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Multi-objective optimisation for generating sustainable solutions considering total effects on the environment

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ABSTRACT

This contribution presents and discusses two multi-objective optimisation approaches considering total (direct and indirect) effects on the environment. Sustainability metrics, conventionally measuring direct harmful effects on the environment, are now upgraded with indirect effects in order to measure the unburdening the environment, e.g. due to the substitution of harmful with benign products. The first approach, based on a relative direct sustainability index, is now upgraded to a total sustainability index, and the second one, based on a concept of eco-cost and net profit, is extended to a recently introduced concept of eco- and total profit. These approaches are illustrated through a case study of the supply chain synthesis for producing biogas from organic and animal wastes. The results indicate that considering total effects enables obtaining more realistic solutions, than in those cases when only direct effects are considered. An appropriate trade-off between economic and environmental criteria can be established when performing a maximisation of total profit.

1. Introduction

The world is currently dealing with a series of environmental, financial, and social crises that have reached almost complete population around the world. This is primarily due to human population growth, globalisation, the unsustainable use of energy and resources, and an unsustainable world economy over the past 60 years [1,2]. In some areas around the world also energy, currency, food and water resource crises are becoming more severe, e.g. in China [3].

Those issues are urgent challenges being handled since the turn of the 21st century [4]. Green solutions and environmental protection are becoming the more common issues of this century [5], and energy saving is becoming the unavoidable responsibility of industries and enterprises. A green economy relating to low carbon energy is, without doubt, the only choice for mankind [4]. However, currently the wind, geothermal, solar, biomass, and waste energies satisfy only 1.8% of global energy consumption [1].

Over recent decades, sustainability, especially its environmental part, has emerged as a key issue amongst governments, policymakers, researchers, public [6] and industry [7]. Environmental indicators are usually defined on the basis of Life Cycle Assessment (LCA) principles [8]. LCA is commonly referred to as a “cradle-to-grave” analysis [9]. It takes into account the system’s full life-cycle: from the extraction and processing of resources through manufacturing, usage, and maintenance to recycling or disposal, including all transportation and distribution steps [10]. LCA methodology and sustainability assessment in general, still has certain major limitations that need to be overcome. The main limitation is the high degree of uncertainty arising from the life cycle inventory (LCI), which gives rise to results with high variability. Another limitation is the lack of a systematic method for generating and identifying sustainable solutions [11,12]. There is no single method that is universally acceptable [13]. It is very challenging to define aggregated indicators that are not too broad or too specific [14]. In addition, LCA and sustainability studies are usually only connected with environmental components [15,16]. However, sustainable development (SD) requires the integration of its environmental and additionally its economic and social components at all levels, with the goal of achieving a balance between these objectives [17]. To pave a path towards sustainability and SD, multi-objective optimisation (MOO) problems should be solved optimally by preventing subjective steps as much as possible.

MOO has attracted an increasing interest within environmental and sustainability applications [8,18]. Nevertheless, the definition of a suitable environmental (sustainability) metric for supporting objective environmental (sustainability) assessments is still an open issue within the literature. The aim of this contribution is twofold: (i) to present two multi-objective optimisation (MOO) approaches, based on sustainability metrics, which overcome the second limitation of LCA (defining systematic method for identifying sustainable solutions, where economic and environmental and/or social aspects are included simultaneously in the objective function), and (ii) and

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besides the direct (burdening) effects to include also the indirect (unburdening) effects from the life-cycle perspective.

One approach is based on the relative direct sustainability index (*RDSI*) [19] (Section 2.2), which is always positive (negative for environment), replaced by relative total sustainability index (*RTSI*), which can be even negative (positive for environment), where different sustainability indicators are compiled within a single index using certain weights. *RDSI* is only composed of direct impacts on the environment and society, whilst *RTSI* also includes the unburdening relating to the substitution of harmful products by newly-produced benign products, and therefore refers to current situations. A two-step MI(N)LP system synthesis is performed. At the first step, an economically-effective synthesis is carried out in order to obtain a solution which is then considered as a base-case or reference solution for the multi-objective MI(N)LP synthesis, performed at the second step. The most commonly used technique for dealing with MOO problems, is the application of the ε-constraint method [20], and a set of Pareto optimal solutions with positive *RDSI* or even non-trade-off optimal solutions with negative *RTSI* are generated that are environmentally-efficient. However, with this approach, subjective weighting [21] between different environmental and/or social indicators cannot be avoided.

