Chongyang Du

ENVIRONMENTAL AND SOCIAL LIFE CYCLE ASSESSMENT OF SUGARCANE IN BRAZIL: COMPARING MANUAL AND MECHANICAL HARVESTING

PhD thesis in Sustainable Energy Systems, supervised by Professor Fausto Miguel Cereja Seixas Freire and Professor Luís Miguel Cândido Dias presented to the Department of Mechanical Engineering, Faculty of Sciences and Technology, University of Coimbra

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Environmental and social life cycle assessment of sugarcane in Brazil: comparing manual and mechanical harvesting

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To my parents,

for love and support.

To my future self,

believe in yourself.

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ABSTRACT

Concerns about environmental and social sustainability of sugarcane production in Brazil have been raised, such as damage on health due to pre-harvest burning and poor working conditions of sugarcane field workers. Meanwhile, the landscape of sugarcane sector in Brazil is rapidly changing due to increasing adoption of mechanical harvesting. Few studies have researched the environmental and social impacts of sugarcane production changing from manual to mechanical harvesting, especially from a life cycle perspective. This thesis compares the life cycle environmental impacts (with a focus on health effects of particulate matter) and social impacts of sugarcane production in Brazil with manual and mechanical harvesting.

An attributional life cycle assessment (LCA) of manual vs. mechanical sugarcane harvesting compared the environmental impacts of one tonne of sugarcane at the distillery. The ReCiPe life cycle impact assessment method was applied to characterize impacts on eight mid-point categories and three end-point categories. Impacts on climate change were assessed considering different soil carbon sequestration scenarios. Characterization factors of health effects of $PM_{2.5}$ for Brazil were calculated differentiating emission sources, population densities and burdens of disease. According to mid-point impact indicators, manual harvesting has higher impacts on photochemical oxidant formation and particulate matter formation mainly due to pre-harvest burning. Mechanical harvesting may lead to higher impacts on fossil depletion, ozone depletion and terrestrial acidification resulting from higher use of fertilizers and diesel. Differences of impacts on climate change between two systems vary depending on the soil carbon sequestration scenario. At the end-point level, manual harvesting has higher impacts on human health but lower impacts on resources use. The health effects of $PM_{2.5}$ vary considerably with population density. Changing from manual to mechanical harvesting close to urban areas leads to a 93% reduction of health effects, while for rural only 15% and for remote areas 5%. When considering average population density, the health effects of $PM_{2.5}$ of manual harvesting are approximately six times higher than mechanical harvesting. Health effects of $PM_{2.5}$ calculated with ReCiPe are much lower and may underestimate the effects of primary $PM_{2.5}$ emissions.

A screening social life cycle assessment (SLCA) was conducted to identify the social hotspots of sugarcane production in Brazil and compare the social impacts of manual and mechanical harvesting. A novel approach integrating Social Hotspots Database (SHDB) and content analysis was developed. First, life cycle social impacts of sugarcane in Brazil were modelled in SHDB. The results derived from SHDB were enhanced by results based on a systematic analysis of relevant literatures. Content analysis was applied to analyze 38 relevant publications including peer-reviewed articles, "grey literature", non-governmental organization reports and conference presentations. Impacts of manual and mechanical harvesting were compared on eight

social themes and visualized by a color scheme. The results suggest that sugarcane sector in Brazil contributes to most of the social impacts among all the country-sectors associated with sugarcane life cycle. Nine social themes are identified as social hotspots. Health & safety and labour rights & decent work are identified as the impact categories with higher negative impacts. Comparing manual and mechanical harvesting, mechanical harvesting performs better on social indicators, except local employment and access to material resources. Besides negative impacts, content analysis is capable of identifying several positive impacts of mechanical harvesting in Brazil, such as improving safe and healthy living conditions, promoting public commitment on sustainability of Brazil´s sugarcane sector, and increasing the average salaries of sugarcane field workers.

To support the evaluation of the overall environmental and social impacts of manual and mechanical harvesting of sugarcane, an additive multi-criteria decision analysis (MCDA) model was developed to improve the robustness of weighting in LCA and SLCA. Brazilian LCA and SLCA experts were surveyed about the weights of relevant environmental and social indicators. The novel MCDA approach explores all the possible convex combinations of the weights provided by the surveyed group. The results of the MCDA model show that mechanical harvesting has lower overall environmental impacts at the end-point level and better social impacts. Decision-making based on the results of environmental impacts at the mid-point level is less robust. Manual harvesting is more likely to have lower negative impacts than mechanical harvesting; but the advantage of mechanical harvesting over manual harvesting can be greater than the reverse.

