly links the conceptual model of the SC-CP process with its mathematical-based programming modelling by allow to fully capture the complexity of reality; secondly, the way these mathematical models are constructed makes their transferability to other collaborative situations easier if some changes arise by enabling a quick evaluation of different collaborative scenarios; finally, it addresses either the temporal or spatial interactions between the DCs placed at different or the same tactical and operational decision levels, respectively.

Some MPM-SC-CP assumptions are as follows: the different SC DCs make decisions based on MILP models; an organisational context is considered; that is, the collaborative decision process aims to fulfil a global common goal between the different DCs by coordination mechanisms, where no oportunistic behaviour exists; a hierarchical context with only one cycle instruction-reaction.

Two main managerials insights can be extracted from this paper:

First, SC managers, jointly with the SC system designers, can use this methodology to analyse in depth their current SC CP process, in a guided, structured and qualitative manner so that the information embedded in the different views can be easily collected in order to perform the mathematical programming (MILP)- based modelling. This initial analysis not only helps SC managers to have a better understanding of the whole process and how decisions are made but also can suggest them some changes, which arise because the data are collected based on subsequent MILP modelling. These changes, agreed by all SC actors, improve the decision making in the collaborative contexts in which temporal and spatial interdependencies take place between the different decision centres.

Remark that this SC CP definition and integrated modelling is often the most time-consuming phase. SC actors must reconsider some of the traditional agreed matters as well as to qualitatively specify objectives and constraints. Regarding the input data, sometimes are known and easily collected from the SC actors databases, sometimes have to be calculated and in other occasions have to be subjectively estimated as they represent priorities and penalties.

Secondly, SC managers can use this methodology to trace economic consequences of stablishing different collaborative schemes, that is, to know a priori which benefits will be reported. For that, the methodology allows to quantitatively evaluate the performance of the current SC CP process, from the integrated execution of the MILP models as well as potential future scenarios as the way these MILP models are constructed makes it easier to implement any change, since they are strongly linked with the definition of the different visions (physical, organisation, decisional and information). Basically, these scenarios affect to the DC´s decision making sequence, the information exchanged and how this latter one is incorporated into the models of other DC´s.

Finally, although MPM-SC-CP can be extrapolated to any industrial sector, it has been implemented in a ceramic SC. The obtained results allowed not only the evaluation of current ceramic SC-CP performance, but also the suggestion of some changes about decision making and the interdependence relationships of some DCs because subsequent MILP modelling was performed.

No different ceramic SC collaborative scenario was evaluated. Future research could evaluate them to see if they affect each SC view more or less profoundly: physical, organisation, decision or informational. For example, centralising decisions at the tactical level to, thus, lower the number of DCs or change the order in which the MILP models corresponding to DCs are executed, or to increase disclosed information so that some DCs can be better anticipated.

One very interesting line would be for some research works to manage the previously mentioned assumptions.

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Declarations

Conflict of interest No potential conflict of interest was reported by the author(s).

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