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Palafox-Alcantar, Giovani; Hunt, Dexter; Rogers, Chris

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The complementary use of game theory for the circular economy: A review of waste management decision-making methods in civil engineering

P.G. Palafox-Alcantar*[1], D.V.L. Hunt*[2], C.D.F. Rogers*[3]

Department of Civil Engineering, School of Engineering, University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom.

[1] *PXP296@student.bham.ac.uk*

[2] *d.hunt@bham.ac.uk*

[3] *c.d.f.rogers@bham.ac.uk*

Highlights

- First study to contrast five decision-making tools with game theory.
- Game theory is still undergoing consideration for use in the circular economy.
- Cooperation is a feature too often missing in waste management decision-making.
- Waste management can benefit from game theory capabilities to resolve conflict.
- An adapted waste management bargaining example shows the potential of game theory.

Abstract

Circular economy principles aim to contribute towards sustainability and resilience through several simultaneous agendas including economic growth, social development and environmental responsibility. Stakeholders from each perspective have their own interests and priorities, which often result in conflict. There are several and varied methodologies which address the decision-making process, however in engineering spheres these techniques are usually limited to optimising resources, time or costs. Decisions that are comprehensive in scope and integrated across all affected systems are required to transition towards a circular economy, effective cross-disciplinary thinking is imperative and cooperation amongst diverse areas is essential. Game theory is a useful technique when analysing the interactions of stakeholders with multiple objectives and perspectives. This paper aims to critically review methodological approaches used in waste management practice and provide a guidance on how game theory differs from, and is complementary to, the primary decision-making tools available where cooperation is a feature too often missing. This review seeks to justify the development of game theory to complement waste management decision-making methods in civil engineering, where resource consumption and waste management is often voluminous. An application of game theory to a waste management example illustrates that this methodological approach is of complementary value. The contribution of this study to circular economy and solid waste agendas is to emphasise the capability of game theory to help facilitate conflict resolution, competition, and stakeholder consensus when capturing multiple (sometimes conflicting) values in line with circular economy principles.

Keywords: circular economy; civil engineering; cooperation; decision-making; game theory; solid waste

List of abbreviations

ABM	Agent-Based Modelling	GT	Game Theory
CBA	Cost Benefit Analysis	IAM	Integrated Assessment Modelling
CE	Circular Economy	IS	Industrial Symbiosis
CO2	Carbon Dioxide	LCA	Life Cycle Assessment
C&D	Construction and Demolition	MCDA	Multi-Criteria Decision Analysis
DEA	Data Envelopment Analysis	MSW	Municipal Solid Waste
DM	Decision-Making	RDM	Robust Decision-Making
EIP	Eco-Industrial Park	SA	Scenario Analysis
GHG	Greenhouse Gas	SW	Solid Waste

1. Introduction

Population growth, and the concomitant increase in the demand for goods and services, is resulting in the progressive depletion of energy and resources stocks around the globe. Since the planet is experiencing a growing scarcity in resources and is becoming rich in waste, the concept of a 'Circular Economy (CE)' has emerged from increasing concerns over resource use efficiency, waste management and materials security (Rogers et al., 2017). CE principles aim to contribute towards sustainability and resilience through several simultaneous agendas, including economic growth, social development and environmental responsibility.

Contributing towards CE transition (and certainly sustainability) implies capturing multiple types of value (Rogers, 2018). Conflict is expected to arise when stakeholder groups from different perspectives have their own interests and priorities. An integrative Decision-Making (DM) process should be able to overcome such barriers to cooperation; this is where Game Theory (GT) presents a promising potential to facilitate such an enabler to the transition towards a CE. The aim of this paper is to critically review different techniques in the CE literature. The review provides guidance on how GT differs from, is both complementary to and able to enhance, the primary DM tools available within a waste management context in civil engineering.

1.1. Importance of Game Theory for the Circular Economy

Before moving on to explore what is the CE interpretation in this study, it is important to clarify that civil engineering is referred to as a discipline that consumes vast quantities of resources and has to engage heavily in waste management, while ensuring that sustainability and resilience is inherent in its infrastructure, and their operating systems; all of which are critical areas to the CE. Thus, civil engineers have a responsibility to work towards safe, sustainable and resilient ‘future-proofed’ decisions for waste management within a CE.

Several recent articles have analysed the CE concept and the evolution of its interpretations: Heshmati (2015) investigated current circular practices and their implementation; Lewandowski (2016) classified circular business models into eight categories; Sauvé et al. (2016) compared the CE with sustainable development and environmental sciences; Lieder and Rashid (2016) developed a comprehensive CE framework in the manufacturing industry; Ghisellini et al. (2016) provided an extensive review of research on the CE; Blomsma and Brennan (2017) investigated the origins of the CE concept; Murray et al. (2017) discussed differences and similarities between sustainable business models and the CE; and Rizos et al. (2017) reviewed definitions, processes and impacts of the CE. Research on the topic is fragmented and interpretation amongst disciplines is varied (Rizos et al., 2017), perhaps because there is a lack of consensus of what a CE is (or is not); indeed, it has been noted that the lack of a shared common understanding between stakeholders could lead to a deadlock for the concept (Kirchherr et al., 2017). There have been recent contributions that seek to mitigate this situation. Prieto-Sandoval et al. (2018) proposed a consensus by highlighting the symbiotic relationship between eco-innovation and the CE frameworks. Saavedra et al. (2018) investigated how Industrial Ecology is embedded in, and contributes theoretically to, the CE. Korhonen et al. (2018) reviewed the literature on the concept and through an innovative research approach have concluded that it is an “essentially contested concept”, meaning that there is consensus on its means and goals, but there is no agreement on its definition, the units to analyse it or suitable methodologies to address it. Nevertheless, the problem of a lack of overarching coherence remains.

Since an objective of this review is to provide arguments for the development of GT in support of the CE and waste management agendas, it is of great importance to differentiate the sustainability and CE concepts. Geissdoerfer et al. (2017) have already compared both terms, and concluded that their conceptual relationships are that "CE is viewed as a condition for sustainability, a beneficial relation, or a trade-off in literature". In line with the definition proposed by Kirchherr et al. (2017), the authors of this paper interpret a CE comprehensively as follows:

> A CE is a set of principles and tools which aim to contribute to the planet's sustainability by minimising the extraction and degradation of materials, promoting resource and energy conservation (reduce, reuse, recover and recycle) and driving the regeneration of its input sources. As such it fosters a willingness to, and facilitates, the repair and upgrade of products through innovative and systems thinking and embraces waste as a primary resource, allowing its reintroduction into the consumption system. The CE is inclusive with the environment, society, governments, companies and academia, and boosts the development of resilient business models in which various forms of value are captured through cooperation.

With regard to the last phrase in this definition, the "Circularity Gap Report" by Circle Economy (2018), identify seven key elements of the CE as potential gaps that need to be filled and processes that need improved facilitation, amongst them cooperation to create and capture joint value. This means that to create shared value and transparency, private and public stakeholders across many different supply chains must work together. Kirchherr et al. (2018) coded the barriers to CE implementation in the European Union, and highlighted the lack of enthusiasm of stakeholders to cooperate across the supply chain as a prominent obstacle to overcome. Veleva and Bodkin (2018) found that many entrepreneurs and corporations in the

USA are collaborating in waste reduction and reutilisation business models, despite the lack of regulations and awareness of the CE paradigm, and proposed an innovative cooperation framework to advance towards a CE between both groups of stakeholders.

GT presents potential to facilitate cooperation, for example, to optimise Eco-Industrial Parks (EIP) (i.e. Industrial Symbiosis (IS)), a key research area and critical enabler for the CE (Boix et al., 2015). The importance of GT for the CE emerges from the need to overcome conflicting objectives through cooperation between participants that captures multiple (sometimes conflicting) value judgements within a negotiation process. In illustrating this concept more clearly, this paper provides a critical insight into how GT might prove to be a useful technique for such processes with a particular focus on the waste management sector in civil engineering. To do this robustly, it is necessary to critically review the primary DM tools that exist within the waste management sector in civil engineering.

1.2. Decision Making tools in waste management within civil engineering

Many tools have been used in engineering to help make informed decisions when facing a host of sustainability challenges; however, DM tools have mainly focused on optimising resources, costs, time and so on. The DM tools selected for this review for comparison with GT are: Agent-Based Modelling (ABM), Multi Criteria Decision Analysis (MCDA), Scenario Analysis (SA), Robust Decision Making (RDM), and Integrated Assessment Modelling (IAM). The relevance of this paper follows from the requirement of underexplored and new research methods to provide helpful tools in the understanding of CE decisions.

Several attempts have been made to review and compare different DM methodologies and/or against GT, for example: Lee (2017) has already made a strong case in comparing econometric techniques in the bio-energy development and CE research agendas, such as: IAM, linear and non-linear programming, and Data Envelopment Analysis (DEA), among others. The comparison aimed to help select the best technique available given their performance on 11 aspects. In comparison, this review focuses on comparing DM methods against GT based on its potential complementary role to improve cooperation in the waste management and CE contexts. Thus they are not included within the scope of this review.

On the other hand, a review of MCDA studies in the Municipal Solid Waste (MSW) management context has been performed by Soltani et al. (2015), and found that the stakeholders with the highest participation are experts and local authorities, followed by local residents. Kastner et al. (2015) have reviewed and compared literature which related to the use of ABM or GT as tools in enhancing the use of IS. Soltani et al. (2016) provided a limited literature review of MSW management studies using GT methods to find solutions to this particular problem. Sinha (2016) investigated how static and dynamic systems modelling support the understanding and monitoring of environmental management. The gap addressed in this paper is that there appears to be no explicit comparison in the CE and Solid Waste (SW) management literature between all the proposed methodological approaches outlined above.

The structure of this paper is organised as follows: Section 2 presents the method of this review and covers a background analysis of the available literature on CE and SW and the DM tools proposed for comparison. Section 3 describes the methodologies and highlights their advantages and shortcomings during the DM process, in addition, it analyses the relevant literature using such methodologies on CE and SW. Section 4 compares and contrasts in more detail the commonalities and differences of the methods with GT, and presents an example in applying the complementary role of GT to address a DM problem in the CE and waste management context. Section 5 finalises with conclusions and a discussion of future research needs.

2. Methodology

Before describing and analysing the differences and commonalities between the methodologies, a rigorous bibliometric search has been carried out. Data have been gathered by searching the related topics from the "SCOPUS" database in April 2019. The terms examined included "circular economy", "game theory", "agent based model", "multi criteria analysis", , "scenario analysis", "robust decision making", "integrated assessment model", and each of the methods in combination with "circular economy" and "solid waste", as shown in Table 1. It is important to note that only articles and reviews that mention explicitly the term "circular economy" or "solid waste" have been considered. Even though there might be publications that could have used related terms (e.g. sustainable production/manufacturing) and may align well with the interpretation of CE; it is the lack of complete alignment with CE principles that would compromise the analysis herein. There is a subtle, but important, difference between the concepts of sustainability and CE, already addressed by Geissdoerfer et al. (2017).

Table 1: Number of results from bibliometric search.

It is important to note also that the search was limited to the following criteria:

1) peer-reviewed journal articles and reviews, as they capture the latest research;
2) publications in the English language only;
3) only publications after the year 1999;
4) the terms searched were included in the title, abstract and/or keywords of the document;
5) the subject area was limited to engineering, in line with the aim of this review.

For each of the combinations of CE and SW, and the different methodologies, the publications arising from the search were reviewed in detail to sieve out unimportant results, i.e. some that appeared in the search mentioned the concept(s) once only and did not use it as a method, while some others did not fit the primary purpose of this paper. Once these relevant publications were reviewed, many pointed to more publications which were important and were also critically reviewed. The important publications for CE and SW research which used one of the six methods in Table 1 are presented yearly in Figure 1 and Figure 2 respectively, and further used to analyse below each methodology capabilities in the following Section 3.

