This is an Author Accepted Manuscript version of the following chapter: **José Craveirinha, João Clímaco, and Rita Girão-Silva, Mathematical Based Models for Group Decision Support in Telecommunication Network Design and Management–Challenges and Trends**, published in ***Collective Decisions: Theory, Algorithms And Decision Support Systems*, chapter 10, pages 215-246, Studies in Systems, Decision and Control, vol. 392**, edited by **Tomasz Szapiro and Janusz Kacprzyk, 2022, Springer** reproduced with permission of Springer Nature Switzerland AG 2022. The final authenticated version is available online at: http://dx.doi.org/10.1007/978-3-030-84997-9_10.

Mathematical Based Models for Group Decision Support in Telecommunication Network Design and Management - challenges and trends*

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December 2020

In memoriam of Professor Gregory Kersten - a great scientist and scholar

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To the faithful and generous Human Being,
To the irreverent and freethinker Citizen,
To my dearest friend Gregory

João

*This work is funded by ERDF Funds through the Centre's Regional Operational Program and by National Funds through the FCT - Fundação para a Ciência e a Tecnologia, I.P. under the project CENTRO-01-0145-FEDER-029312. This work was also partially supported by FCT under project UIDB/00308/2020.

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Abstract

The extremely rapid evolutions of telecommunication network technologies and services and their interactions with complex socio-economic environments, justifies the increasing importance in applying, in certain areas of network planning, design and management, group decision approaches. In fact, there is a significant number of decision problems focused on issues of network planning and design, of multiple natures, where more than one decision maker intervenes or where it is possible to develop mathematical formulations of the problems considering multiple DMs, representing entities of the network itself. Moreover, the evolution of these networks and related industries leads to a great variety of multifaceted and complex problems, usually involving multiple dimensions, very frequently of conflicting nature. These factors justify the interest in addressing the applications of mathematical based models for group decision support in telecommunications. Although mathematical based models have been developed in the framework of operations research, systems science, game theory, etc., and they are an essential part of group decision and negotiation support systems, the scope of this study is limited to multicriteria models and game theory models. In fact, we believe these methodologies are adequate to discuss the challenges and trends of formal models for telecommunication applications. An outline of more relevant evolutions of telecommunication network technologies and services will be presented, followed by a brief overview of major concepts concerning multicriteria group decision (MCGD) and game theory (GT) approaches and methods, relevant to these areas. After identifying the major domains of application of MCGD and GT approaches in telecommunications, an overview of representative contributions in these areas, based on MCGD and GT methodologies, will be put forward. Finally, an analysis and outline discussion of current and future research trends and challenges concerning the use of MCGD and GT approaches in this broad area of decision support, also focusing on some relevant methodological issues, will be presented.
Keywords: Multicriteria group decision, Game theory, Multicriteria decision analysis, Telecommunication networks, Network design, Telecommunication policies.

1 Introduction and Motivation

Telecommunication networks and technologies, as well as the services they support, have been subject and are expected to continue in a process of very fast evolution. This has been fostered by an exponential increase in offered traffics, of multiple types, in parallel with a drastic increase in the demand for more advanced services, with better QoS (Quality of Service). These mega-trends constitute a process of the outmost importance, not only concerning technological advances, but also with respect to their great impacts on the economy and on the society as a whole. The evolution of these networks and related industries leads to a great variety of multifaceted and complex problems, usually involving multiple dimensions, very frequently of conflicting nature. This is related to strong interactions between the complex socio-economic environment of societies and the extremely fast evolution of telecommunication networks and services. Moreover, there is a great number of decision problems focused on issues of network planning and design, of multiple natures, where more than one decision maker (DM) intervenes, such as managers, regulators, network designer experts, for which it is possible to develop mathematical formulations of the problems considering multiple DMs, representing entities of the network itself.

These factors clearly justify the interest in using, in this broad problematic area, group decision evaluation approaches concerning multiple problems of network planning and design. These issues and also some reflections raised by the past research experience of the authors in some of these problems, laid the *leitmotiv* for this work, namely an overview on mathematical based models for group decision support, let it be multicriteria group decision (MCGD) or game theory (GT) models.

Here, we would like to draw attention of the reader to two texts that, in some sense, are the memory of the participation of Gregory Kersten in two conferences – MCDM 94 and GDN 2008 – organized by our research team in Coimbra, Portugal. Namely, [1] and [2]. We believe that the first is useful for introducing the reader to the roots of this research area, and the second one gives a broad idea of its evolution.

We will also discuss major trends and challenges of MCGD and GT in relation to current and expected evolutions of telecommunication networks in a near future.

This contribution is organized as follows. In the next section we will outline most relevant evolutions of telecommunication network technologies and services, emphasizing recent developments in relation to group decision problems. Also in this section we will include a brief overview of major concepts concerning MCGD and GT approaches and methods, relevant in the considered application areas. In Sect. 3 we present an overview of applications of MCGD approaches to telecommunication network planning and design problems, including strategic planning issues. Also an identification of the main areas of application of GT approaches, where a very large number of papers has been presented, will be put forward. An overview of some representative papers will also be presented, in order to illustrate typical applications and formulations of GT in each of these areas. Furthermore, in these overviews we will seek briefly discuss main modelling and methodological aspects of MCGD and GT applications in these areas. Finally, a discussion of current and future trends and challenges in these areas, will be outlined. Particular attention will be paid to modelling and methodological issues concerning MCGD and GT approaches.

2 Telecommunication Networks and Group Decision Analysis

2.1 Highlights on Telecommunication Networks Evolution

The first integrated service broadband networks based on the ATM (Asynchronous Transfer Mode) technology, developed in the 90's, were rapidly abandoned after 2000. This basically resulted from the emergence of cost effective multiservice Internet based technologies, supporting the implementation of connection oriented services and advanced QoS routing and network management mechanisms. In subsequent years MPLS (Multiprotocol Label Switching) and GMPLS (Generalized MPLS), based on optical networks, emerged as more advanced technologies for use in IP (Internet Protocol) based networks. These evolutions were supported, at the level of the transport telecommunication infrastructure – *wired transmission networks* – by the development of advanced optical networks with extremely large bandwidths associated with a great number of very low wavelengths that may be carried by the optical fibers. Another area where there have been extremely rapid evolutions concerns *cellular mobile wireless networks*, driven by the exponential increase in the demand for mobile data services, namely Internet access. The widespread of 4G (4th generation) networks that are interoperable with existing wireless standards, enabled significant improvements in QoS performance and provided an extensive range of services, including HD (High Definition) broadcast, video calls and mobile TV, as well as a multitude of applications for entertainment, business, social networking, education, and so on – see [3]. Other important aspect should be mentioned, concerning new types of service demand, namely the unprecedented increase in *cloud computing* and the emergence of *IoT* (Internet of Things) in which a plethora of devices are equipped with electronic systems, sensors and software, enabling to exchange data through the Internet. The current step in this technology evolution, the 5G (5th generation) mobile networks is expected to provide important quantitative and qualitative advances regarding increased bandwidth and transmission latency. Also, multiple wireless technologies for data/computer networks of various sorts have been developed such as *Cognitive Radio*, *Multi-Radio*, *Wireless LANs*, *Fiber-wireless (FiWi) Access*, *Ad-hoc wireless Networks* including *Ad-hoc Sensor networks*, that pose new problems of network design typically involving multiple technic-economic dimensions. A new technological paradigm that was devised for overcoming important limitations in the working and management of current network structures is Software Defined Networking (SDN) (the basic concept underlying SDN is the separation between the control logic of the network and the devices that implement the forwarding of traffic flows).

We also would like to draw attention to the increasing relevance of multidimensional QoS/QoE (QoE-Quality of Experience, i.e. the multiplicity of performance measures as perceived by the end users, e.g. service availability or communication latency, in a given service) in relation to the various technological platforms. Note that the possible interplay between various technologies, both in wired and wireless networks, in the different functional layers of communication networks, enables the use of a great variety of network architectures and technical solutions in terms of network design.