The results obtained in this study are an incentive to accelerate mechanization of sugarcane harvesting in Brazil considering its health benefits and reduction on overall negative environmental and social impacts. Social hotspots identified can also inform policy-making aiming to improve social sustainability of sugarcane production in Brazil. In addition, this thesis contributes to various aspects of methodological developments of LCA and SLCA.

Keywords: life cycle assessment, social life cycle assessment, health effects, particulate matter, sugarcane, mechanization, multi-criteria decision analysis, sustainability

RESUMO

A produção de cana-de-açúcar no Brasil está associada a diversas questões ambientais e sociais, incluindo impactes na saúde associados à queima pré-colheita e às condições precárias de trabalho nos campos. Actualmente, o sector está a sofrer uma rápida transformação associada à introdução de colheita mecanizada. Poucos estudos abordaram os impactes ambientais e sociais associados a esta transição, de colheita manual para mecanizada, em particular numa perspectiva de ciclo de vida. Esta tese compara os impactes ambientais (com foco nos impactes na saúde associados à emissão de material particulado) e os impactes sociais da produção de cana-de-açúcar no Brasil, com colheita manual e com colheita mecanizada, numa perspectiva de ciclo de vida.

Um estudo de avaliação de ciclo de vida (ACV) atribucional foi desenvolvido para comparar a produção de uma tonelada cana-de-açúcar (até à destilaria) com colheita manual e com colheita mecanizada. Impactes para oito categorias *mid-point* e três *end-point* foram calculados com o método ReCiPe. Relativamente às alterações climáticas, os impactes foram avaliados considerando diferentes cenários de sequestro de carbono pelo solo. Para avaliar os efeitos na saúde associados à exposição material particulado ($PM_{2.5}$), calcularam-se factores de caracterização considerando diferentes fontes de emissão, densidades populacionais e causas de doenças, no Brasil. Relativamente aos indicadores *mid-point*, a colheita manual está associada a maiores impactes na formação de oxidação fotoquímica e de partículas, devido à queima pré-colheita. A colheita mecanizada está associada a maiores impactes nas categorias de depleção fóssil, depleção da camada do ozono e acidificação terrestre, resultantes do uso de fertilizantes e gasóleo. As diferenças nos resultados para alterações climáticas entre os dois sistemas de colheita depende do cenário de sequestro de carbono pelo solo. Relativamente aos resultados *end-point*, a colheita manual está associada a maiores impactes na saúde humana, mas menores impactes a nível do uso de recursos. Os efeitos na saúde associados a $PM_{2.5}$ variam significativamente com a densidade populacional. A transição para uma colheita mecanizada pode reduzir os impactes na saúde em 93% em zonas próximas de áreas urbanas, enquanto em zonas rurais e remotas esta redução é de 15% e 5%, respectivamente. Considerando uma densidade populacional média, os efeitos na saúde associados à emissão de $PM_{2.5}$ na colheita manual são cerca de seis vezes maiores do que na colheita mecanizada. Os efeitos na saúde associados a $PM_{2.5}$ calculados com o método ReCiPe são muito inferiores aos resultados obtidos, e podem subestimar os efeitos associados a emissões primárias.

Em relação aos impactes sociais, foi desenvolvida uma avaliação social de ciclo de vida (ASCV) para identificar os aspectos críticos na produção de cana-de-açúcar no Brasil, que compara os impactes com colheita manual e com colheita mecanizada. Foi desenvolvida uma nova abordagem que integra a *Social Hotspots Database* (SHBD) e análise de conteúdo. Primeiro, modelaram-se os impactes sociais da produção de cana-de-açúcar no Brasil em SHDB. Os resultados foram depois