Figure 1: Number of publications per year of the DM methods and CE.

Figure 2: Number of publications per year of the DM methods and SW.

The fact that the combination of both CE and SW and the six engineering DM tools (the five existing methodologies and GT) occurs in such small numbers of publications suggests that the research in this area is still in its early stages. There is an evident need to utilise the methodologies (ABM, MCDA, SA, RDM and IAM*)* in alignment with CE principles to facilitate its development. Section 3 describes and analyses the main properties of these methods in the CE and SW literature (Table 1 and more relevant publications), with the aim to set the scene for a deeper and thorough contrast in Section 4.

3. Description and Analysis

All the previously mentioned methodologies (ABM, MCDA, SA, RDM and IAM) are useful for analysis of the DM process itself, yet they do not consider the strategic behaviour of the actors involved in a negotiation (Madani et al., 2015). In contrast, GT provides a valuable perspective on how the preferences and decisions of actors have an impact on their opponents' choices, their own further counter-decisions and, the final outcomes of a strategic interaction. For example, the price for which an item will be sold in an auction might be different if one participant bids up drastically as a strategy to discourage competitors to offer more, than if two or more participants bid up gradually until one reaches the maximum perceived value (or value payable by others) for the item. Another advantage of GT is that it considers the behaviour of the individuals based on their interests in practice, seeking to reach the system's optimal results from the individual self-optimising behaviours (Madani et al., 2015).

The following sub-sections describe and discuss the properties and characteristics of six methodologies that purport to study the DM process, trade-offs, objectives and uncertainty within the broad field of sustainability/CE/SW. The objective of this Section 3 is to set the scene for Section 4, which presents the deeper and thorough discussion of commonalities and differences between the studied tools. A brief summary of the relevant literature reviewed is presented in Appendix 1 and Appendix 2, for the CE and SW contexts respectively. As mentioned previously, due to a lack of literature reporting on the six methods and CE, other subject areas within the scope of waste management in civil engineering were searched to complement the analysis; for example: low-carbon design, water treatment and renewable energy.

3.1. Agent Based Modelling (ABM)

ABM simulates the interactions between several independent agents and assesses the impacts of their actions on a system (Zechman, 2011). ABM is used to observe the system impacts of the interactions between agents and their behaviours (Macal and North, 2010). The technique is used to provide simulations of group dynamics derived from the interactions of individual agents in communities (Kandiah et al., 2017). ABM is a useful technique when: dealing with a considerable number of agents in a system; the interactions between, and behaviour of, agents is complex; and when the individuals are different from each other (Bonabeau, 2002). The main properties of an agent in ABM are: (1) it attempts to accomplish a set of goals; (2) the interactions with the environment and other agents are driven by a specified group of social rules (Fraccascia et al., 2017); and (3) they can influence other agents' behaviour through predetermined communication systems (Kandiah et al., 2017). Rather than being defined by the modeller, the interactions within the agents and the interplay between the environment and the agents create the complex behaviour of the system (Macal and North, 2010). Agents are able to learn from the environment and are capable of adapting to varying circumstances and new data (Silvia and Krause, 2016).

When studying an economic system, ABM is capable of easily modelling an evolving macro space derived from the interactions among numerous agents ruled by determined simple actions (Wang et al., 2017). Rather than attempting to predict the future, ABM explores the different futures resulting from alternative conditions (Lange et al., 2017). The technique is capable of understanding the relationship between diffusion processes and customers' purchase decisions derived from them (Lieder et al., 2017). ABM has also been used to study cooperation in industrial districts and inside supply chains (Fraccascia et al., 2017). In ABM, the definition of rules is critical, and a simple change in the rules can have a radical impact on the agents' behaviour, and on the model outcomes (Bonabeau, 2002).

3.2. Multi-Criteria Decision Analysis (MCDA)

MCDA aims to organise the alternatives in a hierarchical way (Hadian and Madani, 2015) and thereby prioritise the criteria effectively (Zhao et al., 2017). It is an operational assessment useful to study issues with high uncertainty, multiple interests and conflicting objectives (Wang et al., 2009). MCDA is able to rank policy alternatives using stakeholder perspectives and cost/benefit information (Ali et al., 2017). MCDA may be used to resolve complicated problems that are ambiguous and highly uncertain. To rank alternatives it is helpful to use a complementary weight determination method (Zhao et al., 2017). MCDA is used when several parameters influence the performance of a task (Sabaghi et al., 2016). The most well-known application of MCDA is addressing DM problems that are influenced by conflicting criteria (Santos et al., 2017).

For example, Kaźmierczak et al. (2019) determined the preferences of the criteria to evaluate new uses to mining waste alternatives. Pettit et al. (2011) developed a DM framework to evaluate sustainable urban pollution alternatives and presented an example application in thermal treatment of MSW. MCDA was chosen to identify sustainable energy from waste alternatives to meet peak-hour energy demand because of its ability to handle simultaneous criteria (Abdulrahman and Huisingh, 2018). Some studies combined linear programming with MCDA to select appropriate landfill sites, for example: Cheng et al. (2003) optimise waste flow costs by introducing the stakeholders' subjective preferences; Xi et al. (2010) evaluate alternatives for SW diversion rates and reduction of net system costs.

3.3. Scenario Analysis (SA)

SA studies how to achieve a set goal in the future (normative) that will happen in an undetermined (exploratory) manner (Madani et al., 2015), or how to move from an explored to an aspirational (normative) scenario, also referred to as transitive scenario (Hunt et al., 2013). This analysis is used to test a range of development strategies and select the best plan by using optimisation methods (Madani et al., 2015). The analysis aims to identify the most preferable scenarios considering technical, social, economic, environmental and political criteria (Santos et al., 2017). Uncertainty in SA is interpreted as a set of plausible future outcomes, in other words the analysis models problems where the uncertain future is the base for DM (Pallottino et al., 2005). SA should not be confused with predictions; on the contrary, they are plausible ways in which the future might develop (Hunt et al., 2012a). Valuable insights are provided for policy-makers when evaluating future implications of current and planned practices (Islam, 2017), for example to analyse the consequences of increasing or decreasing recycling rates (Jiménez Rivero et al., 2016). To reduce the risk of wrong DM, SA considers the temporal evolution of statistically independent scenarios to secure a "robust" choice (Pallottino et al., 2005). This analysis aims to establish the best options by taking into account the short- and long-term costs and benefits of different expected results (Geng et al., 2010).

Hunt et al. (2012a) provided an extensive review of methods that derive scenarios, mainly applied to the case of urban regeneration sites. Hunt et al. (2012b) built on the previous work and identified four scenario archetypes (i.e. Policy Reform, Market Forces, New Sustainability Paradigm and Fortress World) that are formed by consistent narratives, which help in the comprehension of fundamental drivers to accomplish a significant and feasible world change. Hunt et al. (2011) used an urban futures toolkit to define and better measure the current and future performance of UK underground space. This extreme-yet-plausible analysis, which has particular utility in determining the resilience of a proposed policy or action, can be supplemented by aspirational futures approaches to increase alignment with a city's, or its citizens', needs and wants (Hunt and Rogers, 2015a, 2015b; Rogers, 2018). A complete SA can be used to investigate cases of extremes. This allows the user to understand how an intervention might be vulnerable when attempting to deliver the intended solution (Boyko et al., 2012; Lombardi et al., 2012). In the case of the CE, an example of a positive extreme is looking at a scenario which leads to absolutely zero waste, yet what needs to be in place for such a scenario to happen is of considerable concern; these are also regarded as the “necessary conditions” to exist in the future (Rogers et al., 2012).

SA is often used to complement future predictions: Luo et al. (2019) further complemented their study with SA to provide recommendations for different optimal scenarios in the waste household appliance recovery industry. Life Cycle Assessment (LCA) is broadly combined with SA: Deviatkin et al. (2016) compared the environmental impact of multiple approached for utilising deinking sludge; De Figueirêdo et al. (2013) seek to improve the transport and reduce the carbon footprint of the export melon industry; Friedrich and Trois (2016) calculated the total Greenhouse Gas (GHG) emissions of three scenarios for a MSW management system; Ripa et al. (2017) identified many uncertainties, opportunities to improve and driving factors for MSW management scenarios; and Fei et al. (2018) contrasted the energy efficiency and economic and environmental impact of traditional technologies with mechanical-biological MSW treatment. Also SA was integrated to economic and mathematical models to assess the profitability of natural gas power plants (Cucchiella et al., 2018). Moreover, MCDA has been complemented with SA to study the best combination of MSW management strategies for future 2030 scenarios (Estay-Ossandon et al., 2018).

3.4. Robust Decision Making (RDM)

RDM addresses uncertainty based on various future representations instead of solely seeking an optimal outcome as the main criterion for DM (Lempert and Collins, 2007). Characterisation is not the main aim of RDM, rather it is to aid decision-makers in managing deep uncertainty by the identification of robust alternatives (Lempert et al., 2004). RDM is iterative and analytical, it considers stakeholder engagement and is helpful in “deeply uncertain” situations, i.e. when the parties ignore or disagree on the consequences of their actions in the model (Hall et al., 2012). Put slightly differently, RDM may be used to assess adaptation alternatives for highly vulnerable habitats (Darch, 2014) and maintain an expected performance under regular as well as worst-case scenarios (Sawik, 2014). RDM facilitates reaching consensus when parties in a DM problem have significant differences in value appreciation and beliefs (Hall et al., 2012).

This method is analytical rather than intuitive; to eliminate uncertainty it is systematic and it attempts to make effective and safe decisions (Croskerry, 2009). RDM is a 'bottom-up' approach that aims to identify the vulnerabilities and assess the trade-offs among robust strategies, whilst performing satisfactorily to the decision-maker (Hadka et al., 2015) and; it aims to perform adequately for the decision-maker under both favourable and unfavourable conditions (Sawik, 2014). Eschewing attempts at optimisation, RDM attempts to identify robust decisions that would maintain a "convincing performance" in a wide range of plausible scenarios, while highlighting vulnerabilities in a system by exploring combinations of uncertain scenarios (Matrosov et al., 2013), and provide solutions which are adaptable and insensitive to the presence of uncertainty (Daron, 2015).

3.5. Integrated Assessment Modelling (IAM)

IAM is used to combine several disciplinary areas to understand systems linkages and interactions, and thereby meet many objectives such as sustainability, economic costs and others (Madani et al., 2015). IAM reports on interactions between endogenous variables (Lee, 2017) and, for example, has been used to exploit knowledge from multiple disciplines to assess climate change policy alternatives (Weyant et al., 1996). An important advantage of IAM in the air pollution context is that it provides "quick" simulations without having to repeatedly run dispersion models (Oxley et al., 2013). In spite of its advantages, IAM is categorised as a complex, and time and large data consuming, method. IAM can integrate stakeholders in the DM process towards avoiding conflict in search for more sustainable SW management alternatives (Hornsby et al., 2017).

Instead of assessing the effects of suggested policies, IAM aids policy makers in describing optimal outcomes and as a result decisions (Tol, 1997). Lee (2017) compared it with eight other econometric methodologies and ranked it last due to its high operating cost and complicated implementation. In the literature, this method has been mainly applied to climate change policy studies (e.g. Tol, 1997; Zhu and Ghosh, 2014) and air pollution (e.g. Carnevale et al., 2014; Oxley et al., 2013; Zhu et al., 2015). IAM can model effects at both regional and local scales and integrate multiple sub-models, such as energy-economy and climate sub-models, into a single integrated system to assess policies in several different ways (Zhu and Ghosh, 2014). IAM considers both impacts and costs of implementing abatement measures to decide on the best option (Carnevale et al., 2014).