These trends lead to many new decision problems in multiple areas of network planning, design and management where, frequently, multiple criteria, possibly conflicting and of incommensurate nature, are at stake. This led to an increasing interest in using multicriteria approaches. Furthermore, in various of such problems, namely involving market competition, selection of vendors or evaluation and selection of techno-economic alternatives (or of similar nature) there are several DMs intervening in the decision process. This opens clearly a field for the development of MCGD and Game theoretical approaches for tackling several of these problems, as shown in the overview in Sect. 3 of this work.

2.2 Formal mathematical models – Brief overview

Although mathematical based models have been developed in the framework of operations research, systems science, game theory, etc., and they are an essential part of group decision and negotiation support systems, the scope of this study is limited to multicriteria models and game theory models. In fact, we believe these are adequate for discussing the challenges and trends of formal models for telecommunication applications.

2.2.1 Multicriteria Analysis

In recent years, multicriteria decision analysis (MCDA) models have been used in some telecommunication group decision problems – see Sect. 3.1.

Considering that different and conflicting criteria are involved in the model, the concept of optimal solution should be replaced by the concept of non-dominated (also designated as Pareto optimal or efficient) solutions set.

In general, we can state that MCDA approaches seek to obtain one or more non-dominated (or at least approximately non-dominated), solution(s) which may be considered as satisfactory by the DM(s). An important issue in developing these types of models is to evaluate *a priori* if there is the possibility of using interactive procedures, especially taking into account the required speeds of calculation, for a given application. This means that, in certain areas of telecommunication network operational design, an interactive procedure cannot be used because of the time consumed in an interaction, such as in the case of dynamic routing or real-time bandwidth assignment models. The above considerations refer mostly to multicriteria/multiobjective mathematical programming based models, that may be linear, non-linear and, in many cases, may have a specific structure, resulting from the particular features of the addressed problem and of the used mathematical formulation. For instance, [4] argue the adequacy of reference point methods for decision aiding in some telecommunication problems.

There is another type of MCDA models, normally designated as *multiattribute decision models*, that also have suffered significant developments and have important application in certain telecommunication decision problems (including group decision models), for example in the area of market competition and techno-economic evaluations. It should be noted that, while in multicriteria mathematical programming formulations it is assumed that the set of feasible solutions (or alternatives) results implicitly from the constraints, in multiattribute models a discrete and small set of alternatives is specified explicitly. The alternatives in this set have to be analyzed by the DM(s) with respect to the considered criteria (or attributes). It is important to note that in multiattribute decision models it is possible for the DM(s) to carry out a more detailed evaluation of the alternatives and consider a larger consistent family of criteria. Moreover, this can be done without having to pay the price of a computational explosion. Nevertheless, in a large number of problems of network design (such as in typical routing and facility capacity related problems) this may lead to a reductive point of view, which may be unrealistic since it does not enable an adequate exploration of the decision space.

Concerning multiattribute models, we can identify, in the so-called American School, the construction of completely compensatory approaches, where a linear or non-linear multiattribute utility function (defined in the framework of multiattribute utility theory) is used [5]. As for the Analytical Hierarchy Process (AHP) method, it can be viewed as a specific branch of the American School, involving the identification of a hierarchy of interrelated decision levels [6, 7, 8]. AHP models have been used in several telecommunication multicriteria group decision models as it will be reviewed in Sect. 3.1. Moreover, it must be referred to a ranking approach, TOPSIS – Technique for Order Preference by Similarity to an Ideal Solution [9], also used by many authors in the works reviewed in this paper. The use of TOPSIS in these problems is probably due to the fact that it is very simple, comprehensible and computationally efficient. In a few words: ideal and anti-ideal solutions are calculated; a metric is used to calculate the distance of each alternative to these points. Finally, alternatives are ranked according to this coefficient representing the relative closeness to the ideal solution. Note that this coefficient is obtained for each alternative, from the distances to the ideal and anti-ideal solutions.

Furthermore, there are non-compensatory approaches (of the so-called French School), not allowing a complete ranking of alternatives, hence not guaranteeing the principle of optimality, that is neither transitivity nor full comparability of alternatives are verified. Therefore, we can say that their results are less conclusive with respect to the aggregation of the preferences of the DM in comparison. A most relevant methodology of the French School, is the ELECTRE family of methods [10, 11]. Resulting from the features of the problem, the purpose of ELECTRE is the classification of alternatives, the ranking of alternatives, or selection of the most preferred alternative.

More recently, multiattribute and mathematical programming approaches such that the preference aggregation is based on inductive rules, were developed. In particular, the approaches which are rooted in an adaptation of rough sets concepts must be mentioned [12].

Although other multiattribute methods, namely outranking approaches, should be tested in the addressed application areas, till now, as far as we know, only compensatory based approaches were applied to group decision frameworks dealing with telecommunication problems. In the literature we can find MAUT, AHP, TOPSIS and VIP-Analysis. VIP-Analysis (Variable Interdependent Parameters Analysis), which is structured according to MAUT, is an interactive software package dedicated to the choice problematic of the evaluation of a discrete set of alternatives according to a multiattribute additive value function [13, 14]. The principal characteristic of this tool is that no precise values, for the scaling constants/weights, are required. Instead, it can accept imprecise information (i.e. intervals and/or linear constraints) on these values, usually identified by indirect ways, as for example by comparing swings, by ordering scaling constants, etc. The major objectives are the identification of robust conclusions (holding for every feasible combination of the scaling constants), and secondly identifying what is the variability of the results due to the imprecision in the parameter values.

Interactive tools, and in particular learning oriented tools, as VIP-Analysis, seem to be the most interesting in many future developments. In fact, as it is emphasized in [15], in most of the situations "... the intended help does not consist of showing the various actors involved in the course to follow, but rather of constructing a set of coherent recommendations that contribute to the clarification of the process. Thus, the models' goals and values do not run the risk of being replaced by any calculated rationale".

It must be emphasized that MCGD Support is mostly concerned with cooperative group decision, rather than with negotiation processes, though the frontier between these two decision settings is often fuzzy. In fact, MCGD deals with common sets of alternatives and objectives, while in negotiations the proposals are sequentially presented by parties, which involves making concessions. This peculiar interdependence among actors, "rather than conflict, distinguishes negotiation from other forms of decision making" [16]. Nevertheless, as it is explored in [4], multicriteria interactive decision tools can be useful in a preparation phase of negotiation processes. Furthermore, as analyzed in [14] specific group decision problems where the DMs involved may have significantly different and divergent priorities cannot be excluded from consistent and adequate treatment by MCGD approaches. The architecture of the group decision support tool is a key point regarding this issue. See, e.g., in [14] the proposed architecture that makes VIP-Analysis adequate for group settings. Extensions of the methodology of the VIP analysis to address explicitly the differences among the DMs in terms of the weight space are in [17].

2.2.2 Game Theory

As it is stated in [15], "Game Theory is dedicated to the choice of an optimal strategic behavior of two or more rational players (decision agents) interacting strategically. Cost and benefits of each option for one player depend on the choices of the other players" (so decision agents take into account the interdependence of their decisions) and constitute the so-called payoffs of each player. "It is clearly a rigorous approach for dealing with conflicts". To foresee the result of a game, the analyst must focus his attention on possible combinations of the strategies, as the interaction among the strategies of the players determines the outcomes

Remembering that game theory is particularly appropriate to deal with the economics of imperfect economy and that telecommunications live a stormy period immersed in deep and sharp alterations of technology, it seems an adequate approach to address some of its fundamental issues. So, it must be emphasized that this type of mathematically based models is a potentially suitable tool for many telecommunication group decision problems, where, for instance, the analysis of the stability of outcomes is one of its key issues. Many researchers have exploited a great number of game theory approaches, some of them considered in the papers reviewed in Sect. 3.2.

