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Interfaces with Other Disciplines

Sustainable management of fossil fuels: A dynamic stochastic optimization approach with jump-diffusion

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A B S T R A C T

This paper deals with a relevant aspect of energy modeling, i.e. fossil fuels management. The issue is faced by using purely operational research techniques, which are suitable in this context. In particular, a dynamic stochastic optimization model is developed to optimally determine use and stock of resources to be employed in consumption and investments, in a wide economic sense: human and physical capital, R&D, etc. It is assumed that a sustainability criterion drives the optimality rules, i.e. decisions are also grounded on the well-being of future generations. The policymaker maximizes an aggregated intergenerational expected utility under the dilemma of present consumption/conservation of natural resources for the future. In reference to standard environmental economic theory, jump-diffusion dynamics for the stock of natural resources and infinite time horizon are assumed. Extensive numerical experiments complete the analysis and contribute to determine fossil fuels management policies, showing that long-term investments make the difference for the well-being of present and future generations.

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1. Introduction

Can Operations Research contribute to formalize sustainable economies for the exploitation of natural resources? The answer is undoubtedly positive and, in this regard, it is worth to mention some supporting references. Higgins, Hajkowicz, and Bui (2008) develop a multi-objective integer programming model for investments, aiming at maximizing environmental benefits under budget constraints. Munda (2009) describes the concept of sustainability in the context of resource management and argues that economic reasonings cannot be the only routes to follow for taking decisions.

This paper moves from this problem and deals with the development of a stochastic dynamic optimization model for identifying the optimal consumption and stock of fossil fuels (mainly, crude oil, natural gas, coal) to be employed in investment, under sustainability assumptions. The responsible management of natural resources must account for time evolution and uncertainty, which represent key features of the combined human-natural systems. Uncertainty has been previously considered for natural resources management by Querou and Tidball (2010) and Batabyal and Beladi (2004). Querou and Tidball (2010) consider a problem of resource extraction by developing a theoretical game with incomplete information, whose players are involved in repeated interactions. A characterization of the optimal consumption policy is also provided. Batabyal and Beladi (2004) focus on the likelihood that a particular resource will not collapse in the long run by maximizing the time restrictions of its use. While both approaches are useful for some types of natural resources management problems, such as fishery, hunting, and similar contexts, they are not applicable to problems involving fossil fuels, which are the focus of this paper. Indeed, in Querou and Tidball (2010) a strictly positive rate of regeneration of the natural resource – unreasonable when thinking of fossil fuels since it requires millions of years – plays a key role in the analysis. In Batabyal and Beladi (2004) time restrictions imply no use of fossil fuels in some periods. From an economical-practical point of view, when fossil fuels are considered, this assumption seems to be quite unrealistic. The stochastic dynamic optimization approach for identifying the optimal use path of the stock of fossil fuels enables to consider more realistic problems, and then it complements both the approaches proposed by Querou and Tidball (2010) and Batabyal and Beladi (2004).

When fossil fuels are considered, some genuine stochastic elements impact on the uncertain evolution of the system under consideration. It is well known that uncertainty might show up as unpredictable random shocks in the dynamic evolution of

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an ecosystem, either in the form of an ongoing stream of small fluctuations or as abrupt and substantial discrete occurrences. Here, we consider both types of random shocks.[1]

Moreover, uncertain elements affect resource exploitation and management both directly and indirectly via their influence on economy-wide variables. Accounting for such an uncertainty requires an integrated model allowing feedback effects between natural resources, climate change, and the overall economic context. This paper considers a lab-equipment model in which a commodity, the natural resource, in this case, is used up both in consumption and investments (see, e.g., Acemoglu, 2009).[2]

Substantially, we aim at joining the two conflicting targets that an (ethic) policymaker should pursue: to act as homo œconomicus by maximizing the benefits from the use of fossil fuels; to be sustainable and save a stock of such resources for future generations (see Chichilnisky, 1996; Heal, 1998). The relevance of this issue lies in the strict connections between the availability of fossil fuels and the search for alternative sources of energy production. This is the real challenge of the century, being fossil fuels also responsible for global warming and both air and water pollution.

The term sustainability has to be here intended as a concept invoked for guaranteeing the consideration of future generations which comes from the increasing alarm about anthropogenic climate changes. However, such a definition often fails to be effective due to its vague implications.