3.6. Game Theory (GT)

The origins of GT can be traced back to the work of von Neumann and Morgenstern (1944). It has been used for decades in the social sciences, mainly in economics (Ichiisi, 2014; Myerson, 1991; Nash, 1953, 1951) and politics (Brams, 2004), as well as in evolutionary theory in biology (Smith, 1982; Vincent and Brown, 2005). GT is a set of mathematical tools (Madani and Hipel, 2011) to study cooperation and conflict derived from the interactive DM process between intelligent and rational stakeholders (Chew et al., 2009). However, in practice most players have limited rationality (Li and Fan, 2013). The latter meaning that their decisions are bounded by incomplete information about the problem, their limited cognitive capacity and/or restricted time for DM, resulting in barriers to cooperation (Lee, 2011). GT can be used to improve the understanding of stakeholders' relationships (Howard, 2006). Several interactions between players can be modelled and the outcomes of the negotiations may be predicted (Soltani et al., 2016). GT is particularly useful in problems where: (1) a small number of agents are involved in a strategic interaction and there is hidden information and incentives; and (2) there is awareness between stakeholders that their decisions affect each other's outcomes and their potential benefits depend upon other's choices (Grimes-Casey et al., 2007).

In a system where uncertainty and multiple interactions result in complexity, GT is an appropriate DM technique (Lou et al., 2004). GT is able to predict the most probable results in situations where participants are concerned with their own priorities and make strategic decisions based on selfish behaviour (Asgari et al., 2014). GT divides into two main branches[1]. Cooperative GT is concerned with analysing the DM process when the stakeholders have made an agreement to cooperate beforehand. This results in outcomes that are closer to optimal for all involved, while noting that a fair distribution of benefits and costs is of great importance to maintain stable cooperation. There are many methods used to achieve this, often referred to as allocation methods. In contrast, non-cooperative GT analyses conflict when stakeholders have not made a predetermined arrangement to cooperate. It is assumed that players are intent on maximising their own benefits regardless of what the other participants' decisions may be, resulting in stable or equilibrium combinations of strategies which are often optimal for individuals but not for the system.

The nature of GT allows its application in systems design since it covers technical and social issues through simulation and participants' role-play simultaneously (Grogan and Meijer, 2017). GT is able to find the best allocation of benefits and costs in a system, rather than

[1] For a deeper introduction to GT and the main differences between cooperative and non-cooperative GT, refer to Cano-Berlanga et al. (2017).

optimising for each stakeholder separately, and identify the most stable, balanced and favourable combination of strategies. Once the results for fair allocation are calculated it is important to prevent the participants from abandoning the coalition, the application of multiple stability definitions in a non-cooperative game is helpful (Asgari et al., 2014). By introducing government constraints and cooperative costs, cooperation is successfully achieved in SW separation mechanisms (Chen et al., 2018). Additionally, GT has been used to study the effects of uncertainty from remanufacturing technology and recycled products quality in order to set recommendations on varying regulatory situations (Tan and Guo, 2019).

Although there is no review of GT studies applied specifically to technologies that improve sustainability performance, a few examples with such potential can be cited: road networks which cooperate through the use of technology to address traffic congestion problems (Klein and Ben-Elia, 2016), the potential of GT to facilitate the development of smart grids (Saad et al., 2012) or for selecting optimal technologies in waste-to-energy treatment (Soltani et al., 2016).

4. Results and Discussion

When comparing the methods, it is useful to make explicit the steps involved in each of them and highlight the commonalities and differences between them. Figure 3 demonstrates in a set of flowcharts the methodological stages of the approaches. In support of the flowcharts and as a result of the analysis from Section 3, Table 2 compares the characteristics addressed by each method. The ticks have been placed based on reference material, which is also discussed below. In cases where there was insufficient evidence to support this, the authors' opinion has been used based on the review of the description of the methodologies in the literature. Studies which attempted to combine techniques or introduce GT concepts into the methodology are also discussed in the comparisons below.

Table 2 shows that all the methods address uncertainty and DM, though in different ways. Most of the techniques can deliver optimal outcomes except for RDM, which opts for robustness rather than optimality. The ranking of alternatives is specifically addressed only by MCDA and yet, whilst such ranking does not provide an intended starting point for GT analysis, cooperative GT can allocate stable results through different methods, and every allocation has a higher stability capacity, they can be ordered according to a fairer distribution of payoffs. The final superficial observation is that ABM most closely approximates to GT. It must not be overlooked that there are important differences, as discussed below. Even though the properties addressed by GT and ABM are broadly similar, the flowcharts in Figure 3 demonstrate that the procedures are different, and the outcomes vary significantly. While the concepts of GT can be embedded in the action rules in ABM to program the agents to behave accordingly, contrary to GT, the aim of ABM is not to analyse the agents' interactions but to evaluate the effect of their actions in the system simulation. It is therefore of critical importance to make the distinction between GT and ABM.

Table 2: Characteristics comparison of methodologies.

While ABM can be programmed with basic GT principles, ABM "is all about the rules". For example, Romero and Ruiz (2014) introduced ABM to analyse the transformation of industrial eco-systems from former industrial areas and sought to enhance their model by using GT concepts to assess cooperative relationships in bringing about the conversion. ABM – if elements of GT are coupled in the design – was proposed as one of the three most helpful tools to study environmental management and social interactions from a dynamic systems approach

(Sinha, 2016). ABM is useful when modelling complex systems with large numbers of autonomous and heterogeneous agents to investigate how their behaviour impacts the system's outcomes. In contrast, GT analyses the strategic interactions among stakeholders, usually between two players although models can be upgraded to analyse more participants (Myerson, 1991). An important drawback of ABM is that it models human behaviour and yet factors difficult to measure and include in the rules are often not considered, such as emotions, complex psychology and subjective choices. The scope of ABM is not the total system but pitched at the individual units level, and for this reason ABM usually requires large amounts of data which then lead to computation and time issues (Bonabeau, 2002).

Similar to GT, MCDA considers the viewpoints of actors and requires information on costs/benefits or payoffs. Soltani et al. (2016) acknowledge that MCDA is useful in accounting for multiple criteria when ranking or optimising alternatives. MCDA selects the optimal alternatives by ranking them using weighting criteria established subjectively by a single stakeholder, whereas GT provides the optimal combination of strategies by analysing the preferred alternatives between multiple stakeholders. One particular advantage is the ability of GT to complement MCDA when considering conflict and its impact on stakeholders reaching an agreement.

Regarding SA, the main difference is that GT provides predictions for a strategic interaction between participants, whilst scenarios aim to foresight the development of a current problem – exploring how to move to an extreme or to a desired context, or attempt to predict the future state from a set of plausible conditions. Uncertainty is interpreted differently in both methods: for SA it represents a set of feasible future results, whilst for GT it is based on the bounded rationality of participants which derive from limited-informed decisions. SA fails to analyse cooperation between stakeholders, their interactions and their strategic behaviours to achieve (frequently) conflicting objectives.

In spite of addressing uncertainty as multiple future expectations to provide robust alternatives and considering stakeholders' interactions, RDM differs from GT in considering their strategic behaviour, i.e. their ability to predict their counterparts' actions in response of their own decisions. Both methods facilitate cooperation between participants to reach preferred outcomes, particularly when there are differences in value perception and objectives. RDM aims to deliver robust rather than optimal alternatives, which are adaptable and not fragile (or vulnerable to unexpected external impacts), while GT provides optimal and stable results if cooperative and non-cooperative analyses are combined.

Figure 3: Methodologies flowchart comparison.

IAM meets multiple objectives through the integration of several disciplines in its assessment and it considers the interactions and linkages between participants or sub-models, but not their strategic behaviour as with GT. IAM delivers optimal decisions by considering implementation costs, whereas GT considers preferences, payoffs and incentives of stakeholders.

Table 2 suggests that GT's most important attribute is its ability to study the strategic behaviour of actors. This is because cooperation is essential to the successful implementation of circularity, and GT can be applied both in cooperative and non-cooperative modes to provide different essential perspectives on the issue. One lesson that flows from this is that instead of thinking that sustainability is only achievable if policy-makers enforce the equal sharing of environmental costs, business model leaders should understand the importance of improving their businesses by being proactive in comprehending sustainability better than their competitors (Robèrt and Broman, 2017) and sharing this understanding amongst the actors. This discussion reinforces the idea that when stakeholders adopt competitive (non-cooperative) behaviour, they aim to maximise their own benefits and this will most likely lead to non-optimal outcomes for the system as a whole (Lou et al., 2004). To encourage cooperation, apart from incentives and fees imposed by a third-party, the stakeholders may send clear cooperative signals to their competitors to show explicitly their will to cooperate (Madani, 2010).

Given the limited number of publications that refer to a combination of methodologies and CE, it is instructive to mimic some work which used GT in DM in sustainability research. For example: Lozano (2011) used GT to help company leaders identify the influencing role they play on other stakeholders to move towards sustainability; Pineiro-Chousa et al. (2016) used GT to integrate three dimensions of reputation management as a sustainability driver (i.e. reputation is viewed by the entrepreneurs as a risk source, a competitive advantage or a strategic asset); and Taboada-González et al. (2017) valorised recyclables in two domestic waste generation scenarios and used GT to identify the best strategy of the municipality to minimise landfill-derived carbon emissions.

One final observation is that strategies of individual actors are commonly unknown to others, which results in conflict (Lou et al., 2004). In spite of the multiple benefits from cooperation, one of the most prominent barriers to cooperation are the stakeholders' conflicting interests (Chew et al., 2011). The study and practice of CE could benefit from the use of techniques incorporating GT elements. GT advocates the study of cooperation and conflict of participants/stakeholders. Since cooperation is a feature too often missing in CE and waste management DM, the successful implementation of CE could be facilitated if GT is adopted as another methodological approach.

4.1. Application example of GT to a DM waste management problem

To illustrate the complementary potential of GT to its peer-methods in DM in waste management within civil engineering, an example is provided on how GT can be used in advancing CE principles by building on the application from Karmperis et al. (2013). This application used three DM methods (i.e. Cost-Benefit Analysis (CBA), LCA and MCDA), and combines them with GT principles to find the most optimal solution to a waste bargaining problem.

There are many well-known GT models, for example: prisoner’s dilemma, snowdrift, battle of the sexes, peace-war, tragedy of the commons, stag hunt, etc. The purpose of the example presented below is to explain in simple terms, how GT can be used as a complementary technique to study cooperation in a bargaining situation between an agent (City Council) and a service provider (waste management operator). Other well-recognised GT models include: the Stackelberg (1937) models address the competition between two or more companies, usually studying the market leader and a follower in sequential games; also the incentives to collude and form a monopoly or to not cooperate and remain in an oligopoly, open market, etc; the Cournot (1897) model studies two manufacturers determining on how much to produce, given their costs, demand and the market price of a product. They decide simultaneously and independently from each other. These and other models can certainly focus on many waste management and CE cases, however, these applications fall beyond the scope of this review.

The example assumes that there is a negotiation between the member of a City Council, representing the citizens, and the manager of a waste recycling firm to agree on the service fee. With the CBA tool, it is calculated that the operating cost of the waste recycling treatment plan is £100/tonne, and through MCDA weighting methods, the willingness to pay of the citizens for the service is estimated to be £150/tonne. Both organisation representatives know the cost is less than £150/tonne and the value to be paid is greater than £100/tonne. There is a surplus of £50/tonne which should be divided between them, i.e. an agreement on the service fee is then needed.

It is assumed that individuals are both rational players, they will always wish to maximise their utility value. Likewise, it is assumed they are both intelligent – they have the same information, they understand the situation and can make inferences about it. The boxes in Table 3 show the payoffs of their decisions given by the decisions of their counterparts: the value on the left is the payoff for the waste recycling company and the value on the right is the payoff for the City Council. These values represent the £50/tonne surplus to be shared by the stakeholders. If both individuals agree to divide the surplus, each will receive a £25/tonne payoff. If one agrees and the other disagrees, the agreeing player will receive £50/tonne whilst the other will receive no share. On the other hand, if both stakeholders disagree, then the outcome would be (d1, d2) = (0, 0).