Nevertheless, many situations of complex real applications are not adequately tractable by GT due to the need of oversimplifying the models. Otherwise, it would be impractical to put them into operation. Plus, as it is emphasized in [18]: "The weakness of game-theoretic approaches includes the treatment of the process and its impact on the game itself, and strict rationality assumptions which, for numerous reasons, rarely hold (e.g. imperfect information, parties cognitive limitations, and deception) ... Thus, while game-theoretic methods have a significant role to play in the prior or posterior analysis of the group decision or negotiation problems, their usefulness as a support tool during the process is limited."

Next, we make a very short summary of some Game Theory key concepts relevant in the applications overviewed in Sect. 3.2:

- We can classify the games as cooperative, when there is cooperation among the players, and non-cooperative otherwise. Note that in many situations cooperation and conflict can coexist.

- A game is static when all players make their moves simultaneously and independently. On the other hand, in dynamic games the moves of the players may happen successively, the most common case in the application to network design models (such as in models of channel and bandwidth assignment, routing and congestion control).

- A zero-sum game is a game where the sum of payoffs of the players is zero, independently of the chosen strategies.

- Pure strategies of a player are the strategies belonging to his space of strategies.

- A mix strategy of a player consists of selecting it randomly, assigning probabilities to the strategies belonging to the strategies space of the player. It is chosen when the player is indifferent regarding pure strategies.

- An equilibrium is a combination of strategies formed by the "best" strategy for each one of the players.

- A strategy of a player is dominant if all the others are strictly dominated; and a strategy is strictly dominated by another one if it is strictly worse than the second one, independently of the choices of the other players.

- An equilibrium of dominant strategies is a combination of dominant strategies including a dominant strategy of each player.

- A Nash equilibrium (NE) is a combination of strategies such that no player takes advantage of dodging from his strategy assuming all the others maintain their strategies. So, in equilibrium, the strategy of each player is the best answer to the strategies of the others.

- A combination of strategies is Pareto optimal if it is not possible to improve the payoff of a player without worsening the payoff of at least another one.
- A game is a perfect information game if a player knows the full history of the game when he/she makes a move. Otherwise it is an imperfect information game.
- A game is a complete information game if the rules of the game (structure and payoffs) are common knowledge of the players.
- Evolutionary games assume the players learn about the process progressively. Their strategies are obtained by trial and error. So, it is assumed that complete rationality of the players does not occur in practice many times.
- Repeated game: a modelling interaction in a repeated manner, in cases where the players interact several times.
- Mean-field game theory considers strategic decision making in very large populations involving small interactions among the decision agents.

3 Overview on Applications of Formal Mathematical Models to Group Decision in Telecommunication Networks

3.1 Applications of Multicriteria Group Decision Approaches to Telecommunication Networks

Herein, we will present an overview of works focusing on the application of Multicriteria Group Decision (MCGD) to telecommunication network planning and design.

An area where there has been a number of proposals on applications of MCGD has to do with problems related to *competition in telecommunication network markets* including the role of regulatory entities, or management related decision problems. This includes as typical decision problems: vendor selection by a telecommunication company, the role and influence of regulatory entities or the selection of a manager for a telecommunication company. Also, there are works concerning the evaluation and selection of technological or architectural network solutions, usually in association with cost and/or investment analysis, in a given market context, which we may designate as *techno-economic evaluation* problems. These two types of issues may be aggregated in a broad area which we will identify as a *competition and evaluation decision problem* domain. In this area we may include also the contributions on applications of MCGD approaches to specific operational design problems in *wireless networks* and the evaluation and selection of *routing methods* in wired networks.

Firstly, we will refer to some papers that, although not addressing *per se* a group decision making problem (that is how a given group decision problem could be supported with a given modelling and decision support method approach), seem very useful in tackling preliminary and conditioning issues of problem modelling and decision support method implementation.

[4] present an overview of multicriteria analysis methods that may be applied to the planning and design of telecommunication networks, focusing on important methodological issues. The authors identify design and management problems where MCDA techniques can be used and show why they are particularly adequate for dealing with such problems, involving multiple criteria, giving particular attention to the possible application of reference point methods. This paper also discusses, in realistic *problems of strategic management*, involving several DMs, how MCDA methods could be used by the DMs as an adequate methodological tool in a preparation phase of a negotiation process. In [19] a model of analysis on *de facto* interaction between regulatory actors (within a given country) involved in making regulatory decisions about the telecommunications market, is presented. It uses inferential Social Network Analysis (SNA) techniques to analyze the dynamics of the relationships of the DMs/actors (including regulators, operators and user organizations) and the underlying factors. The second part of the proposed data analysis method involves hypotheses testing, using a technique of inferential network analysis with Exponential Random Graph Models (ERGM) by [20] – a statistical technique of inferential analysis with relational data that uses the characteristics of nodes (corresponding to DMs) and links (types of relations between DMs, in the form a network). [21] analyze factors influencing the process of decision making in the telecommunication sector concerning the capabilities of the DMs and of the organizations, namely company management. A statistical software of regression analysis is used to implement the analytical model. [22] provide a systematic analysis of technical and economic frameworks for the metrics involved in the characterization and performance evaluation of broadband networks in the context of the fast growing digital economy, based on OECD recommendations [23, 24]. A comprehensive list of the metrics of different classes and their features as well as of the associated measurements, is presented.

Another important issue related to the practical implementation of MCGD, is the characterization, from a decision science point of view, of communication technologies and techniques which can be used for supporting MCGD tools in a geographical distributed environment. This issue is thoroughly analyzed in [25] where it is proposed that four sets of dimensions for evaluating the features of communication systems/technologies adequate for implementation of a MCGD friendly electronic environment, be considered.

We will now address concrete contributions of MCGD models in the wide area concerning *competition and evaluation decision problems*.

In [26] a very important decision problem in the telecommunication industry market is addressed: the selection of a vendor of a telecommunication system by a telecom company, considering a MCGD approach. A key issue of the decision aid model is centered on the identification and prioritization of the criteria and sub-criteria for vendor selection through a systematic approach based on the inputs of the DMs, originated from different functional departments of the company, taking into account the existence of conflicting criteria. The authors then develop a AHP model for tackling this problem, considering a four phases approach. [27] present a MCGD approach for selecting a manager of a telecommunication company by using a fuzzy set based methodology. The authors use Type-2 fuzzy sets (cf. [28]) and consider three kinds of fuzzy ranking methods, proposed in [29], based on arithmetic average, geometric average and harmonic average operators, for computing the ranking of the fuzzy intervals. The DMs inputs to the model are made through the specification of fuzzy numbers (concerning the relations between alternatives and the criteria values) and criteria weights. The results of the model are compared with those of a TOPSIS method based on Type-1 fuzzy sets (originally defined in [30]) for a numerical example.

Let us now consider a network design area where evaluation/selection methods based on MCGD approaches have been proposed: wireless networks.

[31] propose a MCGD model for dynamic selection of a RAT (Radio Access Technology) by a call or multiple calls in a Heterogeneous Wireless Network (HWN). These are particular types of wireless networks where an end-to-end connection may use different technological platforms such that a service demand (call) or a group of calls (from an end user), originated at a Multimode Terminal (MT) has to select one of the available RAT telecommunication systems/networks. Note that both the calls/groups of calls (corresponding to the DMs/groups of DMs in the MCGD model) and the available RATS may vary in time. Each user is supposed to specify his/her preference information for choosing a particular RAT for each class of calls, in terms of weights associated with the RAT selection criteria, concerning different technic-economic attributes. A dynamic RAT selection algorithm using the fuzzy TOPSIS MCGD method in [32] is then described and its performance analyzed through simulation. The same type of decision problem as in [31] is addressed in [33] where a network, in a set of available networks with different technologies, has to be selected (in an automated manner) at a MT terminal, by considering that each service profile demand corresponds to a 'DM'. The MCGD model

uses the AHP method for obtaining the weight vector of all network attributes for each service, then enabling to synthetize these weight vectors. A utility function is used to calculate the utility value of each network attribute, that is it represents the degree to which a certain 'DM' (corresponding to a service class) is satisfied with that attribute for each available network with a certain technology. The aggregation of the attribute utility values, results from a weighted sum, constructed from synthetic performance matrices previously obtained from network design experts, using the method in [34].