refinados com base numa análise sistemática da literatura relevante: fez-se uma análise de conteúdo para 38 publicações relevantes, incluindo artigos com revisão por pares, literatura publicada informalmente ("grey literature"), relatórios de organizações não-governamentais e apresentações em conferências. Impactes associados à colheita manual e à colheita mecanizada foram comparados em oito temas sociais e visualizados através de um esquema de cores. Os resultados sugerem que o sector de produção de cana-de-açúcar é o que contribui mais para os impactes sociais no país. Nove aspectos sociais são identificados como críticos. Entre estes, "saúde e segurança" e "direitos e trabalho digno" estão associados aos impactes negativos mais significativos. Comparando a colheita manual e a mecanizada, a segunda tem melhores resultados do ponto de vista social, excepto nas categorias de "emprego local" e "acesso a recursos materiais". Além dos impactes negativos, a análise de conteúdo permite identificar vários impactes positivos da colheita mecanizada no Brasil, como é o caso da contribuição de acabar com a prática da queima pré-colheita que contribui para a melhoria das condições de segurança e saúde, para a promoção do compromisso e empenho da comunidade na sustentabilidade do sector da cana-de açúcar no Brasil e para o aumento da média salarial dos trabalhadores dos campos de cana-de-açúcar.

Para apoiar a avaliação dos impactes ambientais e sociais da produção de cana-de-açúcar com colheita manual e com colheita mecanizada, desenvolveu-se um modelo aditivo de análise de decisão multicritério (ADM) que permite analisar a robustez de conclusões obtidas a partir da ponderação de impactes em ACV e em ASCV. Fez-se um questionário a peritos em ACV e ASCV no Brasil no sentido de recolher opiniões sobre o peso de diversos indicadores ambientais e sociais relevantes. O modelo de ADM explora todas as combinações convexas possíveis dos pesos sugeridos pelo grupo de peritos. De acordo com os resultados do modelo de ADM, a colheita mecanizada está associada a impactes mais baixos na avaliação ambiental *end-point*, bem como melhores impactes na avaliação social. Os resultados para impactes ambientais a nível *mid-point* são menos robustos para o apoio à decisão: a colheita manual estará com maior probabilidade associada a menores impactes do que a mecanizada; no entanto, a mecanizada pode superiorizar-se à manual por uma diferença maior do que o contrário.

Os resultados obtidos nesta tese são, antes de mais, um incentivo para acelerar a transição para a colheita mecanizada de cana-de-açúcar no Brasil, tendo em conta os benefícios evidentes na saúde e a redução geral de impactes ambientais e sociais. A identificação e avaliação de aspectos sociais críticos pode também informar e apoiar a tomada de decisão e o desenvolvimento de políticas com vista à melhoria da sustentabilidade social da produção de cana-de-açúcar. Esta tese contribui ainda em vários aspetos de desenvolvimento metodológico da ACV e da ASCV.

Palavras-chave: avaliação de ciclo de vida, avaliação social de ciclo de vida, efeitos na saúde, partículas, cana-de-açúcar, mecanização, análise de decisão multicritério, sustentabilidade

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CHAPTER 1 INTRODUCTION

1.1 Background and motivation

The history of Brazilian sugarcane is a bitter-sweet one. Sugarcane, originated from Southeast Asia, was brought to Brazil by the Portuguese in the early 16th century when the country was a colony of Portugal (Nastari 1983). Sugarcane cultivation requires a tropical or temperate climate with plentiful supply of water, which makes Brazil one of the most suitable places for this plantation. Cultivation, harvest and processing sugar manually was highly labour-intensive. Because of the rising popularity of sugar in Europe and huge profit from sugar trade, between the 16th and 18th century, millions of slaves from Africa were brought to Brazil. Slave labour was heavily relied on to power the growth of Brazilian sugar economy (Rogers 2015). From 1600 to 1650, sugar accounted for 95% of Brazil´s exports, and Brazil became the world´s largest sugarcane producer. The steadily declining price of sugar resulted in the shrinking share of sugar in the total exports from Brazil. In the decade of 1970, Brazil became the world´s largest sugarcane producer again, with the government-led creation of ProAlcool Program (National program of alcohol), which promoted ethanol as vehicle fuel in response to the first oil crisis (Nastari 1983). As the main sugarcane products, Brazilian sugar is exported to more than 100 countries, and the adoption of sugarcane ethanol as fuel in Brazil has been considered one of the most successful examples of biofuels, which has replaced more than 40% of the domestic gasoline consumption (UNICA 2017).