The second approach is an absolute approach and is based on the concept of eco-cost [22], and on a novel concept of eco-profit [23,24] (Section 2.3). Eco-cost is a measurement for expressing the amount of environmental burden by a product on the basis of preventing that burden, where the calculations are based on LCA [22–24]. On the other hand, eco-profit includes besides burden also unburden on the environment, and is defined as a difference between unburdening (eco-benefit) and burdening (eco-cost) the environment. Unburden is related to benefit on the environment, e.g. when waste is used, since their direct harmful impact on the environment is thus avoided, or when currently used harmful products are substituted by newly-introduced benign products. The MOO is performed by the summation of:

(i) The economic profit and eco-cost, and the preferred solutions are those with maximal net profit (the sum of economic profit and eco-cost).

(ii) The economic and eco-profit, the preferred solutions are those with maximal total profit (here the sum of economic and eco-profit).

Both profits and eco-costs are expressed in a monetary value per time unit. Those process solutions are introduced that are the more economically profitable and yet offer the most positive impacts regarding the unburdening of the environment.

Both approaches are illustrated through a case study that is comprised of integrated bioprocesses for the production of biogas from organic and animal wastes, with or without the rendering plant [25–27].

2. MOO approaches

This section reviews two MOO approaches based on sustainability metrics in order to support sustainability assessment. Sustainability assessment requires, in addition to environmental performance, other considerations such as social, technical, and economic factors [28]. Processes, technologies, products, or activities should be economically-viable, environmentally-benign, and socially-just in order to be the more sustainable. As these desired qualities often represent conflicting targets, simultaneous MOO must be performed in order to obtain compromise solutions (trade-offs) that reveal the possibilities for achieving improvements in the system [29]. The use of MOO requires translating environmental and/or social aspects into suitable sustainability metrics that should be optimised in conjunction with traditional economy-based criteria [11]. Different methodologies can be applied when solving MOO problems. Amongst them the ε-constraint method for generating the Pareto set is the more applied technique [20]. This method was applied during this current contribution, by solving a sequence of constrained single-objective problems.

2.1. Direct, indirect and total effects

The direct effects of systems (products, services, or activities) on the environment and society represent the direct burdens of those systems due to the extraction of resources, materials' production, usage, maintenance, recycling, and/or disposal, including all transportation steps. On the other hand, the indirect effects are those sets of impacts that indirectly unburden or benefit the environment when e.g. waste is utilised instead of being deposited, or environmentally-benign raw materials, products or services are used instead of harmful ones. The total effect is the sum of direct and indirect effects.

A systematic approach was applied in order to define direct, indirect, and total effects. For this purpose, different sets were defined for raw materials and products ($p \in R_B \cup R_{UNB} \cup P_B \cup P_{UNB}$).

Sets for raw materials:

- R_B – set of those raw materials that only burden the environment if processed, e.g. fossil fuels, since they were stored under the Earth's crust over millions of years and now moved into the biosphere; crops, since they use chemicals and fuels in relation to their production; water, since if processed it should be cleansed, etc.
- R_{UNB} – set of those raw materials that also unburden or benefit the environment when used; e.g. the utilisation of waste (industrial wastewater, manure, sludge, etc.), since their direct harmful impact on the environment is thus avoided; but note that some burdens are still released, e.g. when transporting to the plant.

Sets for products:

- P_B – set of those products that only burden the environment in relation to processing, disposal and transportation.
- P_{UNB} – set of those products that also unburden or benefit the environment, e.g. if they are substitutes for harmful products; but note that some burdens are still released, mainly due to processing and transportation.

2.2. Direct, indirect and total sustainability indicators

2.2.1. Direct sustainability indicator

The direct sustainability indicators ($I_f^d, f \in F$) represents the burdenings of the environment. It is defined as the sum of different burdens, where each burden is further defined as a product between the raw materials and products (p) mass, molar, volume, energy, etc. flow-rate (q_{m_p}/(t/y, GJ/y...)) and its specific indicator ($I_{f,p}^s$/(kg/t, ha/t,...)):

$$I_f^d = \sum_{p \in R_B \cup R_{UNB} \cup P_B \cup P_{UNB}} q_{m_p} \cdot I_{f,p}^s + \sum_{p \in R_B \cup R_{UNB} \cup P_B \cup P_{UNB}} q_{m_p} \cdot l_p \cdot D_p \cdot I_{f,p}^{s,t} \quad \forall f \in F \tag{1}$$

Note that the summation is performed over all raw materials and products, as all of them contribute to the burdening. The second term represents burdening due to transportation, where the pth flow-rate is multiplied by an inverse of the load factor, l_p, the distance, D_p/(km), and a specific sustainability indicator for