The performance *comparison of routing models* in telecommunication networks, usually implies the necessity of an evaluation in terms of multiple, potentially conflicting, frequently incommensurate criteria, often involving imprecise information regarding the relative importance of the various network performance criteria. This is particularly relevant for flow-oriented, decentralized routing optimization methods, having in mind their inherent limitations (see e.g. the analysis in [35]). In the short paper [36] a multicriteria decision problem concerning the evaluation and selection of flow-oriented, decentralized, optimization routing models in telecommunication wired networks, is formulated. In the proposed model various measurable network performance attributes are considered that enable the evaluation of the global effect in the network of using the various routing methods. Moreover, it is assumed that the additive value function to be used in this interactive decision model should be inherently prepared to deal with imprecise information, associated with the scaling constant values (also designated as importance parameters or weights), ascribed to a DM for each attribute. The features of a MCDA method for tackling this problem, based on the VIP-Analysis software in [13], also considering its possible extension to a cooperative group decision setting, are outlined. An overview on this issue, concerning *comparison and selection of routing models* and the complete development and application, in a given network setting, of a MCDA method with the above methodological features, are described in [37]. The adequacy of the features of this interactive multiattribute decision analysis model, based on the VIP software, prepared for coping with imprecise preference parameters, are analyzed. The proposed method is applied to a case study in a reference network setting in the context of Carrier-Ethernet and MPLS-TP (Multiprotocol Label Switching - Transport Profile) technologies, as described in [38]. Also the extension of this approach to a face-to-face cooperative group decision (with a facilitator) situation is carried out. The interplay between a tolerance parameter defining quasi-dominance relations between two alternatives and α-majority relations concerning preferences elicited by the DMs is analyzed, following the concepts in [14], and applied to the case study.

3.2 Applications of Game Theory Approaches to Telecommunication Networks

There has been a very large number of papers concerning applications of game theoretical approaches to communication network planning and design for the last two decades. We would like to refer that a complete overview of papers on game theory applications in these areas is out of the scope of our contribution. Instead, we will discuss main modelling and methodological aspects of these approaches and key issues vis a vis other Operation Research based approaches of different nature, namely MCGD (Multicriteria Group Decision). We will also present an overview of some representative papers, illustrating typical applications and formulations in the main areas where GT has been applied.

We will begin by identifying the main application areas and sub-areas of GT in this context. Firstly, we can consider decision problems concerning *competition in telecommunication network markets*. Also a problematic area of decision problems focused on *techno-economic evaluation* and selection of technologies/technical network solutions and/or strategic investments, can be identified, similarly to what happens in MCGD applications. It is important to note that the players (or decision makers, DMs) of the game models in these two broad areas – which we have identified in the previous subsection as 'competition and evaluation problem domain' – are essentially human agents external to the networks, namely company managers, service directors, network designers, customers or a mix of similar agents. Therefore, from this point of view, *unlike what happens in the other areas of application of GT in telecommunications*, as identified hereafter, alternative approaches to GT in these two areas are precisely multicriteria group decision approaches (MCGD).

The other main areas of GT applications where there has been an explosion of publications refer to problems of network design – classically encompassed in the category of *network operational planning* – have been focused on a great variety of technic or technic-economic issues, namely: *Wireless network design* (usually data packet networks with multiple technological and architectural types including ad-hoc structures); *Medium access control mechanisms* (in different types of networks); *congestion control in Internet type networks* and *routing methods* (in various types of networks). An overview of some representative contributions in these areas, will be presented next.

We would like to draw attention to the fact that, in these network design areas, the 'players' of the GT approaches are typically technical entities internal to the system/network upon which the decision falls on, such as routers, switches, base stations, moving transceivers, satellites or centralized network management entities, typically represented by nodes (or particular sets of nodes) of the network representation. The strategies of each player of the formulated game are technical actions (for example channel assignment, bandwidth allocation in a link or choice of an end-to-end route for given traffic or service demand). The payoffs are expressed through utility functions encompassing QoS and/or economic related measures. This means that the definition of 'players', in this context, is a conceptual artifice so that these decision problems may be formulated mathematically in GT terms, thence having an inherent nature different from the DMs in MCGD, assumed as agents external to the system, usually human. Therefore, we can state that, in these particular areas, unlike in the *competition and techno-economic evaluation problem domain*, MCGD should not be considered as the alternative methodological choice to GT. Instead we can state that the alternative OR approaches to GT, in these areas, are single or multicriteria decision approaches (with one DM alone), mainly based on mathematical programming (and, in particular, in network flow programming), combinatorial optimization methods or on optimal control algorithms.

Regarding the GT approaches to Internet design problems, very common in the literature, these have three fundamental elements: a set of players (congestion-sensitive data flow sources, typically the routers or a subset of routers), a set of possible actions/strategies for each player (congestion control and/or channel/bandwidth assignment strategies or, in routing design, a concatenation of transmission links), and a set of utility functions (such as throughput, packet delay, other quality of service parameters or pricing related parameters).

[39] present a comprehensive survey of applications of game theoretical approaches to telecommunication network design problems, which can be considered as a particular application domain of 'networking games'. The authors identify some of the mathematical challenges and methodologies that are involved in these problems and classify, under different telecom network design topics, a quite significantly large number of publications in this area. Also particular attention is paid to the application of NE solutions or its variants, namely by applying equilibrium concepts used in transportation networks. Also in [40] it is presented a review of basic concepts of GT and a summary overview of possible applications to the design of communication networks.

Next, we will refer to papers representative of each of the identified application areas.

Market competition and techno-economic evaluations The early reference [41] reviews concepts and game theory models related to the 'struggle for the first move' and the origins of cooperation in the context of the modelling of the economics of imperfect competition (namely in duopoly or oligopoly scenarios) in the *telecom network markets*. Some broad considerations concerning the game theoretical models that could be used in different conditions and an analysis of advantages/disadvantages of cooperation versus confrontation of the incumbent operator with new competitors when facing the expansion and exploration of optical networks, are put forward. Note that although the application context of this publication is much outdated some of its broad conclusions may be useful in similar telecommunication oligopolistic contexts. One of the first publications concerning the application of game theory approaches to the *analysis of competitive markets in telecommunications industry* is in [42]. The authors describe a general analytical model for this purpose, using an *evolutionary game theory* approach based on the theoretical framework in [43, 44]. Different scenarios of possible strategies of the incumbent/primary operator and of the newcomers are constructed, considering mixed strategies. A work in [45] presents a methodology, coupled with the detailed description of a game theory model, for *techno-economic evaluation* of the market competition for 3G mobile networks, involving two operators: a dominant operator and a newcomer competitor. The payoff functions of the players, defined in terms of NPVs (Net Present Values), represent the techno-economic evaluations of each competitor and are described in terms of NPVs concerning investments, costs and revenues. The authors apply the resulting non-cooperative game model to a case study developed in European Projects, to obtain NE solutions. [46] present a full game-theoretic analysis model for another type of problem in a telecom market, focused on competing telecom service providers and concerning the *migration of customers* from one operator to another. Assumptions are made regarding the customer behavior (a 4-state Markov model, for two providers) and the strategies are defined through the retention times imposed by the losing provider; the utility functions also depend on the net revenues of retaining the customer and the sanction cost resulting from the possible suing in court of the operator by the customer. The application of the mathematical model to a simplified setting shows that both stable and unstable NE solutions do exist.