In the past decade, the sugarcane sector in Brazil has expanded rapidly. With an annual growth rate of 4.3% by weight since 2006, Brazil produced 651.8 million tonnes of sugarcane in the harvest year 2016/2017, accounting for 36% of the world production. The planted area of sugarcane in Brazil increased at an even higher annual growth rate of 6.5% (UNICA 2017). Sugarcane is produced both in the centre-south and north-northeast of Brazil, with the centre-south accountable for most of the production activities. São Paulo is the leading state in Brazil concerning sugarcane production, resulting in 56% of the total production in the 2013/2014 harvest year (UNICA 2017).

The operations of Brazilian sugarcane production have evolved drastically with the most noticeable change of increasing use of mechanical harvesting. Sugarcane has been conventionally harvested manually, and burning the leaves and tops before harvesting has been a common practice to improve the harvest productivity, facilitate transportation and protect field workers from venomous animals. Sugarcane pre-harvest burning has been associated with increasing public health risks mainly due to particulate matter emissions (Arbex et al. 2000; Cançado et al. 2006). With incentives from government and the Brazilian Sugarcane Industry Association (UNICA), the fraction of sugarcane harvesting area with pre-harvest burning in the State of São Paulo dropped from 77% to 15% from 2005 to 2014. Meanwhile, the percentage of mechanical sugarcane harvesting without pre-harvest burning quadrupled in the same period (CTC 2014). The perspective is that sugarcane sector in Brazil will expand mechanization to more regions with sugarcane plantations.

The sugarcane sector has historically shaped Brazilian economy and had enormous impacts on the environment and society. With the increase of global trade, more than ever, environmental and social impacts of Brazilian sugarcane are embedded in all the sugarcane products consumed domestically and overseas. To measure the environmental and social impacts of Brazilian sugarcane, it is necessary to take a supply chain perspective and consider both global and local impacts. Moreover, with the rapid adoption of mechanical harvesting, it is important to assess how automation and associated changing operations affect the impacts from sugarcane production in Brazil.

One of the most important regional impacts of sugarcane production in Brazil is the damage of human health due to particulate matter emissions from pre-harvest burning. Several epidemiology studies have pointed out the correlation between particulate matter emissions due to pre-harvest burning and the rising occurrence of respiratory diseases in the communities near sugarcane fields (Arbex et al. 2000; Arbex et al. 2007; Cançado et al. 2006; Mazzoli-Rocha et al. 2008; Uriarte et al. 2009; Goto et al. 2011). Arbex et al. (2007) evaluated the relation between total suspended particles generated from pre-harvest burning and asthma hospital admissions in Araraquara, São Paulo. The authors concluded that pre-harvest burning was closely related with asthma hospital admissions. Uriarte et al. (2009) and Cançado et al. (2006) studied the impacts of particulate matter emissions due to sugarcane burning on the respiratory health of children and the elderly. Both studies sustained that sugarcane pre-harvest burning was the main cause of hospital respiratory admissions for both age groups.

Life cycle assessment (LCA) is a widely applied method to assess environmental impacts associated with the life cycle of a product (or service) from cradle to grave (Guinée et al. 2011). LCA has been increasingly used to support environmental policy-making and business decision-making. The application of a life cycle perspective to assess impacts avoids shifting of burdens among life cycle phases, impact categories, regions or generations (Guinée et al. 2011). Life cycle studies have been conducted to assess the environmental impacts of sugarcane ethanol in Brazil (Macedo et al. 2008; Luo et al. 2009; Ometto et al. 2009; Seabra et al. 2011; Cavalett et al. 2013; Galdos et al. 2013; Tsiropoulos et al. 2014; Chagas et al. 2016). Most studies have assessed environmental impacts of sugarcane ethanol, focusing on energy use and greenhouse gas emissions (GHG). However, health effects were not addressed in the aforementioned life cycle studies, with the exception of Galdos et al. (2013) and Tsiropoulos et al. (2014), who calculated human health impacts at the end-point level applying global characterization factors using established life cycle impact assessment methods, Ecoindicator 99 and Impact 2002+, respectively. According to previous studies, the agricultural phase (sugarcane production) contributed the most to the life cycle environmental impacts of bioethanol. Harvesting is among the largest contributors on GHG emissions, but has been treated as a combination of manual and mechanical operations, assuming a certain ratio or scenarios of different ratios of mechanical harvesting. *A life cycle study assessing the broad environmental impacts in the conversion from manual to mechanical harvesting of sugarcane production, with a focus on health impacts of particulate matter emissions is lacking.*

