



Environmental impact assessment of chicken meat production via an integrated methodology based on LCA, simulation and genetic algorithms

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ABSTRACT

This study performed a Life Cycle Assessment (LCA) to evaluate the environmental impact of chicken meat production from a Mexican case study, with a “cradle-to-slaughterhouse gate” approach. To overcome the LCA's limitations and provide a more holistic picture of the system, simulation and artificial intelligence techniques were integrated. First, raw material/energy requirements were obtained from the case study and simulated using Process simulation (PS) and Monte Carlo (MC) simulation to estimate the emissions and quantify their uncertainty. Then, IMPACT 2002 + was used to calculate the overall impact using Ecoinvent and LCA Food databases. The results highlight that chicken farms are the main factors responsible for the environmental impacts assessed, where feed production (use of chemicals and energy requirements) and on-farm emissions (organic waste decomposition) are the main contributors. Concerning the slaughterhouse, the energy production (electricity and steam) and the cooling-related activities present a significant impact. Afterwards, three impact allocation procedures (mass method, neural networks, and stepwise regression) were tested, showing similar results. Finally, a multiobjective optimization model based on a Genetic Algorithm was applied looking to minimize the environmental impacts and maximize the economic benefits. The selected alternative achieved a reduction of 15.14% per functional unit at the environmental indicators. The results encourage the use of support techniques for LCA to perform a reliable assessment and an environmental/economic optimization of the system.

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1. Introduction

Chicken meat is one of the most consumed food products in the world (Magdelaine et al., 2008). Not only does the growing world population cause the high demand of this product, but also its nutritional benefits, such as a high content of proteins, vitamin B and minerals, and a low level of saturated fats (Windhorst, 2006). In parallel, the costumers' needs have shown an important evolution

toward high-quality food produced under more environmentally friendly conditions (de Boer, 2003; González-García et al., 2014; Iribarren et al., 2011; Sala et al., 2017).

Broiler meat production follows two main stages: farms and slaughterhouses. Slaughterhouses are also called poultry processing plants (PPP). On farms, chickens raise until they gain the desired weight. Then, they are sent to PPPs to obtain meat. These activities require large amounts of energy and raw materials, which can generate environmental impacts (González-García et al., 2014).

Life Cycle Assessment (LCA) is one of the most accepted and used tools to assess environmental impacts (Nwe et al., 2010; Roy

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et al., 2008). LCA helps to quantify and evaluate the emission of a product from the extraction of raw materials to final disposal, including manufacture and use (Ekvall, 1999; Sonnemann et al., 2004). LCA framework involves the goal and scope definition, the life cycle inventory (LCI) analysis, the life cycle impact assessment (LCIA), and the interpretation phase (ISO, 1997). Different tools can be applied to carry out these steps. As recommended by Ekvall et al. (2007), LCA should be complemented by other techniques to increase its scope and applicability.

Poultry meat production has a lower consumption of resources and energy than other meat productions; therefore, lower emissions per unit of live weight (LW). Chicken meat production generates 4.6 ton CO₂e ton LW⁻¹, which is equivalent to 29% and 72% of emissions generated by beef and pig meat production respectively (Williams et al., 2006). Some emissions are directly related to the meat yield (meat for human consumption·LW⁻¹). Even if the chicken industry has a better environmental performance compared to other industries, it is necessary to develop more sustainable systems, as in any food sector (Notarnicola et al., 2012).

Most studies focus on the farm stage (Baumgartner et al., 2008; Leinonen et al., 2012; Pelletier, 2008). Only a few include the PPP stage (da Silva et al., 2014; González-García et al., 2014; Williams et al., 2006) and the logistics and consumer-related activities (Bengtsson and Seddon, 2013; Weidema et al., 2008).