Wireless networks In [47] a review on GT approaches in wireless networks, mainly focusing on network design problems concerning power control, radio channel access control, cooperation between mobile terminals and security, is presented. [48] present an updated review on papers with applications of game theory approaches to wireless networks, namely *wireless local area networks* (WLAN), *wireless sensor networks* (WSNs), *ad hoc wireless networks* (AWNs) and *satellite communication networks.* These approaches are based on the fact that the network nodes (the 'players') compete for network resources, mainly data transmission wireless channels and associated bandwidths. Furthermore, in many situations, a node needs the other nodes' collaboration to relay the data message, situations which can be associated with price coefficients. The review is particularly focused on problems concerning the choice of resource allocation strategies taking into account QoS objectives and relay pricing and in problems involving energy efficiency objectives.

A game theoretic model for the problem of spectrum pricing in a *cognitive radio network* where multiple primary service providers compete to offer spectrum access to the secondary users, is described in [49]. Cognitive radio networks are a special type of the software defined radio networks concept where it is possible to operate in multiple frequency bands by using multiple transmission protocols and to estimate the communication parameters so that the users can adapt to a changing communication environment. This approach is formulated in terms of an oligopoly market problem with a few firms and a consumer. A dynamic game model for price competition is formulated to analyze the impacts of several technical parameters on the NE. The players in this game are the primary services and the strategies of the players concern the prices per unit of spectrum. An interesting conclusion of the case study, with two primary services, is that the NE solution is inefficient in the sense that is not Pareto optimal with respect to the total profit of the primary services and that a collusion among primary services could be obtained in order to maximize such profits. A similar problem, focused on the spectrum sharing among a primary user and multiple secondary users is tackled in [50], also using a dynamic game approach.

Another problem, concerning adaptive channel allocation, in cognitive radio networks, was tackled in [51] using a GT approach. The authors consider possible utility functions for selfish and for cooperative nodes (the players), depending on several technical parameters related to transmission quality and discuss the advantages and limitations of such functions in relation to the game resolution algorithms and their theoretical properties.

Another problem of *channel assignment* in a special type of wireless networks – MRMC (*Multi-Radio Multi-Channel Wireless Networks*) with mesh topology – MRMC Mesh Networks (these are broadband wireless access networks in the user premises, such that the routers are mutually interconnected and use multiple transceivers that can be tuned to multiple non-overlapping channels) – is tackled in [52] using a game theoretic model. The model is a non-cooperative game with incomplete information where the players correspond to flows originated by end nodes and considers a network structure with multiple transmission collision-domains. This model is shown to converge, in certain conditions, to a stable NE solution and a distributed algorithm is obtained for its resolution in finite time. This work extends the analysis of the pioneering work in this area in [53] and particularly the results in [54] which addressed the same problem, formulated in a single collision domain network and where it was proved that this type of game converges to a stable NE solution such that each node gets an equal share of the channel resources. [40] address the same problem of channel assignment in MRMC networks with multiple collision-domains, now considering a non-cooperative bargaining mechanism among end users. The motivation for this variant of the game theoretic model in [52] was the fact that, in these networks, the NE solution of the pure non-cooperative formulation does not always lead to maximal data rate (throughput) for end users; experimental results of the case study confirm that non-cooperative games with bargaining can, in many instances, perform better than NE, in terms of end-to end throughput. An extension of this non-cooperative game model study for the same type of MRMC Mesh Networks, now considering network topologies with explicit channel interference constraints, is presented in [40]. These works are closely related to [55] which also addressed the same problem and extends the initial result of [54] by showing that it is possible to obtain NE solutions by requiring a payment from each player, that enables that optimal fairness (defined as the minimum of the max-min throughput difference, for all users) be attained. [56] also studied a channel assignment problem in *multi-hop ad-hoc wireless networks* modelled as a static cooperative game, in which some players collaborate in order to achieve high data rates across end-to-end paths. The authors derive the necessary conditions of a 'min-max coalition-proof Nash equilibrium' allocation scheme which aims at maximizing the throughput of the transmission links. [57] present an overview of applications of game theoretical approaches to another particular type of ad-hoc wireless network that recently has gain increasing interest: *wireless communications with Unmanned Aerial Vehicles (UAVs)*. In these ad-hoc networks UAVs equipped with high performance transceivers, are used as data relay transmitters, working as aerial base stations to provide services in geographical areas without network infrastructure and also enabling interconnections to ground stations. The addressed design problems are specially focused on the optimization of energy consumption, enhancement of network coverage and connectivity improvement. For example, in [58] a non-cooperative game theory model with perfect information for locating the UAVs, is proposed. The UAVs act as players that seek selecting the best actions (in a set of flying instructions) to maximize the number of mobile users for which the UAVs provide coverage. The game theoretical solution is compared with evolutionary algorithm solutions according to various technical criteria. A power optimization problem in this context is tackled by [59], considering the use of periodic beaconing for UAVs that act as substitutes of aerial base stations. The UAVs are the players of a non-cooperative game model where each payoff function is defined as the difference between the successful encounter rate and energy consumption during the beaconing period and the strategies correspond to the beaconing periods scheduling. The conditions for the existence and uniqueness of the NE are checked and the scheduling procedure is tested via simulations.

Medium access control mechanisms Another important issue in some wireless networks is the design of *medium access control mechanisms*, that is the mechanisms that determine the access and share of a wireless channel by contending wireless nodes. This is in fact a complex optimal control problem (see [60]) and several techniques may be used with the aim of obtaining high throughput, low packet collision frequency and improved fairness. [61] put forward a GT model for tackling this issue, called 'random access game', a game in which the wireless node's (player) strategy is its channel access probability and its payoff function includes the utility gain from channel access and the cost associated with packet collision. A general mathematical framework for this game and its application to single-cell wireless LANs (Local Access Networks), and multicell wireless LANs is presented and the existence and convergence properties for NE solutions, in certain conditions, are derived. Also, a practical medium access procedure for distributed control is proposed.

A particular problem of medium access control in a specific type of wireless network architecture – *Fiber-wireless (FiWi) access mesh networks* (where the fibers go as far as possible from the central office and then the network becomes wireless at the front, up to the end users) – is tackled in [62], using a repetitive game approach. The players are certain nodes of the network, corresponding to the forward routers, and the strategies of a player indicate the cooperation levels that it uses in every stage of the game, in terms of how much bandwidth that wireless router needs to share for 'foreign' traffic forwarding; the aim is that services of local users and services of foreign users can have access to bandwidth in the available channels in a balanced way. Preliminary results indicate that NE solutions are possible, depending on the parameterization of a scheduling algorithm.

Another important technical problem in wireless networks is the design of *power control mechanisms*. This problem, in conjunction with the pricing of a single resource among several users, is addressed in [63] in the context of *CDMA (Code Division Multiple Access) mobile wireless networks*, via a non-cooperative game theoretic approach, using a cost function depending on power levels (pricing component) and signal-interference ratios (transmission utility component). The underlying optimization problem for each user is to minimize its cost, given the sum of powers of other users as received at the base station. The existence and mathematical properties of the NE solutions of the game are analyzed and two practical control algorithms, based on this formulation, are presented.