The Brundtland Commission proposed a generally accepted definition of sustainable development: it is (quoting) the *development that meets the needs of the present without compromising the ability of future generations to meet their own needs* (see also Goodland, 1995; Krysiak, 2009; Krysiak and Krysiak, 2006 and references therein). The ethical appeal of this statement is grounded on the requests of actions taken today to allow future generations to be treated fairly. If we agree that sustainability requires that a certain amount of goods should remain available in the long run, the key issue is to build a measure that allows evaluating whether a generation leaves enough to the future. As present and future generations need to be considered together, the discount factor of consumption and well-being of future generations play a key role. In this respect, Nordhaus (2007) and Weitzman (2007) suggest to apply the current interest rate and thus take 4 percent (or even 6 percent) over the next century, determining a discount factor of 0.985 per year. Stern (2007); 2008) indicates that the only acceptable justification for discounting future well-being is the risk-aversion for the possibility that future generations might not exist, for which the corresponding discount factor is 0.999 per year. Even if discounting future consumptions is a commonly accepted procedure, particularly in the macroeconomic literature, many scholars such as Sidgewick (1907), Pigou (1912), Ramsey (1928) and Harrod (1948) objected that it is unacceptable to treat adversely future generations. This concern about future generations has given rise to the literature on ranking utility streams. Unfortunately, its key result is the difficulty of aggregating each generation's well-being into a social welfare function that is sensible to the interest of each, and treats all generations equally (Diamond, 1965).[3] Here, the crucial assumption is the measurability and comparability of well-being across generations but, to our knowledge, economic theory does not yet provide a way to construct such well-being indexes from individual's choices. A different approach concerns recent advances in social choice theory. In particular, Fleurbaey and Maniquet (2005), collecting and extending previous works, propose a compelling framework for studying resource distribution problems and the aggregation of individual's welfare in terms of social ordering functions, associating a complete ranking of feasible alternatives to each problem. A similar contamination from social choice theory to intergenerational equity can be found in Asheim, Bossert, Sprumont, and Suzumura (2010). They study the problem of selecting an appealing intergenerational distribution of a single good for each specification of the time-invariant production technology. In particular, they show that a planner concerned with procedural and redistributive equity should select sustainable consumption paths.

Under a theoretical point of view, we adopt a stochastic dynamic optimization approach and solve it through dynamic programming and numerical analysis. In particular, we develop and solve an aggregated intergenerational expected utility maximization problem by selecting the optimal consumption and utilized stock of resource. The problem is constrained by the random dynamics of the available quantity of the resource, which are assumed to follow a jump-diffusion process. The resulting jump-diffusion stochastic optimal control problem is not trivial and includes several aspects which need peculiar attention. The adopted strategy of joining the pure theoretical analysis of the corner problems – the so-called dictatorship cases, see Section 3 for details – and the numerical procedures for the general case – see Section 4 – meets the requirement of being scientifically rigorous and also affordable under a mere practical point of view. The techniques used for the theoretical study of the model – i.e. the dynamic programming principle and the resulting Hamilton–Jacobi–Bellman equation in a jump-diffusion setting – are widely used in the field of applied dynamic optimization theory. In this respect, we address the reader to the recent contributions of Josa-Fombellida and Rincon-Zapatero (2012), Ren and Wu (2013), Huang, Yang, and Zhou (2016) and – for an overview of theory and applications – to Ø.ksendal and Sulem (2007). The numerical analysis complements and completes the analysis (see e.g. Castellano & Cerqueti, 2012; 2014).

The stochastic processes used to model the dynamics of the stock of the natural resource formalize the sources of randomness to which it is submitted: continuous-time normal flows – captured by a Brownian Motion – and extraordinary events of random size, occurring at random times, described through suitable point processes. The available stock of resource admits an absorbing state, which is related to the exhaustion of the resource. Needless to say that the target of being sustainable is not reached when the absorbing state is achieved. The presence of such a barrier represents a further constraint of the optimization problem. The time-horizon is assumed to be infinite since the time-span of the problem must include current and future generations. In this respect, generations can overlap and are fully contained in bounded time intervals.

Three main contributions are provided in this paper. Firstly, we propose a novel stochastic model which is a generalization of the deterministic set-up proposed by Chichilnisky. This leads to a more realistic and reasonable framework that can be effectively faced by adopting operational research techniques, grounded in stochastic optimal control theory with jump diffusions. Secondly, we avoid the application of a discount factor for intergenerational utility and rather propose a suitably chosen weight function.[4] In particular,

[1] Other main sources of uncertainty consist in the lack of understanding of the key natural and economic parameters. See Tsur and Zemel (2014) for a review related to various forms of uncertainty.

[2] The need for an integrated framework led to the development of the so-called Integrated Assessment Models (IAMs). As integrated models tend to be analytically intractable, they call for the use of numerical analysis. Even if IAMs provide the key tool in the study of resource management and climate change since the foundation of the Intergovernmental Panel on Climate Change (IPCC) (Clarke et al., 2009), they are not safe from criticisms (see Farmer, Hepburn, Mealy, & Teytelboym, 2015).

[3] More recent contributions provide rather negative results: Svensson (1980), Basu and Mitra (2003), Zame (2007), Lauwers (2010) and (Zuber & Asheim, 2012).

[4] This technicality has been already adopted by Chichilnisky (1996), but the Chichilnisky's weight inevitably leads to underweight the utilities of the future generations.

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