Table 3: Waste management service fee negotiation model.

Figure 4: Solution of the waste management service fee negotiation model with GT approach.

Stability in this context means that the state is highly unlikely to change due to a lack of incentives to deviate strategies to get better payoffs. If the state of the game is (d1, d2), the City Council would have incentives to deviate to strategy *u* as it would get a preferred surplus (£50/tonne), likewise the waste recycling company is incentivised to change its strategy to *u*. Both states (d1, u2) and (u1, d2) are considered to be unstable for the waste recycling firm or the City Council respectively, as if they deviate their strategies, they would get the same £25/tonne payoff if they move to the state (u1, u2), respectively. It is then observable that the state (u1, u2) is stable for both players, as deviating would mean obtaining a less preferred payoff for the City Council (u1, d2) (50, **0**) or for the waste recycling firm (d1, u2) (**0**, 50). State (u1, u2) is known as a Nash equilibrium (Nash, 1951). It is a solution concept on GT which states that the participants have no incentives to get a better payoff from deviating strategies unilaterally; as opposed to a Pareto optimal which states that players have maximised their utilities and cannot get a better payoff without decreasing those of others. Thus, a Nash equilibrium is regularly not Pareto efficient. This happens often in other GT models such as the prisoner's dilemma, contrary to the example above where the solution is both a Nash equilibrium and also Pareto efficient.

As shown in Figure 4, both stakeholders have symmetric utility functions, then for the surplus division negotiation: (u1, u2) = (25, 25) is the Nash bargaining solution, i.e. £125/tonne is the service fee that should be agreed upon to be paid. It is clear that the GT example presents potential to improve cooperation towards a CE waste management as it helps in the fair allocation of benefits and costs between stakeholders, in this case a City Council representing the citizens and a waste management firm.

5. Conclusions

The review of literature on the CE reveals that many interpretations of the concept have been proposed, although the authors generally highlight the importance of cooperation between stakeholders as a key enabler. This supports the overarching conclusion that the concept of a CE provides the opportunity for a wide range of stakeholders (governments, companies, consumers and cities) to jointly work towards designing more sustainable, resilient and inclusive business models (Palafox et al., 2017). Even though the issue of "conflict of interest" is not the key engineering factor, it should be addressed to inform the DM process. The contribution of GT for the CE and waste management research agendas has been established based on the ability of the technique to study cooperation and facilitate stability when business models are designed to capture multiple types of value in line with CE principles for waste management.

When analysed alongside comparable methods, it is evident from the literature that GT is not the most-often used technique in DM in engineering. In comparison, there are few studies which investigate the application of CE principles, and the movement towards a CE, using the proposed techniques, and very few consider a combination of two or more of them. The number of publications on CE has been increasing at an accelerating rate, which suggests that the area is still developing and unsaturated.

This paper is the first to have critically reviewed and compared five DM methodologies commonly used in waste management and civil engineering (i.e. ABM, MCDA, SA, RDM and IAM) against, or in combination with GT, and provided evidence for why it could play a potential role in the DM process in moving to a CE. While GT might seem superior to some reviewed tools, others are preferable according to the characteristics examined, which is why it could contribute if used in parallel in DM in waste management in civil engineering. In this regard, GT can borrow ideas used in sustainability for use in the CE agenda, as mentioned in Section 2.

Future research should compare the empirical results of distinct methodologies applied to DM towards a CE. As this paper proposes, it is important to apply more GT models in waste management in civil engineering DM, particularly when transitioning to a more sustainable approach such as a CE. To transform civil engineering and waste management to design circular processes, the consideration of many perspectives and dimensions – indeed, all stakeholder groups involved – is required. In this respect, GT presents the potential to improve the understanding of the negotiation process when adopting circularity in waste management civil engineering thinking. Future research should seek to use primary data to provide empirical evidence for the use of GT in the CE and SW agendas.

Cooperation is a feature too often missing in CE waste management DM and it has not yet been addressed sufficiently. GT is useful for situations where conflict derives from different stakeholders' priorities and value perceptions. GT is still undergoing consideration or use in the CE. In the context of implementing CE in waste management, many disputes and partnerships should be expected; for example, deciding whether recycling or incinerating waste is the best strategy for the environment, citizens, local authorities or business owners. Certainly, many factors come into play – land space, investments, infrastructure, technologies available, local environmental concerns, social attitudes, etc. – in the DM process, which could represent barriers or opportunities for cooperation. Embedding GT concepts and elements into DM methodologies to study waste management and CE would be valuable.

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References

Abdulrahman, A.O., Huisingh, D., 2018. The role of biomass as a cleaner energy source in Egypt's energy mix. J. Clean. Prod. 172, 3918–3930. https://doi.org/10.1016/j.jclepro.2017.05.049

Ali, G., Pumijumnong, N., Cui, S., 2017. Decarbonization action plans using hybrid modeling for a low-carbon society: The case of Bangkok Metropolitan Area. J. Clean. Prod. 168, 940–951. https://doi.org/doi.org/10.1016/j.jclepro.2017.09.049

Angelo, A.C.M., Saraiva, A.B., Clímaco, J.C.N., Infante, C.E., Valle, R., 2017. Life Cycle Assessment and Multi-criteria Decision Analysis: Selection of a strategy for domestic food waste management in Rio de Janeiro. J. Clean. Prod. 143, 744–756. https://doi.org/10.1016/j.jclepro.2016.12.049

Asgari, S., Afshar, A., Madani, K., 2014. Cooperative Game Theoretic Framework for Joint Resource Management in Construction. J. Constr. Eng. Manag. 140.

Blomsma, F., Brennan, G., 2017. The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity. J. Ind. Ecol. 21, 603–614. https://doi.org/doi.org/10.1111/jiec.12603

Boix, M., Montastruc, L., Azzaro-Pantel, C., Domenech, S., 2015. Optimization methods applied to the design of eco-industrial parks: a literature review. J. Clean. Prod. 87, 303–317. https://doi.org/dx.doi.org/10.1016/j.jclepro.2014.09.032

Bonabeau, E., 2002. Agent-based modeling: Methods and techniques for simulating human systems. Proc. Natl. Acad. Sci. U. S. A. 99, 7280–7287. https://doi.org/doi/10.1073/pnas.082080899

Boyko, C.T., Gaterell, M.R., Barber, A.R.G., Brown, J., Bryson, J.R., Butler, D., Caputo, S., Caserio, M., Coles, R., Cooper, R., Davies, G., Farmani, R., Hale, J., Hales, A.C., Hewitt, C.N., Hunt, D.V.L., Jankovic, L., Jefferson, I., Leach, J.M., Lombardi, D.R., MacKenzie, A.R., Memon, F.A., Pugh, T.A.M., Sadler, J.P., Weingaertner, C., Whyatt, J.D., Rogers, C.D.F., 2012. Benchmarking sustainability in cities: The role of indicators and future scenarios. Glob. Environ. Chang. 22, 245–254. https://doi.org/doi.org/10.1016/j.gloenvcha.2011.10.004

Brams, S.J., 2004. Game Theory and Politics. Dover Publications Inc, New York, USA.

Cano-Berlanga, S., Giménez-Gómez, J.M., Vilella, C., 2017. Enjoying cooperative games: The R package GameTheory. Appl. Math. Comput. 305, 381–393. https://doi.org/10.1016/j.amc.2017.02.010

Carnevale, C., Finzi, G., Pederzoli, A., Turrini, E., Volta, M., Guariso, G., Gianfreda, R., Maffeis, G., Pisoni, E., Thunis, P., Markl-Hummel, L., Blond, N., Clappier, A., Dujardin, V., Weber, C., Perron, G., 2014. Exploring trade-offs between air pollutants through an Integrated Assessment Model. Sci. Total Environ. 481, 7–16. https://doi.org/doi.org/10.1016/j.scitotenv.2014.02.016

Chen, F., Chen, H., Guo, D., Han, S., Long, R., 2018. How to achieve a cooperative mechanism of MSW source separation among individuals — An analysis based on evolutionary game theory. J. Clean. Prod. 195, 521–531. https://doi.org/10.1016/j.jclepro.2018.05.226

Cheng, S., Chan, C.W., Huang, G.H., 2003. An integrated multi-criteria decision analysis and inexact mixed integer linear programming approach for solid waste management. Eng.

Appl. Artif. Intell. 16, 543–554. https://doi.org/10.1016/S0952-1976(03)00069-1

Chew, I.M.L., Tan, R.R., Foo, D.C.Y., Chiu, A.S.F., 2009. Game theory approach to the analysis of inter-plant water integration in an eco-industrial park. J. Clean. Prod. 17, 1611–1619. https://doi.org/doi.org/10.1016/j.jclepro.2009.08.005

Chew, I.M.L., Thillaivarrna, S.L., Tan, R.R., Foo, D.C.Y., 2011. Analysis of inter-plant water integration with indirect integration schemes through game theory approach: Pareto optimal solution with interventions. Clean Technol. Environ. Policy 13, 49–62. https://doi.org/doi.org/10.1007/s10098-010-0280-x

Circle Economy, 2018. The Circularity Gap Report. Amsterdam, Netherlands.

Cong, L., Zhao, F., Sutherland, J.W., 2019. A Design Method to Improve End-of-Use Product Value Recovery for Circular Economy. J. Mech. Des. 141, 044502. https://doi.org/10.1115/1.4041574

Cournot, A.A., 1897. Researches into the Mathematical Principles of the Theory of Wealth. Macmillan, New York, USA.

Croskerry, P., 2009. A Universal Model of Diagnostic Reasoning. Acad. Med. 84, 1022–1028. https://doi.org/doi:10.1097/ACM.0b013e3181ace703

Cucchiella, F., D’Adamo, I., Gastaldi, M., Miliacca, M., 2018. A profitability analysis of small-scale plants for biomethane injection into the gas grid. J. Clean. Prod. 184, 179–187. https://doi.org/10.1016/j.jclepro.2018.02.243

Darch, G., 2014. Planning for climate change adaptation - it’s time to face those difficult decisions [WWW Document]. Bull. Chart. Inst. Ecol. Environ. Manag. URL cieem.net/data/files/InPractice_back_issues/InPractice85_Sept2014.pdf (accessed 9.13.18).