The goal of this study is to assess the environmental impacts of chicken meat production from cradle to PPP gate by coupling the LCA methodology with simulation and artificial intelligence techniques to overcome its limitations. Process simulation allows quantifying inputs and outputs of the process according to both the real system conditions and parameters not to create a *black box* (complex processes modeled by using literature data). Monte Carlo simulation makes possible to quantify and propagate variability and uncertainty into the LCA results. The classical mass allocation method and alternative impact allocation procedures were compared. The results obtained showed similar results. Finally, a multiobjective optimization model was used to generate alternatives of optimal process parameters that reduce environmental impacts in the system per functional unit (FU). The model considers three criteria based on technical, economic and environmental aspects, and a Genetic Algorithm (GA) is used to generate optimal alternatives. GA solves the problem caused by both the non-linear nature of a system and the multiple criteria assessment. The GA results were evaluated through a multi-criteria decision-making (MCDM) method to find the best solution.

The proposed approach was applied to a Mexican case study. Mexico ranks seventh in poultry production and sixth in consumption worldwide, being chicken the most consumed meat in the country (34 kg·cap⁻¹·year⁻¹). In 2015, Mexico produced 3.20 Mton broiler meat, against 1.88 Mton of beef, and 1.32 Mton of pork (USDA, 2016). Despite this, no study addresses LCA approach to this industry.

Next section presents a review of benefits of coupling MC simulation and GA to LCA methodology. Then, the LCA-based methodology is described through the case study. Finally, specific results of the case study are presented and compared with existing works.

2. Literature review

2.1. LCA and Monte Carlo simulation

Huijbregts (1998) identified three types of uncertainty (parameter uncertainty, model uncertainty, and uncertainty due to choices) and variability (spatial variability, temporal variability, and

variability between objects). Because of their difficult to be represented by models, LCA studies do not take into account uncertainty and variability. However, some authors have tried to include them into models by using ranges in inputs variables (Basset-Mens et al., 2006), probability distributions (Henriksson et al., 2012), or simulation (Leinonen et al., 2012).

According to Geisler et al. (2005), variability and uncertainty can be conveniently propagated into LCA results using MC simulation. Bieda (2014) found that using MC simulation in LCA studies results in more flexible models since probability distributions describe the variables, a better understanding of the behavior of specific outputs (products and emissions), and a better capacity to identify the most representative variables of the model.

2.2. LCA and process simulation

Process simulation (PS) has been widely used in process design to illuminate the *black box*. PS is used to faithfully represent operating conditions in a process to obtain better results for the LCI.

Therefore, process simulation is used either to overcome the difficult to obtain LCI data or to implement changes without affecting the performance of the real system.

Chemical, thermal and biological processes have used it with very satisfactory results (Brunet et al., 2012; Leonzio, 2016; Morales Mendoza et al., 2012; Morales Mendoza et al., 2014; Petchkaewkula et al., 2016). The purpose is to inject PS results into LCA (Jacquemin et al., 2012) to enhance the scope of its results.

2.3. LCA and optimization

The decision variables of a system can be evaluated and then improved/optimized to reduce environmental impacts. However, it is more useful for decision-makers when the optimization process involves other aspects (e.g., economic and technical) at the same time. This kind of problems needs to be solved by multiobjective models. These techniques aid the optimization of economic indicators such as net present value (NPV), costs, profit, and net revenue coupled to environmental indicators (Amudha et al., 2015; González-García et al., 2014; Kostin et al., 2011, 2012; Liu et al., 2014). Technical and social objectives can also be included, but they need to be quantifiable.

Some studies focus on customer satisfaction (Nwe et al., 2010), crop yield (Khoshnevisan et al., 2015), energy payback time (Pérez et al., 2014) and the design of processes (Alexander et al., 2000; Dietz et al., 2006) and entire supply chains (You et al., 2012).

GA can be very useful in this kind of problems due to its flexibility to deal with both linear and non-linear functions, the advantage it has to handle multi-objective situations, and its capability to avoid local minimums/maximums.

Techniques mentioned above look to increase the LCA's scope and overcome its limitations, such as those identified by Ekvall et al. (2007): static models, environmental focus only, and use of linear steady-state models, while most systems are non-linear.

Table 1 summarizes the main features of these techniques when used in addition to LCA and compares them. Table 2 contains a summary of some research where LCA is complemented with MC, PS, GA, and other techniques. None of the studies mentioned in Table 2 has implemented the techniques described in this section at the same time.

2.4. LCA in chicken production

The application of LCA in poultry systems has not been explored completely. Most studies only address the traditional LCA

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