Congestion control in generic Internet-type networks A critical problem in Internet-type networks is the design of the *congestion control mechanism*, since the congestion control algorithm of the TCP (Transmission Connection Protocol), was introduced in 1988. An in-depth mathematical analysis and modelling study for this type of algorithms was addressed in the pioneering work of [60] where the resource allocation problem underlying the congestion control design, was addressed as an optimal control problem involving a non-linear mathematical programming formulation (maximization of the sum of user utilities within the bandwidth constraints of the links). Primal and dual algorithms were proposed and their equilibrium and dynamic properties, focusing on fairness, delay instability and stochastic instability, were thoroughly analyzed. An extensive study based on this mathematical framework is in [64]. Inspired on some of these results, a non-cooperative GT approach was developed in [65] for tackling the control mechanism design problem. An objective function (to be minimized) is defined for each user (player), which includes a pricing function proportional to the experienced delay and a general utility function of the type in [60] expressing the user demand for bandwidth; the strategies of each user correspond to flow rates assigned to the available communication channel. A unique approximation to the NE solution is shown to exist and its stability conditions are analyzed. A discretization of the user cost function enables the formulation of a distributed control procedure (a possible improvement to the TCP/IP protocol) and tested in simple network topologies using a packet simulator.

A problem of *congestion control in satellite networks* is addressed in [66] seeking to achieve an allocation of bandwidth (of an outgoing link) by the input flows (more or less congestion sensitive) that be fair and eliminate unnecessary bandwidth waste. The authors propose a non-cooperative game model where routers implement certain queueing scheduling mechanism (associated with possible bandwidth allocations strategies) to the input flows (selfish agents) and show that there exists a fair NE solution. The resulting scheduling mechanism is tested in a very simple network and the authors draw attention to the importance of achieving a tradeoff between efficiency and fairness in this context.

Routing methods [67] present a summary overview and a classification, from a game theory point of view, of a list of papers on game theory applications in telecommunication network routing.

Many papers in this area are based on the application to telecommunication networks of the concept of *selfish routing models*, a type of non-cooperative '*congestion game*' originally formulated by [68] for road transport routing problems. In this game the origin-destination pairs correspond to the players, the arcs of network represent the resources and the strategies available to a particular player type are the paths in the network while the cost of an arc is the delay experienced by traffic in that arc. A 'social optimum' is defined (it corresponds to an optimal multicommodity flow solution with minimum total delay), while a NE solution corresponds to an equilibrium flow solution, where every player is traveling on a shortest path under certain conditions. This modelling approach to routing can be applied straightforwardly to telecommunication routing problems with adequate adaptations concerning cost/payoff functions or traffic engineering constraints, depending on the particular nature of the network or the features of the specific design problem being addressed. It is important to note, as analyzed in [69], that NE are quite often inefficient solutions since in general these solutions may not minimize the social cost (the global network optimum) leading the author to introduce the so-called *price of anarchy* defined as he ratio of the worst social cost of a NE solution to the cost of an optimal routing solution. Theoretical results on this 'price of anarchy' are analyzed in [70] in terms of the mathematical properties of the cost functions. A closely related paper with theoretical results on selfish routing game models in capacitated networks (where there are upper bounds on arc flows, which is the case of telecommunication networks) is [71], also including results for nonconvex and non-differentiable arc cost functions (having in mind that convexity and differentiability properties for the cost/utility functions are usually assumed for obtaining NE).

Concerning the mathematical properties of 'selfish routing models' based on GT in relation to network capacity design it should be referred to that some standard approaches of network capacity expansion conjugated with that type of non-cooperative routing methods, may lead to severe degradation of network performance. This is the case when the expansion strategy is based on bottleneck analysis, that is when the network operator adds capacity to identified bottleneck links so that they cease to be a bottleneck for the expected traffic offered under a certain routing method. It was originally shown in [72] that in road transport networks (these are analog to pure delay queueing communication networks), in a non-cooperative routing approach, the bottleneck based capacity expansion may lead to a drastic increase in the delays of all users thence to a much worse network design solution – the so-called *Braess paradox*. An extension of this theoretical result to other networking contexts was carried out by other authors, such as [73, 74], and, for loss networks, in [75, 76]. [77] review this problematic and propose forms of avoiding the Braess paradoxical situation when upgrading a communication network for a general payoff function for each user (utility or cost function). Note that some models of channel assignment in wireless networks with multiple domains such as in [52], also enable the joint calculation of end-to-end transmission routes. This is the case in [78] where a routing and channel assignment problem in wireless mesh networks (WMNs) is tackled. This is formulated as a non-cooperative game the players of which are all the sink-source node pairs and the aim is to choose a path (one of the possible strategies) between them with feasible channel assignment, satisfying certain radio transmission constraints – a game model designated as 'Strong Transmission Game'. The utility function of each player encompasses transmission costs and QoS parameters. A proof of the existence of a pure strategy NE solution is shown, and a heuristic for obtaining a feasible computational solution, is proposed and tested.

Problems focused on *security issues* are clearly important in communication networks. The general problem of detecting intruding packets in TCP/IP based communication networks, based on packet sampling (of the network links), was tackled in [79] using a GT approach with two players: the service provider and the intruder. The payoff functions of the players are min-max functions expressed in terms of the sampling rates and the probability of a path being used by the intruder and lead to a classical two persons zero-sum game. The authors show that the optimal strategy for the service provider is obtained from the resolution of a max-flow non-convex optimization problem and devise heuristic procedures for solving it. [80] propose a dynamic routing method for Internet type networks, modeled as a non-cooperative routing game, where the players are the routers. The model assumes traffic splitting among feasible paths and that frequent traffic measurements are performed by the routers in the network arcs so that the possible paths (player strategies) are associated with a cost function depending on the arc sampling rate and on traffic engineering parameters; thence routers compete in order to minimize their own costs for the downstream paths. The authors derive the existence of NE solutions and analyze conditions for their stability; a distributed routing procedure is obtained and tested through packet simulations. In [81] a routing problem in Internet type networks, assuming a certain congestion control mechanism (max-min fair congestion), is addressed considering a non-cooperative game model. This formulation is a type of the 'bottleneck routing game' model described in [82]. Each player corresponds to a source-destination node pair of the network and seeks to choose a route which maximizes its available bandwidth but it is subject to a max-min fairness congestion scheme such that all paths using an arc are assigned an equal share of bandwidth unless a path receives less bandwidth at another link. A distributed routing procedure is devised, enabling a user to find a path with maximal bandwidth under max-min fair congestion control in polynomial time, supposing the paths of other users to be fixed. The authors prove the existence of NE solutions and obtain the corresponding theoretical convergence speed as well bounds for the price of anarchy. In [83] a very specific network design problem involving a routing problem in Internet type networks, aiming at selecting the nodes which can be switched off in order to *optimize energy saving*, while guaranteeing that the resulting routes (set of available paths for each node pair, after switching off those nodes) satisfy traffic carrying objectives. This complex problem is tackled through a coalition game designated as 'Green Game' (where the nodes are the 'players' and the strategies correspond to associated feasible routes) and a heuristic is used to obtain the solutions. The solutions are tested in a reference Internet access/metropolitan network segment and puts in evidence that there is a tradeoff between QoS and energy saving. Related papers on this problematic area focused on the so-called 'green Internet', using different modelling approaches are for example [84, 85, 86].

Concerning problems on *security issues* these are most relevant in wireless networks, namely in AWNs, particularly vulnerable to malicious attacks. In the report [87] a problem of this type, aimed at enforcing node cooperation in AWNs and detect possible intruders, is addressed. For this purpose, a GT approach using a particular formulation of the 'prisoner's dilemma' game, is developed. The players are the mobile nodes of the network and can choose to defect or to cooperate. The security mechanism is modeled through the payoff structure of this game (where the energy cost has a central role), using as inputs data monitoring and based on a model of preferences, designated as 'equity, reciprocity, and competition' due to [88]. The resulting routing procedure enables the calculation and storage in every node of the network of the reputation ratings associated with other nodes and so detect passive attacks.

4 Trends and Challenges

We will put forward an outline of future research trends and challenges in various areas of network planning, design, and management focusing topics where it seems likely that more opportunities and challenges for MCGD and GT approaches may arise. For facilitating this exercise, in the following these trends will be organized around three great areas: decision problems associated with the interactions between *telecommunication networks evolution and socio-economic issues*; problems *involving market competition and techno-economic evaluation and selection*; *new problems of network planning and design* in wired and wireless networks. Note that these types of decision issues have no strict boundaries and are often mixed, explicitly or implicitly, in the modelling of the problem.