Daron, J., 2015. Challenges in using a Robust Decision Making approach to guide climate change adaptation in South Africa. Clim. Change 132, 459–473.

https://doi.org/doi.org/10.1007/s10584-014-1242-9

De Figueirêdo, M.C.B., Kroeze, C., Potting, J., Da Silva Barros, V., De Aragão, F.A.S., Gondim, R.S., De Lima Santos, T., De Boer, I.J.M., 2013. The carbon footprint of exported Brazilian yellow melon. J. Clean. Prod. 47, 404–414. https://doi.org/10.1016/j.jclepro.2012.09.015

Demesouka, O.E., Vavatsikos, A.P., Anagnostopoulos, K.P., 2016. Using MACBETH Multicriteria Technique for GIS-Based Landfill Suitability Analysis. J. Environ. Eng. 142, 04016042. https://doi.org/10.1061/(asce)ee.1943-7870.0001109

Deviatkin, I., Kapustina, V., Vasilieva, E., Isyanov, L., Horttanainen, M., 2016. Comparative life cycle assessment of deinking sludge utilization alternatives. J. Clean. Prod. 112, 3232–3243. https://doi.org/10.1016/j.jclepro.2015.10.022

Edwards, J., Othman, M., Crossin, E., Burn, S., 2018. Life cycle assessment to compare the environmental impact of seven contemporary food waste management systems. Bioresour. Technol. 248, 156–173. https://doi.org/10.1016/j.biortech.2017.06.070

Estay-Ossandon, C., Mena-Nieto, A., Harsch, N., 2018. Using a fuzzy TOPSIS-based scenario analysis to improve municipal solid waste planning and forecasting: A case study of Canary archipelago (1999–2030). J. Clean. Prod. 176, 1198–1212. https://doi.org/10.1016/j.jclepro.2017.10.324

Fei, F., Wen, Z., Huang, S., De Clercq, D., 2018. Mechanical biological treatment of municipal solid waste: Energy efficiency, environmental impact and economic feasibility analysis. J. Clean. Prod. 178, 731–739. https://doi.org/10.1016/j.jclepro.2018.01.060

Feyzi, S., Khanmohammadi, M., Abedinzadeh, N., Aalipour, M., 2019. Multi- criteria decision analysis FANP based on GIS for siting municipal solid waste incineration power plant in the north of Iran. Sustain. Cities Soc. 47. https://doi.org/10.1016/j.scs.2019.101513

Fraccascia, L., Giannoccaro, I., Albino, V., 2017. Efficacy of Landfill Tax and Subsidy Policies for the Emergence of Industrial Symbiosis Networks: An Agent-Based Simulation Study. Sustainability 9, 1–18. https://doi.org/doi.org/10.3390/su9040521

Friedrich, E., Trois, C., 2016. Current and future greenhouse gas (GHG) emissions from the management of municipal solid waste in the eThekwini Municipality - South Africa. J. Clean. Prod. 112, 4071–4083. https://doi.org/10.1016/j.jclepro.2015.05.118

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy – A new sustainability paradigm? J. Clean. Prod. 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Geng, Y., Tsuyoshi, F., Chen, X., 2010. Evaluation of innovative municipal solid waste management through urban symbiosis: A case study of Kawasaki. J. Clean. Prod. 18, 993–1000. https://doi.org/doi.org/10.1016/j.jclepro.2010.03.003

Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Grimes-Casey, H.G., Seager, T.P., Theis, T.L., Powers, S.E., 2007. A game theory framework for cooperative management of refillable and disposable bottle lifecycles. J. Clean. Prod. 15, 1618–1627. https://doi.org/doi.org/10.1016/j.jclepro.2006.08.007

Grogan, P.T., Meijer, S.A., 2017. Gaming Methods in Engineering Systems Research. Syst. Eng. 20, 542–552. https://doi.org/doi.org/10.1002/sys.21409

Hadian, S., Madani, K., 2015. A system of systems approach to energy sustainability assessment: Are all renewables really green? Ecol. Indic. 52, 194–206. https://doi.org/10.1016/j.ecolind.2014.11.029

Hadka, D., Herman, J., Reed, P., Keller, K., 2015. An open source framework for many-objective robust decision making. Environ. Model. Softw. 74, 114–129.

https://doi.org/doi.org/10.1016/j.envsoft.2015.07.014

Hall, J.W., Lempert, R.J., Keller, K., Hackbarth, A., Mijere, C., Mcinerney, D.J., 2012. Robust Climate Policies Under Uncertainty: A Comparison of Robust Decision Making and Info-Gap Methods. Risk Anal. 32, 1657–1672. https://doi.org/doi.org/10.1111/j.1539-6924.2012.01802.x

He, Z., Xiong, J., Ng, T.S., Fan, B., Shoemaker, C.A., 2017. Managing competitive municipal solid waste treatment systems: An agent-based approach. Eur. J. Oper. Res. 263, 1063–1077. https://doi.org/10.1016/j.ejor.2017.05.028

Heshmati, A., 2015. A Review of the Circular Economy and its Implementation [WWW Document]. URL https://www.iza.org/publications/dp/9611/a-review-of-the-circular-economy-and-its-implementation (accessed 9.12.18).

Hong, S., Bradshaw, C.J.A., Brook, B.W., 2013. Evaluating options for sustainable energy mixes in South Korea using scenario analysis. Energy 52, 237–244. https://doi.org/10.1016/j.energy.2013.02.010

Hornsby, C., Ripa, M., Vassillo, C., Ulgiati, S., 2017. A roadmap towards integrated assessment and participatory strategies in support of decision-making processes. The case of urban waste management. J. Clean. Prod. 142, 157–172. https://doi.org/10.1016/j.jclepro.2016.06.189

Howard, J., 2006. Using Game Theory to Explain the Behaviour of Participants Involved in a Regional Governance Process. Rural Soc. 16, 254–270. https://doi.org/doi.org/10.5172/rsj.351.16.3.254

Hunt, D.V.L., Jefferson, I., Rogers, C.D.F., 2011. Assessing the Sustainability of Underground Space Usage - A Toolkit for Testing Possible Urban Futures. J. Mt. Sci. 8, 211–222. https://doi.org/doi.org/10.1007/s11629-011-2093-8

Hunt, D.V.L., Lombardi, D.R., Atkinson, S., Barber, A., Barnes, M., Boyko, C.T., Brown, J., Bryson, J., Butler, D., Caputo, S., Caserio, M., Coles, R., Cooper, R., Farmani, R., Gaterell, M., Hale, J., Hales, C., Hewitt, C.N., Jankovic, L., Jefferson, I., Leach, J.M., MacKenzie, A.R., Memon, F.A., Pugh, T.A.M., Rogers, C.D.F., Sadler, J.P., Weingaertner, C., Whyatt, J.D., 2012a. Using Scenarios to Explore Urban UK Futures: A review of Futures Literature from 1997 to 2011. Urban Futures Monograph, Birmingham, UK.

Hunt, D.V.L., Lombardi, D.R., Atkinson, S., Barber, A.R.G., Barnes, M., Boyko, C.T., Brown, J., Bryson, J., Butler, D., Caputo, S., Caserio, M., Coles, R., Cooper, R.F.D., Farmani, R., Gaterell, M., Hale, J., Hales, C., Hewitt, C.N., Jankovic, L., Jefferson, I., Leach, J., MacKenzie, A.R., Memon, F.A., Sadler, J.P., Weingaertner, C., Whyatt, J.D., Rogers, C.D.F., 2012b. Scenario Archetypes: Converging Rather than Diverging Themes. Sustainability 4, 740–772. https://doi.org/doi.org/10.3390/su4040740

Hunt, D.V.L., Rogers, C.D.F., 2015a. Aspirational City Futures : 3 models for city living [WWW Document]. Foresight, Gov. Off. Sci. London, UK. URL www.gov.uk/government/collections/future-of-cities (accessed 10.23.18).

Hunt, D.V.L., Rogers, C.D.F., 2015b. Aspirational City Futures: 3 models for city living – workshops (Bristol and Birmingham) [WWW Document]. Foresight, Gov. Off. Sci. London, UK. URL www.gov.uk/government/collections/future-of-cities (accessed 10.23.18).

Hunt, D.V.L., Rogers, C.D.F., Jefferson, I., 2013. Scenarios analysis through a futures performance framework, in: Proceedings of the Institution of Civil Engineers - Engineering Sustainability. pp. 258–271. https://doi.org/10.1680/ensu.12.00040

Ichiisi, T., 2014. Game Theory for Economic Analysis. Academic Press Inc, New York, USA.

Islam, K.M.N., 2017. Greenhouse gas footprint and the carbon flow associated with different solid waste management strategy for urban metabolism in Bangladesh. Sci. Total

Environ. 580, 755–769. https://doi.org/10.1016/j.scitotenv.2016.12.022

Jiménez Rivero, A., Sathre, R., García Navarro, J., 2016. Life cycle energy and material flow implications of gypsum plasterboard recycling in the European Union. Resour. Conserv. Recycl. 108, 171–181. https://doi.org/10.1016/j.resconrec.2016.01.014

Kandiah, V., Binder, A.R., Berglund, E.Z., 2017. An Empirical Agent-Based Model to Simulate the Adoption of Water Reuse Using the Social Amplification of Risk Framework. Risk Anal. 37, 2005–2022. https://doi.org/10.1111/risa.12760

Kapilan, S., Elangovan, K., 2018. Potential landfill site selection for solid waste disposal using GIS and multi-criteria decision analysis (MCDA). J. Cent. South Univ. 25, 570–585. https://doi.org/10.1007/s11771-018-3762-3

Karmperis, A.C., Aravossis, K., Tatsiopoulos, I.P., Sotirchos, A., 2013. Decision support models for solid waste management: Review and game-theoretic approaches. Waste Manag. 33, 1290–1301. https://doi.org/10.1016/j.wasman.2013.01.017

Kastner, C.A., Lau, R., Kraft, M., 2015. Quantitative tools for cultivating symbiosis in industrial parks: a literature review. Appl. Energy 155, 599–612. https://doi.org/10.1016/j.apenergy.2015.05.037

Kaźmierczak, U., Blachowski, J., Górniak-Zimroz, J., 2019. Multi-Criteria Analysis of Potential Applications of Waste from Rock Minerals Mining. Appl. Sci. 9, 441. https://doi.org/10.3390/app9030441

Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., Hekkert, M., 2018. Barriers to the Circular Economy: Evidence from the European Union (EU). Ecol. Econ. 150, 264–272. https://doi.org/10.1016/j.ecolecon.2018.04.028

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: An analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Klein, I., Ben-Elia, E., 2016. Emergence of cooperation in congested road networks using ICT and future and emerging technologies: A game-based review. Transp. Res. Part C 72, 10–28. https://doi.org/10.1016/j.trc.2016.09.005

Korhonen, J., Nuur, C., Feldmann, A., Birkie, S.E., 2018. Circular economy as an essentially contested concept. J. Clean. Prod. 175, 544–552. https://doi.org/10.1016/j.jclepro.2017.12.111

Kucukvar, M., Egilmez, G., Tatari, O., 2014. Evaluating environmental impacts of alternative construction waste management approaches using supply-chain-linked life-cycle analysis. Waste Manag. Res. 32, 500–508. https://doi.org/10.1177/0734242X14536457

Lange, K.P.H., Korevaar, G., Oskam, I.F., Herder, P.M., 2017. Developing and Understanding Design Interventions in Relation to Industrial Symbiosis Dynamics. Sustainability 9. https://doi.org/10.3390/su9050826

Lee, C., 2011. Bounded rationality and the emergence of simplicity amidst complexity. J. Econ. Surv. 25, 507–526. https://doi.org/10.1111/j.1467-6419.2010.00670.x

Lee, D.H., 2017. Econometric assessment of bioenergy development. Int. J. Hydrogen Energy 42, 27701–27717. https://doi.org/10.1016/j.ijhydene.2017.08.055

Lempert, R., Nakicenovic, N., Sarewitz, D., Schlesinger, M., 2004. Characterizing climate-change uncertainties for decision-makers. Clim. Change 65, 1–9. https://doi.org/10.1023/B:CLIM.0000037561.75281.b3

Lempert, R.J., Collins, M.T., 2007. Managing the Risk of Uncertain Threshold Responses: Comparison of Robust, Optimum, and Precautionary Approaches. Risk Anal. 27, 1009–1026. https://doi.org/10.1111/j.1539-6924.2007.00940.x

Lewandowski, M., 2016. Designing the Business Models for Circular Economy-Towards the Conceptual framework. Sustainability 8, 1–28. https://doi.org/10.3390/su8010043

Li, J.S., Fan, H.M., 2013. Symbiotic Cooperative Game Analysis on Manufacturers in

Recycling of Industrial Wastes. Appl. Mech. Mater. 295–298, 1784–1788. https://doi.org/10.4028/www.scientific.net/AMM.295-298.1784

Li, N., Zhao, H., 2016. Performance evaluation of eco-industrial thermal power plants by using fuzzy GRA-VIKOR and combination weighting techniques. J. Clean. Prod. 135, 169–183. https://doi.org/10.1016/j.jclepro.2016.06.113

Lieder, M., Asif, F.M.A., Rashid, A., 2017. Towards Circular Economy implementation: an agent-based simulation approach for business model changes. Auton. Agent. Multi. Agent. Syst. 31. https://doi.org/10.1007/s10458-017-9365-9

Lieder, M., Rashid, A., 2016. Towards circular economy implementation: a comprehensive review in context of manufacturing industry. J. Clean. Prod. 115, 36–51. https://doi.org/10.1016/j.jclepro.2015.12.042

Lombardi, D., Leach, J., Rogers, C., Aston, R., Barber, A., Boyko, C., Brown, J., Bryson, J., Butler, D., Caputo, S., Caserio, M., Coles, R., Cooper, R., Coyne, R., Farmani, R., Gaterell, M., Hale, J., Hales, C., CN, H., Hunt, D., Jancovic, L., Jefferson, I., MacKenzie, A., Memon, F., Phenix-Walker, R., Pugh, T., Sadler, J., Weingaertner, C., Whyatt, J., 2012. Designing Resilient Cities: A Guide to Good Practice. IHS BRE Press, Bracknell, UK.

Lou, H.H., Kulkarni, M.A., Singh, A., Huang, Y.L., 2004. A game theory based approach for emergy analysis of industrial ecosystem under uncertainty. Clean Technol. Environ. Policy 6, 156–161. https://doi.org/10.1007/s10098-003-0235-6

Lozano, R., 2011. Addressing Stakeholders and Better Contributing to Sustainability through Game Theory. J. Corp. Citizsh. 43, 44–62. https://doi.org/10.9774/GLEAF.4700.2011.au.00004

Lu, H.W., Huang, G.H., Xu, Y., He, L., 2012. Inexact two-phase fuzzy programming and its application to municipal solid waste management. Eng. Appl. Artif. Intell. 25, 1529–

1536. https://doi.org/10.1016/j.engappai.2012.08.006

Luo, M., Song, X., Hu, S., Chen, D., 2019. Towards the sustainable development of waste household appliance recovery systems in China: an agent-based modeling approach. J. Clean. Prod. 220, 431–444. https://doi.org/10.1016/j.jclepro.2019.02.128

Macal, C.M., North, M.J., 2010. Tutorial on agent-based modelling and simulation. J. Simul. 4, 151–162. https://doi.org/10.1057/jos.2010.3

Madani, K., 2010. Game theory and water resources. J. Hydrol. 225–238. https://doi.org/10.1016/j.jhydrol.2009.11.045

Madani, K., Darch, G., Parra, F., Workman, M., 2015. Using Game Theory to Address Modern Resource Management Problems. Grantham Institute, Imperial College London, London, UK.

Madani, K., Hipel, K.W., 2011. Non-Cooperative Stability Definitions for Strategic Analysis of Generic Water Resources Conflicts. Water Resour. Manag. 25, 1949–1977. https://doi.org/10.1007/s11269-011-9783-4

Matrosov, E.S., Woods, A.M., Harou, J.J., 2013. Robust Decision Making and Info-Gap Decision Theory for water resource system planning. J. Hydrol. 494, 43–58. https://doi.org/10.1016/j.jhydrol.2013.03.006

Murray, A., Skene, K., Haynes, K., 2017. The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context. J. Bus. Ethics 140, 369–380. https://doi.org/10.1007/s10551-015-2693-2

Myerson, R.B., 1991. Game Theory: Analysis of Conflict. Harvard University Press, Cambridge, MA, USA.

Nash, J., 1953. Two-Person Cooperative Games. Econometrica 21, 128–140.

Nash, J., 1951. Non-Cooperative Games. Ann. Math. 54, 286–295.

Nguyen-Trong, K., Nguyen-Thi-Ngoc, A., Nguyen-Ngoc, D., Dinh-Thi-Hai, V., 2017.

Optimization of municipal solid waste transportation by integrating GIS analysis, equation-based, and agent-based model. Waste Manag. 59, 14–22. https://doi.org/10.1016/j.wasman.2016.10.048

Niero, M., Negrelli, A.J., Hoffmeyer, S.B., Olsen, S.I., Birkved, M., 2016. Closing the loop for aluminum cans: Life Cycle Assessment of progression in Cradle-to-Cradle certification levels. J. Clean. Prod. 126, 352–362. https://doi.org/10.1016/j.jclepro.2016.02.122

Oxley, T., Dore, A.J., ApSimon, H., Hall, J., Kryza, M., 2013. Modelling future impacts of air pollution using the multi-scale UK Integrated Assessment Model (UKIAM). Environ. Int. 61, 17–35. https://doi.org/10.1016/j.envint.2013.09.009

Palafox, G., Lee, S., Bouch, C., Hunt, D., Rogers, C., 2017. The Little Book of Circular Economy in Cities: A Short Guide to Urban Metabolism and Resource Flows. Imagination Lancaster, Lancaster, UK.

Pallottino, S., Sechi, G.M., Zuddas, P., 2005. A DSS for water resources management under uncertainty by scenario analysis. Environ. Model. Softw. 20, 1031–1042. https://doi.org/10.1016/j.envsoft.2004.09.012

Pettit, C., Chung, W., Sharifi, V., Chalabi, Z., Fletcher, T., Cleall, P., Thomas, H., De Munck, C., Sinnett, D., Jefferies, S., Jones, M., Azapagic, A., 2011. Sustainable management of urban pollution: An integrated approach. Build. Serv. Eng. Res. Technol. 32, 21–34. https://doi.org/10.1177/0143624410394528

Pineiro-Chousa, J., Vizcaíno-González, M., López-Cabarcos, M.Á., 2016. Reputation, Game Theory and entrepreneurial sustainability. Sustain. 8, 1–13. https://doi.org/10.3390/su8111196

Prieto-Sandoval, V., Jaca, C., Ormazabal, M., 2018. Towards a consensus on the circular economy. J. Clean. Prod. 179, 605–615. https://doi.org/10.1016/j.jclepro.2017.12.224

Rezaei, M., Ghobadian, B., Samadi, S.H., Karimi, S., 2018. Electric power generation from municipal solid waste: A techno-economical assessment under different scenarios in Iran. Energy 152, 46–56. https://doi.org/10.1016/j.energy.2017.10.109

Ripa, M., Fiorentino, G., Vacca, V., Ulgiati, S., 2017. The relevance of site-specific data in Life Cycle Assessment (LCA). The case of the municipal solid waste management in the metropolitan city of Naples (Italy). J. Clean. Prod. 142, 445–460. https://doi.org/10.1016/j.jclepro.2016.09.149

Rizos, V., Tuokko, K., Behrens, A., 2017. The Circular Economy: A review of definitions, processes and impacts [WWW Document]. URL https://www.ceps.eu/system/files/RR2017-08_CircularEconomy_0.pdf (accessed 9.10.18).

Robèrt, K.-H., Broman, G., 2017. Prisoners' dilemma misleads business and policy making. J. Clean. Prod. 140, 10–16. https://doi.org/10.1016/j.jclepro.2016.08.069

Rogers, C.D.F., 2018. Engineering Future Liveable, Resilient, Sustainable Cities Using Foresight. Proc. Inst. Civ. Eng. Eng. 171, 3–9. https://doi.org/10.1680/jcien.17.00031

Rogers, C.D.F., Hunt, D.V.L., Leach, J.M., Purnell, P., Roelich, K.E., 2017. Resource Scarcity and Resource Security – A Suppressed Civil Engineering Challenge. Proc. Inst. Civ. Eng. Waste Resour. Manag. 170, 49–51. https://doi.org/10.1680/jwarm.17.00008

Rogers, C.D.F., Lombardi, D., Leach, J.M., Cooper, R.F.D., 2012. The urban futures methodology applied to urban regeneration. Proc. Inst. Civ. Eng. Eng. Sustain. 165, 5–20. https://doi.org/10.1680/ensu.2012.165.1.5

Romero, E., Ruiz, M.C., 2014. Proposal of an agent-based analytical model to convert industrial areas in industrial eco-systems. Sci. Total Environ. 468–469, 394–405. https://doi.org/10.1016/j.scitotenv.2013.08.049

Saad, W., Han, Z., Poor, H.V., Başar, T., 2012. Game-Theoretic Methods for the Smart Grid, in: IEEE Signal Processing Magazine. pp. 86–105. https://doi.org/10.1109/MSP.2012.2186410

Saavedra, Y.M.B., Iritani, D.R., Pavan, A.L.R., Ometto, A.R., 2018. Theoretical contribution of industrial ecology to circular economy. J. Clean. Prod. 170, 1514–1522. https://doi.org/10.1016/j.jclepro.2017.09.260

Sabaghi, M., Mascle, C., Baptiste, P., 2016. Evaluation of products at design phase for an efficient disassembly at end-of-life. J. Clean. Prod. 116, 177–186. https://doi.org/10.1016/j.jclepro.2016.01.007

Santos, M.J., Ferreira, P., Araújo, M., Portugal-Pereira, J., Lucena, A.F.P., Schaeffer, R., 2017. Scenarios for the future Brazilian power sector based on a multi-criteria assessment. J. Clean. Prod. 167, 938–950. https://doi.org/10.1016/j.jclepro.2017.03.145

Santos, V.E.N., Magrini, A., 2018. Biorefining and industrial symbiosis: A proposal for regional development in Brazil. J. Clean. Prod. 177, 19–33. https://doi.org/10.1016/j.jclepro.2017.12.107

Sauvé, S., Bernard, S., Sloan, P., 2016. Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. Environ. Dev. 17, 48–56. https://doi.org/10.1016/j.envdev.2015.09.002

Sawik, T., 2014. On the robust decision-making in a supply chain under disruption risks. Int. J. Prod. Res. 52, 6760–6781. https://doi.org/10.1080/00207543.2014.916829

Shi, X., Thanos, A.E., Celik, N., 2014. Multi-objective agent-based modeling of single-stream recycling programs. Resour. Conserv. Recycl. 92, 190–205. https://doi.org/10.1016/j.resconrec.2014.07.002

Silvia, C., Krause, R.M., 2016. Assessing the impact of policy interventions on the adoption of plug-in electric vehicles: An agent-based model. Energy Policy 96, 105–118. https://doi.org/10.1016/j.enpol.2016.05.039

Sinha, R., 2016. Systems Modeling Approaches to Physical Resource Management: An Industrial Ecology Perspective. Doctoral Thesis, KTH Royal Institute of Technology, Stockholm, Sweden.

Smith, J.M., 1982. Evolution and the Theory of Games. Cambridge University Press, Cambridge, UK.

Soltani, A., Hewage, K., Reza, B., Sadiq, R., 2015. Multiple stakeholders in multi-criteria decision-making in the context of Municipal Solid Waste Management: A review. Waste Manag. 35, 318–328. https://doi.org/10.1016/j.wasman.2014.09.010

Soltani, A., Sadiq, R., Hewage, K., 2016. Selecting sustainable waste-to-energy technologies for municipal solid waste treatment: A game theory approach for group decision-making. J. Clean. Prod. 113, 388–399. https://doi.org/10.1016/j.jclepro.2015.12.041

Stackelberg, H.F. von, 1937. Market Structure and Equilibrium. Springer.