Telecommunication networks evolution and socio-economic issues The widespread social penetration of communications technologies and services and the resulting socio-economic implications are in the agenda nowadays. In fact, their present remarkable relevance is indisputable, however the future trends are still of non-expectable dimensions stemming from the very rapid evolution of the underlying technological and socio-economic factors. Of course, the associated problems are multidimensional and it seems that multicriteria group decision models can be a very helpful tools of analysis. However, as these issues are relatively new, evolving quickly and requiring also very fast options, the number of studies testing the usefulness of new models is still very limited. Some key issues deserve attention, such as those associated with the evaluation of interactive multimedia and various types of distributional services (such as video streaming or cloud computing) based on broadband network technologies and the explosion of wireless networks in most regions/countries. In fact, these revolutions in telecommunication networks are making it available many new services with great socio-economic impacts. Among them we emphasize those related to healthcare, education, e-commerce, financial services, administrative services, etc. Of course, there are very positive socio-economic impacts, but also potential risks and negative consequences. We believe that, in the future, MCGD analysis can be used in order to help policy makers in a reality evolving very fast, requiring timely decisions. Besides the consequences of broadband capabilities and the availability of new societal/personal services, it must be emphasized some structural consequences of the communications revolution, namely related to the growth of classical and virtual economy, the innovation, the equity and employment issues, the mass media evolution, the local governance vs global governance, as well as regulatory and policy issues. Concerning the issues briefly addressed in this paragraph, we would refer to the contributions in the following papers: [89, 90, 91, 92, 93, 94, 95, 96, 97, 98]. It must remarked that in applications of this type it is particularly relevant the complexity of the problems, namely "involving conflicting/collaborations, tactics/strategies, cognitive/emotional and social/cultural issues, but also the cross-fertilization of large number of disciplinary areas, such as theory of organizations, political science, sociology, psychology telecommunications/internet, systems science, operations research, information systems, decision support systems, etc" [15]. So, it is particularly relevant building new learning oriented multicriteria group decision support systems, open to the combination of inputs from diversified areas. Note that, in the end of Sect. 2.2.1, some considerations related to this issue, were made.

Market competition and techno-economic evaluation issues Having in mind the extremely rapid evolution of telecommunication technologies and associated markets, ranging from those concerning international and national networks to a very wide variety of smaller range networks serving regions, companies, public institutions or private premises, it is expected that new problems (or new forms of similar problems already tackled in the literature) will appear. Needless to say that market competition in these areas is usually very intense regarding all levels of demand supply let it be the choice of network operator(s), service operator(s), technology for given network/service requirements, equipment vendors or any market contests involving simultaneously various of these issues. As it is clear from the literature overview these problems may typically involve various DMs. Also new problems of competition, among service operators or service providers, for customers in different market scenarios, will appear, both in the context of wired and wireless networks of all types. Furthermore, as already stressed, these problems are inherently multicriteria in nature since multiple, often conflicting, incommensurate aspects are at stake in the decision process. Therefore, this is clearly an area where MCGD or GT approaches and models, adequate to each new problem setting, are needed. We could present, as an example, the public tenders for installing and operating the 5G mobile wireless networks, under the auspices of public regulators. In terms of modelling issues raised by this type of problems one could put forward the representation of the role of the regulator(s) and of possible oligopolistic situations, a theme already treated in similar market contexts by classical GT frameworks – see e.g. [41]. The main involved challenges are, in our view, the form in which the representation and aggregation of the DM's preferences is considered in the model and the way of tackling the interactivity of the DMs with the decision support system as well as the interaction among the DMs, having in mind that a learning process should be enabled. Similar considerations apply to problems of vendor selection for a particular network technological context with the necessary adaptations. Concerning the use of MCGD approaches in these new market competition problems it should be noted, as pointed out in Sect. 3.1, that the scope of applications of MCGD is essentially concerned with cooperative group decision, not negotiation processes involving non-cooperative/antagonistic decision agents, although the frontier between the two settings be often fuzzy. Nevertheless, as exemplified in [4] in a strategic management problem involving conflicting actors, MCGD can be very useful for the DMs in a preparation phase of the negotiation process. Of course, this may be a relevant issue to explore in the future, concerning the application of MCGD methods in some telecommunication decision problems of similar nature.

Regarding problems of *technic-economic evaluation/selection* a wide range of new problems is arising, both in wired and wireless networks, having in mind the increasingly great variety of technologies, service types and technical alternatives that may be used in a given networking context. An example was presented in Sect. 3.1 for wired networks concerning the choice of a routing method for a transport network, using a MCGD method. Similar decision problems arise concerning the choice of fault protection mechanisms for various types of transmission networks, taking also into account the multilayer functional nature of modern telecommunication networks. The aspects involved, namely resiliency objectives in the event of equipment or software failures or abnormal working conditions (for example, disaster situations or malicious attacks), and the economic evaluation of the network functioning in failure conditions in multiple and uncertain scenarios, clearly open challenging issues for the development of GT or MCGD approaches. An overview of research trends in the area of *robust network design*, including MCDA applications in this area, is in [99]. Problems of techno-economic evaluation also will arise in wireless networks having in mind the great variety of technological and architectural solutions already available and the foreseeable technological evolution. An example of decision problem in this area concerns LANs, when alternative networking solutions are considered such as fibre/cable LAN, Hybrid Fiber-Wireless LAN or pure wireless LAN (WLAN). Note that for these types of problems, after selecting a networking techno-economic solution the network operator may have to address the problem of vendor selection for particular types of needed new equipment, again a MCGD problem since usually more than one DM is involved. Ideally, the two problems should be integrated in one bi-level, more complex, challenging group decision problem involving, simultaneously, the evaluation/selection of the networking solution and the equipment vendor. A specific type of problems in this area where MCGD and GT approaches could be used is *modernization planning* of the access networks for residential or institutional customers, having in mind the generalized introduction of broadband services and the existence of different technical solutions, so that a preliminary level of decision analysis for evaluating the alternatives, is worth considering. Again MCGD (this is clearly a multiattribute decision problem where more than one DM may be involved) and GT models could be used in this context. Note that, in many situations in this context, complex real applications are not adequately tractable in GT due to the necessity of oversimplifying the model, otherwise its operationalization would become impractical.

New problems of network planning and design The rapid evolution of communication technologies and network architectures has raised and will continue to raise new problems of network planning and design which may be formulated as GT problems, as illustrated in the overview section. Also some of these problems, typically involving multiple criteria, may also be tackled with MCGD approaches, when more than one DM external to the networks, is involved.

This is particular true concerning the use of GT approaches for network design problems in wireless networks and IP based networks. Here, the development of new technologies/architectures will naturally foster the appearance of many contributions of GT to new problems the types of which were already identified, namely focused on network resource allocation issues (such as *channel assignment*, *bandwidth allocation*, *route selection* and *congestion control*). These problems take multiple forms depending on the types of wireless networks, the QoS/economic performance objectives and the technical-economic constraints. Concerning the objectives/constraints, great importance has to be given to the energy issues. This kind of issues may naturally continue to be tackled by GT approaches, raising significant challenges concerning the development of cooperative or non-cooperative networking games capable of leading to feasible resolution algorithms in terms of computational requirements. [48] present a review on applications of GT to wireless networks and briefly outline future research directions. [39] discuss theoretical challenges in the framework of GT, namely the difficult application of hierarchical optimization/Stackelberg equilibrium in telecommunications and the need to develop appropriate models and solution procedures for the new networking game problems.

It should be added that the developments in SDN technologies, both in wired and wireless networks, enabling the *softwarization* of various control functions opens field for new capabilities in network control related design, thence leading to new design problems in these areas, where GT and multicriteria approaches can give relevant contributions.