Strantzali, E., Aravossis, K., Livanos, G.A., Nikoloudis, C., 2019. A decision support approach for evaluating liquefied natural gas supply options: Implementation on Greek case study. J. Clean. Prod. 222, 414–423. https://doi.org/10.1016/j.jclepro.2019.03.031

Taboada-González, P., Aguilar-Virgen, Q., Márquez-Benavides, L., 2017. Recyclables Valorisation as the Best Strategy for Achieving Landfill CO2e Emissions Abatement from Domestic Waste: Game theory. Sustain. 9, 1–10. https://doi.org/10.3390/su9071154

Tan, Y., Guo, C., 2019. Research on two-way logistics operation with uncertain recycling quality in government multi-policy environment. Sustain. 11. https://doi.org/10.3390/su11030882

Tol, R.S.J., 1997. On the optimal control of carbon dioxide emissions: an application of FUND. Environ. Model. Assess. 2, 151–163. https://doi.org/10.1023/A:1019017529030

Tong, X., Nikolic, I., Dijkhuizen, B., van den Hoven, M., Minderhoud, M., Wäckerlin, N., Wang, T., Tao, D., 2018. Behaviour change in post-consumer recycling: Applying agent-based modelling in social experiment. J. Clean. Prod. 187, 1006–1013. https://doi.org/10.1016/j.jclepro.2018.03.261

Veleva, V., Bodkin, G., 2018. Corporate-entrepreneur collaborations to advance a circular economy. J. Clean. Prod. 188, 20–37. https://doi.org/10.1016/j.jclepro.2018.03.196

Vincent, T.L., Brown, J.S., 2005. Evolutionary Game Theory, Natural Selection, and Darwinian Dynamics. Cambridge University Press, Cambridge, UK.

von Neumann, J., Morgenstern, O., 1944. Theory of Games and Economic Behavior. Princeton University Press, Princeton, NJ.

Wang, D., Li, J., Wang, Y., Wan, K., Song, X., Liu, Y., 2017. Comparing the vulnerability of different coal industrial symbiosis networks under economic fluctuations. J. Clean. Prod. 149, 636–652.

Wang, J.J., Jing, Y.Y., Zhang, C.F., Zhao, J.H., 2009. Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renew. Sustain. Energy Rev. 13, 2263–2278. https://doi.org/10.1016/j.rser.2009.06.021

Weyant, J., Davidson, O., Dowlatabadi, H., Edmonds, J., Grubb, M., Parson, E.A., Richels, R., Rotmans, J., Shukla, P.R., Tol, R.S.J., Cline, W., Fankhauser, S., 1996. Integrated Assessment of Climate Change: An Overview and Comparison of Approaches and Results, in: Climate Change 1995: Economic and Social Dimensions of Climate Change. Cambridge University Press, Cambridge, UK, pp. 367–396.

Wu, J., Wang, R., Pu, G., Qi, H., 2016. Integrated assessment of exergy, energy and carbon dioxide emissions in an iron and steel industrial network. Appl. Energy 183, 430–444. https://doi.org/10.1016/j.apenergy.2016.08.192

Xi, B.D., Su, J., Huang, G.H., Qin, X.S., Jiang, Y.H., Huo, S.L., Ji, D.F., Yao, B., 2010. An integrated optimization approach and multi-criteria decision analysis for supporting the waste-management system of the City of Beijing, China. Eng. Appl. Artif. Intell. 23, 620–631. https://doi.org/10.1016/j.engappai.2010.01.002

Yazan, D.M., Fraccascia, L., 2019. Sustainable operations of industrial symbiosis: an enterprise input-output model integrated by agent-based simulation. Int. J. Prod. Res. 0, 1–23. https://doi.org/10.1080/00207543.2019.1590660

Zechman, E.M., 2011. Agent-Based Modeling to Simulate Contamination Events and Evaluate Threat Management Strategies in Water Distribution Systems. Risk Anal. 31, 758–772. https://doi.org/10.1111/j.1539-6924.2010.01564.x

Zhao, Haoran, Zhao, Huiru, Guo, S., 2017. Evaluating the comprehensive benefit of eco-industrial parks by employing multi-criteria decision making approach for circular economy. J. Clean. Prod. 142, 2262–2276. https://doi.org/http://dx.doi.org/10.1016/j.jclepro.2016.11.041

Zhu, L., Duan, H.-B., Fan, Y., 2015. CO2 mitigation potential of CCS in China – an evaluation based on an integrated assessment model. J. Clean. Prod. 103, 934–947. https://doi.org/10.1016/j.jclepro.2014.08.079

Zhu, Y., Ghosh, M., 2014. Impacts of Technology Uncertainty on Energy Use, Emission and Abatement Cost in USA: Simulation results from Environment Canada's Integrated Assessment Model. Energy J. 35, 229–247. https://doi.org/10.5547/01956574.35.SI1.12

Appendices

Appendix 1: Previous research using the compared DM methodologies in the CE context.

Method	Author(s)	Application	Country / Region
ABM (Section 3.1)	Lieder et al. (2017)	Studied the behaviour of customers towards accepting new CE business models.	Stockholm, Sweden
	Wang et al. (2017)	Designed a model to measure the vulnerability and impacts of economic fluctuations on coal IS networks using three networks.	China
	Tong et al. (2018)	Evaluated the behavioural change of local residents when a recycling program is started in the community.	Beijing, China
	Luo et al. (2019)	Analysed the behavioural trends of the waste household appliance recovery industry.	China
	Yazan and Fraccascia (2019)	Simulated the mechanisms in which firms distribute the economic benefits obtained from adopting IS.	N/A
MCDA (Section 3.2)	Sabaghi et al. (2016)	Considered five parameters influencing the disassembly process of an aircraft at its end-of-life.	Quebec, Canada
	Li and Zhao (2016)	Evaluated the performance of eco-industrial thermal power plants and integrate the preferences of decision-makers on performance criteria.	China
	Zhao et al. (2017)	Proposed a framework to evaluate comprehensive benefits of EIP from a CE point of view.	China
	Strantzali et al. (2019)	Developed a DM model to logistically optimise the liquified natural gas imports in cryogenic tanks.	Greece
	Kaźmierczak et al. (2019)	Assessed the potential new uses of mining waste.	Silesia, Poland
SA (Section 3.3)	Deviatkin et al. (2016)	Compared the environmental performance of different scenarios for the deinking sludge process.	Finnish-Russian border
	Niero et al. (2016)	Analysed 20 different scenarios for renewable energy and recycled content for aluminium cans based on LCA.	United Kingdom

	• Cucchiella et al. (2018) • Cong et al. (2019) • Luo et al. (2019)	• Evaluated the profitability of natural gas grid plants based on mathematical and economic models. • Proposed a method to determine the viability of recyclable end-of-use products in the design stage. • Complemented their analysis on the waste household appliance recovery industry and proposed different policy suggestions for optimal scenarios.	• Italy • N/A • China
RDM (Section 3.4)		– No relevant publications were found for CE research using an RDM approach.	
IAM (Section 3.5)	• Lee (2017)	• Reviewed and compared nine methods when seeking to advance the bio-energy development research agenda.	• N/A
GT (Section 3.6)	• Tan and Guo (2019)	• Studied the effect on different regulatory situations from the uncertainty arising from the quality of recycled products and remanufacturing technology.	• China

Appendix 2: Previous research using the compared DM methodologies in the SW context.

Method	Author(s)	Application	Country / Region
ABM (Section 3.1)	• Shi et al. (2014) • He et al. (2017) • Nguyen-Trong et al. (2017)	• Identified the sources of concern in single-stream recycling programs and simulate its alternatives. • Investigated private operators' selfish behaviour which led to competition in the MSW treatment markets. • Modelled the optimisation of collection services of MSW.	• Florida, USA • Singapore • Hagiang, Vietnam
MCDA (Section 3.2)	• Cheng et al. (2003) • Xi et al. (2010) • Pettit et al. (2011)	• Integrated MCDA and linear programming to optimise the selection of a landfill site and the waste flows costs. • Revealed the most favourable alternative for landfill site selection. • Introduced a DM framework to assess alternatives of sustainable urban pollution management.	• Regina, Canada • Beijing, China • N/A

	• Soltani et al. (2015) • Demesouka et al. (2016) • Angelo et al. (2017) • Abdulrahman and Huisingh (2018) • Kapilan and Elangovan (2018) • Feyzi et al. (2019)	• Reviewed in detail MSW management studies focusing on the stakeholder perspective. • Addressed the issue of numerous environmental and social criteria to be considered in landfill siting. • Reduced the number of admissible food waste treatment choices by including the LCA of differing satisfying alternatives. • Evaluated energy from waste alternatives to meet sustainability criteria and meet the overstressed energy demand. • Used geographical information in combination with MCDA to show the least harmful place to site landfill. • Evaluate sustainability-based criteria to select the most appropriate site for SW incineration power plants.	• N/A • Thrace, Greece • Rio de Janeiro, Brazil • Egypt • Coimbatore, India • Rasht, Iran
SA (Section 3.3)	• Geng et al. (2010) • Lu et al. (2012) • Hong et al. (2013) • De Figueirêdo et al. (2013) • Friedrich and Trois (2016) • Jiménez Rivero et al. (2016) • Ripa et al. (2017) • Islam (2017)	• Simulated waste management strategies to compare their CO2 emissions and investment costs. • Identified critical indicators that affect the outputs of MSW management. • Evaluated the feasibility of sustainable energy generation scenarios based on current technologies and their limitations. • Analysed the exporting industry of melon in order to reduce its carbon footprint and improve its transport. • Calculated the Greenhouse Gas (GHG) emissions derived from three MSW management scenarios from an LCA approach. • Compared different gypsum waste recycling scenarios for Construction & Demolition (C&D) waste arising from the construction industry. • Recognised driving aspects, potential improvements and critical issues of predictive scenarios of MSW management. • Analysed the different impacts on GHG emissions and carbon flow of five combinations of waste management strategies.	• Kawasaki, Japan • N/A • South Korea • Low Jaguaribe and Açu, Brazil • Durban, South Africa • European Union • Naples, Italy • Bangladesh

	• Estay-Ossandon et al. (2018) • Rezaei et al. (2018) • Fei et al. (2018) • Santos and Magrini (2018)	• Predicted the evolution of MSW management system until 2030 under three different future scenarios. • Discussed the economic performance of energy from waste technologies and the appropriate selection between incineration and gasification from MSW. • Contrasted the economic and environmental performance and energy efficiency of mechanical-biological treatment and other MSW technologies. • Studied the potential agro-IS network to be developed with the connection of IS and bio-refineries in traditionally agricultural areas.	• Canary Islands, Spain • Iran • Changzhou, Jiangsu, China • Norte Fluminense, Brazil
RDM (Section 3.4)	• Kucukvar et al. (2014) • Edwards et al. (2018)	• Assessed the recycling, landfilling and incineration strategies for C&D waste materials. • Compared multiple food waste management systems to rank the best performance in terms of environmental impact.	• USA • Australia
IAM (Section 3.5)	• Wu et al. (2016) • Hornsby et al. (2017)	• Assessed environmental effectiveness by integrating CO2 emissions, exergy and energy analyses in a steel and iron IS network. • Integrated the participation of stakeholders and scientists in a DM toolkit towards more sustainable SW management solutions.	• China • Naples, Italy
GT (Section 3.6)	• Grimes-Casey et al. (2007) • Karmperis et al. (2013) • Soltani et al. (2016) • Chen et al. (2018)	• Found that the decision of the bottler to choose between refillable and disposable bottles is related directly to the expected behaviour of the customer, rather than replacement costs, the product itself, or other characteristics. • Reviewed LCA and MCDA models and introduced the waste management bargaining game to support DM in the SW context. • Performed a study including GT to choose the optimal option from a set of energy from waste alternatives. • Studied the mechanisms in which individuals and local governments successfully cooperate towards SW separation.	• USA • N/A • Vancouver, Canada • China

Tables

Table 1: Number of results from bibliometric search.

Search term	Number of results found in "SCOPUS"
"Circular Economy" AND Game Theory	1
"Circular Economy" AND Agent Based Model	3
"Circular Economy" AND Multi Criteria Decision Analysis	6
"Circular Economy" AND Scenario Analysis	4
"Circular Economy" AND Robust Decision Making	0
"Circular Economy" AND Integrated Assessment Model	1
"Solid Waste" AND Game Theory	4
"Solid Waste" AND Agent Based Model	3
"Solid Waste" AND Multi Criteria Decision Analysis	8
"Solid Waste" AND Scenario Analysis	11
"Solid Waste" AND Robust Decision Making	2
"Solid Waste" AND Integrated Assessment Model	3

Table 2: Characteristics comparison of methodologies.

Characteristic	Methodology					
	GT	ABM	MCDA	SA	RDM	IAM
Conflictive objectives	✓		✓[3]		✓	
Cooperation	✓	✓			✓[6]	
Decision making	✓	✓	✓	✓	✓	✓
Foresight	✓			✓	✓[7]	
Optimisation	✓	✓	✓	✓[5]		✓[8]
Rank alternatives			✓[4]			
Stakeholders' interactions	✓	✓[2]				✓[1]
Strategic behaviour	✓[1]					
Uncertainty	✓	✓	✓	✓	✓	✓

[1] (Madani et al., 2015), [2] (Zechman, 2011), [3] (Santos et al., 2017), [4] (Ali et al., 2017; Hadian and Madani, 2015; Zhao et al., 2017), [5] (Geng et al., 2010), [6] (Hall et al., 2012), [7] (Matrosov et al., 2013), [8] (Tol, 1997).

Table 3: Waste management service fee negotiation model.

		City Council	
		Disagree (d2)	Agree (u2)
Waste Recycling Company	Disagree (d1)	0 , 0	0 , 50
	Agree (u1)	50 , 0	25 , 25

Figures

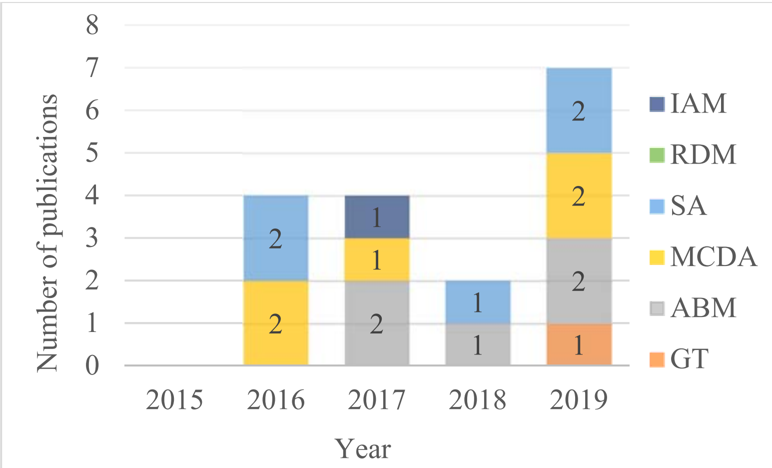


Figure 1: Number of publications per year of the DM methods and CE.

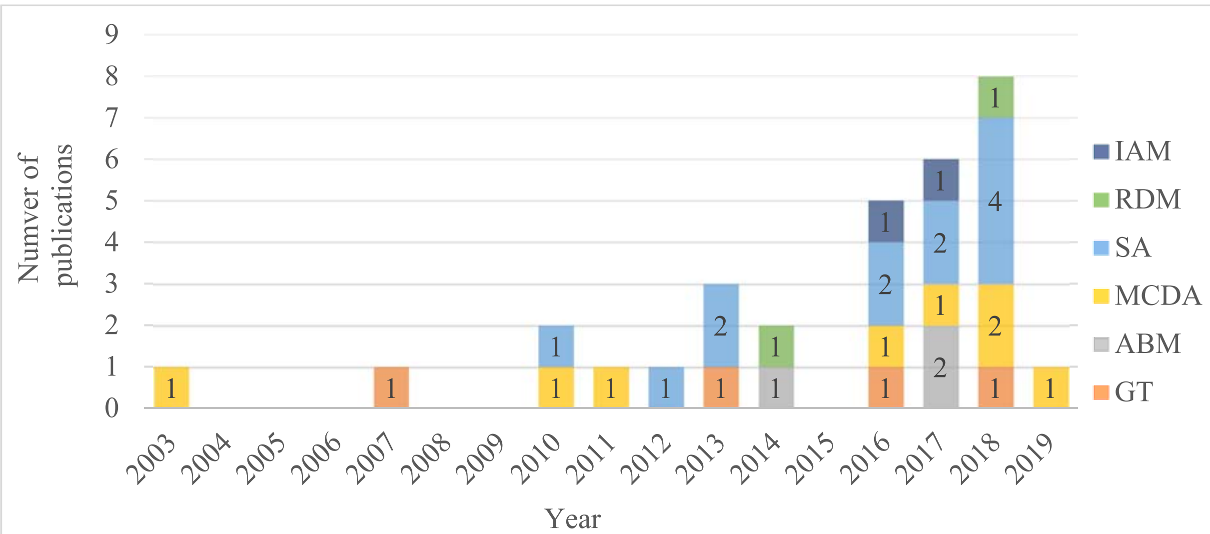


Figure 2: Number of publications per year of the DM methods and SW.

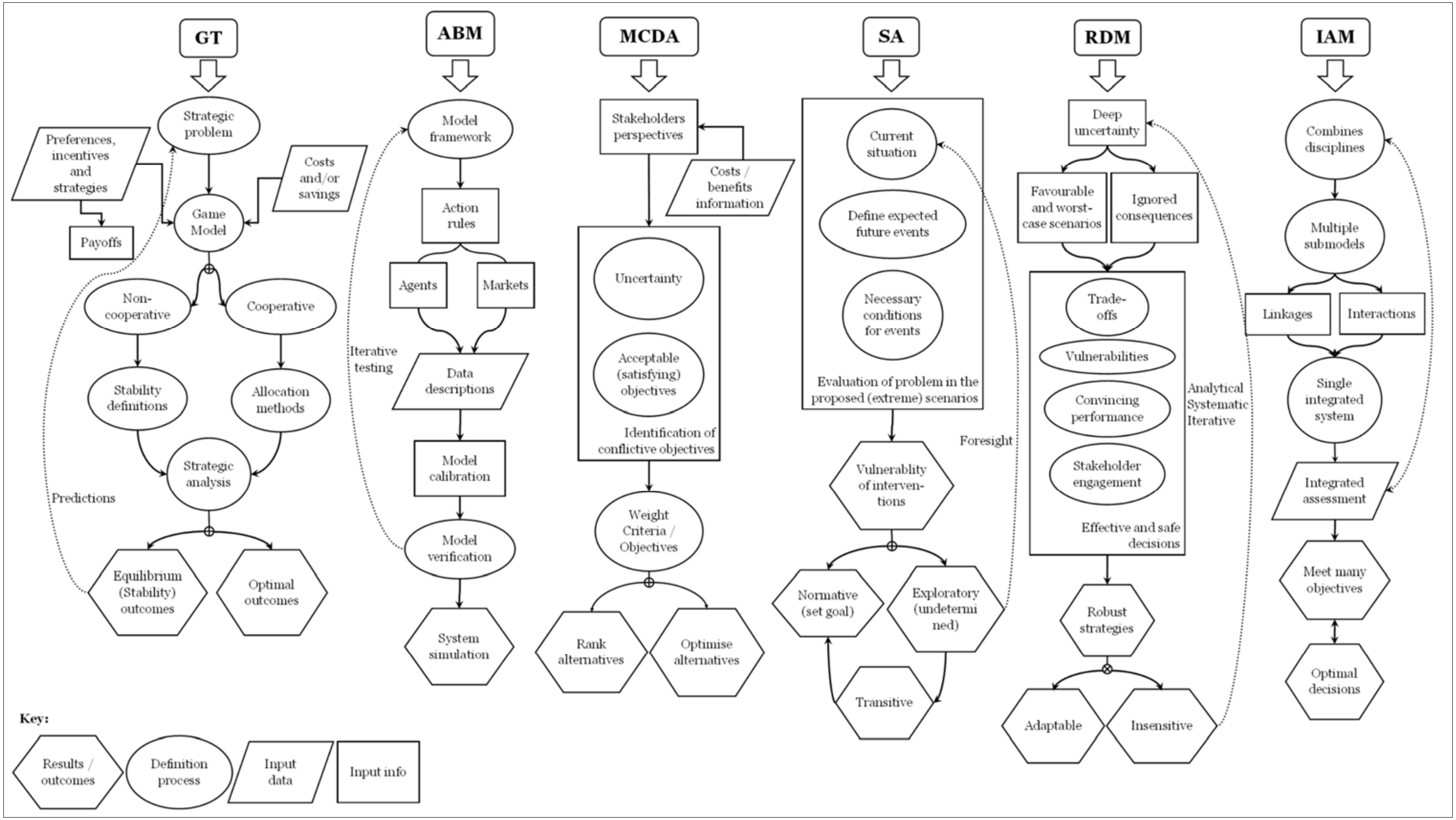
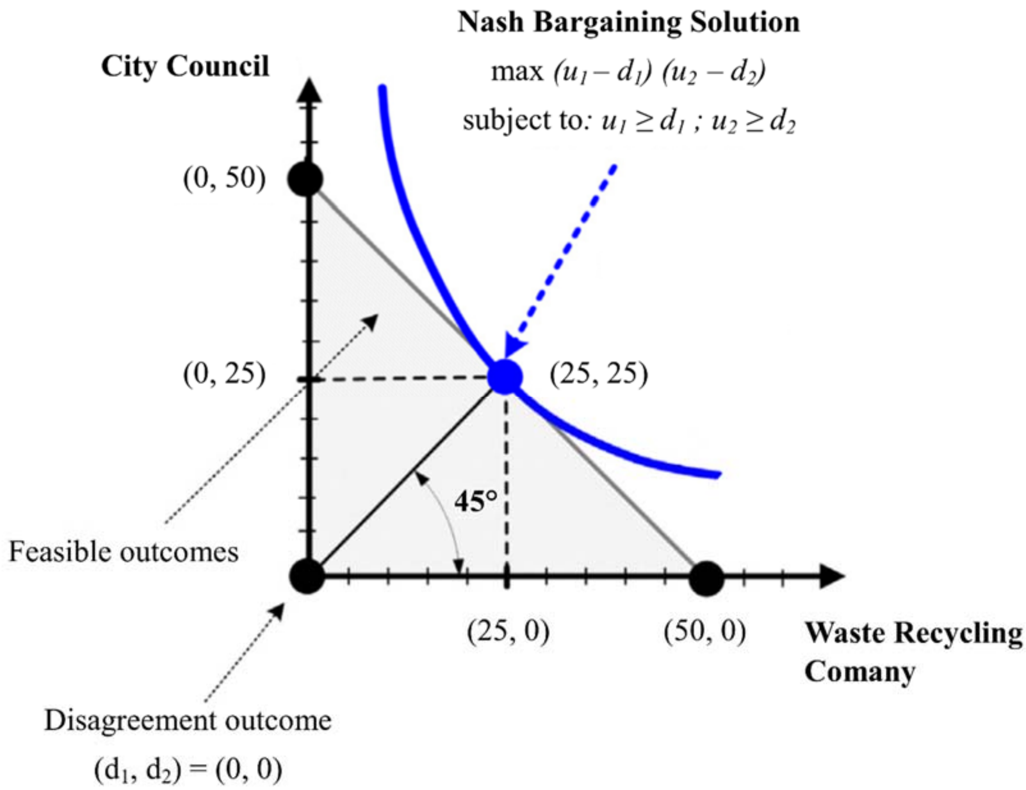


Figure 3: Methodologies flowchart comparison.



1111 **Figure 4:** Solution of the waste management service fee negotiation model with GT approach.

1113 *Source:* Adapted from Karmperis et al. (2013).