New forms of *routing problems*, associated with technological evolutions and the rapid increase in the demand for new and more bandwidth greedy services in wired and wireless networks, are expected to come forward. There is great advantage (or, in many cases, a methodological necessity) of tackling these problems through multicriteria approaches taking into account the multidimensional nature of QoS/cost metrics and the need to address tradeoffs between often conflicting and incommensurate metrics. This is particularly important having in mind the trend for the increasing importance of certain forms of multipath routing, namely: calculation of two or more node-to-node maximally risk disjoint paths in *resilient routing* methods; *multicast routing* (when a set of paths has to be calculated from an originating node to a given set of destination nodes, as in distributional services or for interconnecting two given sub-sets of network nodes, as in teleconferencing; if all nodes have to be connected it is designated as *broadcast routing*) and *anycast routing* (involving the calculation of paths from one originating node to one of many possible destination nodes, as in cloud computing), see e.g. [100]. Naturally, appropriate modelling formulations will have to be considered, capable of taking into account the technic-economic specificities of each particular decision environment both in terms of optimization objectives or constraints. This is clearly an area where a quite significant number of multicriteria models, assuming only one DM (the network routing designer) have been proposed as analyzed in the state-of-art review [101] and in the overviews in [102, 103]. [104] analyze, in depth, the features required by routing approaches which may be considered as consistently multicriteria; a conceptual analysis of various forms of understanding "hierarchies" in routing and in multicriteria routing optimization, is also presented. Note that these MCDA-based routing methods can be fully automated, since that is usually required by the application, namely in dynamic routing, by imbedding in the routing method a system of preferences previously determined by the network designer/DM. This can be done in various ways, namely: by defining dynamic preference regions in the objective function space (see e.g. in [105] for broadcast routing), by using reference point methods, a combination of reference points and priority regions (see e.g.

in [106] for unicast routing) or by using a method based on the concept of objective ranking and recurring to achievement functions, in a reference point approach context, as proposed in [104].

Of course, these routing problems can also be formulated in terms of GT approaches by aggregating in the utility functions assigned to the originating nodes (the players) the various optimization objectives. This was the form, already used in many of the GT models (see examples in Sect. 3.2), for tackling routing issues and other design problems when more than one objective is to be explicitly included in the payoff representation. This type of procedure uses, in general, a weighted sum of the measures of each of the considered objectives (i.e. the criteria to be optimized by each user) and we think that there are various issues concerning possible limitations of this type of approach that deserve a discussion in this context. Firstly, the problem of setting of weights which although being devised as importance coefficients, are in most situations associated with tradeoffs between the criteria, so leading to fully compensatory parameters concerning the considered dimensions. Note that the fully compensatory nature of such parameters is questionable in many circumstances, namely when we are dealing with incommensurate dimensions, for example when comparing the loss in a QoS measure with an increase in revenue. Also, beyond the problem of the construction and normalization of scales for each criterion there is the underlying assumption of the independence of the dimensions, essential when an additive model is used, something that is often unrealistic for some pairs of criteria. In this respect we think that MCDA based approaches seem more adequate to deal with the exploration of the tradeoffs. This is clear in interactive models in MCGD approaches as it is typically the case in the applications to socio-economic and technical-economic evaluation problems, as far as the models and the associated decision support tools are adequately prepared to deal with the inherently imprecise nature of the importance parameters and enabling the exploration of the interactivity with the DM(s). If these methodological requirements are met the multicriteria approach may lead, desirably, to a learning process by the DM(s), developed around the choice of a final solution in the Pareto optimal set. On the other hand, it can be argued that GT approaches are inherently better prepared to deal with a direct representation of the conflict between users/players, a feature that may be particularly relevant in market competition problems.

These issues are also relevant in the case of models requiring an automated selection of a solution, for given input information in terms of the service demand requirements and network status information. This is the case in most problems of routing (the only exception is static/quasi static routing or dynamic routing methods with large updating periods) and in network operational design problems as those analyzed in the overview section. As noted above, in these types of problems the alternative approaches to GT, are single or multicriteria decision approaches (with one DM alone), mainly based on mathematical programming (and, in particular cases, in network flow programming), combinatorial optimization methods or on optimal control algorithms. Concerning routing problems, multicriteria shortest paths, muticriteria spanning trees and multicriteria Steiner tree algorithms are most relevant for application in unicast, broadcast and multicast/anycast problems, respectively. Note that for specific problems in this area there are procedures for calculating Pareto optimal solutions, computationally very efficient, namely based on shortest path, k-shortest paths and minimal cost spanning tree algorithms. A review on multicriteria shortest path and tree problems can be seen in [107]. Note that in these areas multicriteria approaches can be used (with some intrinsic advantages) but require that the system of preferences of the DM be imbedded in the resolution method, through an appropriate computational procedure, for example the choice of the first non-dominated solution obtained in a highest priority region in the objective function space, after calculating the convex hull of the Pareto set, or using a weighted Chebyshev distance to an ideal reference point or a combination of both techniques.

We also would like to mention some methodological and theoretical challenges. Firstly, an important issue has to do with the treatment of the uncertainties in various types of MCGD or GT models. In particular, in many network design models, the uncertainty associated with service demands or traffic flows offered to the network is of great relevance but it is an issue the importance of which is frequently underestimated. The representation of this uncertainty is a task with two major aspects: the use of adequate stochastic models (even as mere approximations) in the context of the model, and the determination of estimates of the statistical parameters of these stochastic sub-models. Uncertainties and/or imprecisions inherent to other quantities involved in the MCGD models, that may be of different natures, for instance data collection or modelling of preference aggregation (see [108]) are also relevant issues in this regard. This type of concerns and challenges also apply to GT approaches having also in mind the key role of the utility functions representing the player payoffs and the importance, in this context, of the associated parameters. Secondly, several of the more complex of the addressed decision problems, in particular those involving several interrelated levels of decision/optimization, lead to clear modelling and methodological challenges. A known problem of hierarchical optimization in GT in this context has to do with the hierarchical relationship between the objectives of the network manager (the player who defines the network parameters so as to optimize some objective), and other, lower level players (the users) who respond to the values of such parameters (for example related to pricing) by seeking (through their strategies) to achieve some equilibrium solution. This type of problem can be modeled trough a bilevel optimization program (see [109]) also known as the Stackelberg leader-follower problem (due to [110]). As analyzed in [39] this is clearly a relevant problem in some applications to telecommunication networks but also very difficult to solve and it is a challenging issue for GT. Thirdly, the possible choice between GT and MCGD approaches for a given network application – beyond the discussion of possible advantages or limitations associated with methodological differences, in a given decision environment context –, should take into consideration several other aspects. A first issue is the adequacy of the model and of the mathematical formulation developed for the addressed decision problem (involving the evaluation of the inevitable underlying assumptions and of the simplifications on the network representation) to the particular technical features and the available information on the network under analysis. A second and relevant issue is the form in which the interaction of the DMs with the developed computational system should be made in association with the representation in the model of the DM's preferences. A third issue is to obtain sets of data, relevant to the addressed problem, as realistic as possible, namely concerning the network features and the DMs preferences, related to technical and economic aspects. In this respect, the involvement of multidisciplinary contributing teams it is clearly very advantageous, namely by including experts in the used methodology and in the relevant network design aspects, agents capable of understanding each other in the essential aspects of the application of their expertise to the addressed problem. Finally, the development of a resolution procedure computationally feasible and as efficient as possible for the desired application environment, that can vary significantly, is a key issue. For example, in dynamic routing methods we may have CPU time limitations that, at transport network level, may vary from a few minutes to few tenths of milliseconds, depending on the application setting. Although studies of a more prospective or theoretical nature do not impose necessarily these types of concerns, these are important aspects that raise many challenges in the forthcoming research in the new problematic areas of application of GT and MCDA in telecommunications.

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