In regard to social impacts of sugarcane in Brazil, sugarcane producers have been increasingly paying attention to measure and report their social impacts through widely used sustainability reporting and certificate schemes, such as Global Reporting Initiative (GRI) and sustainable sugarcane certificate e.g. BONSUCRO

(UNICA 2010; BONSUCRO 2017; Global Reporting Initiative 2017). These sustainability reporting and certificate schemes mainly include social indicators focused on workers, leaving out other stakeholders. Similarly, publications documenting the social impacts of sugarcane production in Brazil generally concentrate on worker-related topics, covering working conditions, working hours and occupational health and safety (Du et al. 2015; Junior et al. 2012; Luz et al. 2012; Rocha et al. 2010; Souza et al. 2016). Most existing studies are restricted to specific activities in sugarcane production such as planting and/or harvesting, but Souza et al. (2016) investigated the social impacts related to the life cycles of first and second generation sugarcane ethanol in Brazil; economic input-output models were used, but only inventory indicators within the Brazilian economy were accounted for. Souza et al. (2016) concluded that agricultural operations dominate the impacts of sugarcane ethanol, regardless of the ethanol production technology adopted, because it is by far the most labour-intensive activity in the supply chain. *A study focusing on social impacts of sugarcane production in Brazil considering all relevant stakeholders and covering the full life cycle is lacking.*

Derived from life cycle assessment, social life cycle assessment (SLCA) is an emerging method to evaluate social impacts related to supply chains (Du et al. 2014). Compared to other tools assessing social impacts, such as Social Accountability 8000, AccountAbility´s AA1000 series, Social Impact Assessment and Global Reporting Initiatives (GRI) (Vanclay et al. 2015; AccountAbility 2017; Global Reporting Initiative 2017; Social Accountability Intl 2017), SLCA focuses on a product (or service) level, and considers the entire life cycle and a broader range of stakeholders, including workers, local community, society, consumers and value chain actors (UNEP/SETAC 2009). Depending on the goal and scope of the study, a SLCA study can be based on generic and/or site-specific data. Generic data are not site or enterprise specific, and may be collected through literature review, web search or national statistics. Site-specific data can be gathered through document auditing (i.e. enterprise, authorities and NGOs documentation), interviews, questionnaires and participatory evaluation. Generic assessment is appropriate when the aim is to analyze a generic product or to screen social hotspots (i.e. unit processes located in a specified region involving a social theme of interest that may be considered a problem, a risk or an opportunity). If practitioners need to evaluate the social impacts related to a specific product, site-specific data should be collected for the unit processes considered as social hotspots, but generic data can be used to guide data collection. A further difference between SLCA and LCA is the treatment of positive impacts. As pointed out in the UNEP/SETAC Guidelines for SLCA (2009), a hotspots assessment focuses on potential negative impacts, and often does not cover many of the positive impacts. By contrast, SLCA aspires to include both positive and negative impacts associated with supply chains.

An LCA or SLCA study entails four phases, namely the goal and scope definition, inventory analysis, impact assessment and interpretation of results. Results of life cycle studies can be presented after characterization, in which environmental or social impacts on various indicators are expressed in various units (ISO14040 2006). Normalization, weighting and aggregation are optional steps in life cycle impact assessment (LCIA), where characterized results are converted to comparable measures and then aggregated into a single score based on the weight allocated to each indicator (Guinée et al. 2002). Weighting is considered controversial in the LCA community, because it is subjective and implies a value judgement about LCA or SLCA results and this step may influence the results and conclusions of a life cycle study. As specified in the leading standards for LCA, ISO 14040 and ISO14044, weighting is an optional step in LCIA; whereas it should not be used with comparative assertions intended to be disclosed to the public (ISO14040 2006; ISO14044 2006). However, weighting is commonly used in studies due to its practicality for comparing impacts of different products or scenarios, supporting decision-making and results communication (Pizzol et al. 2017).

Giving equal weights to all the indicators is a common workaround in life cycle studies (Pizzol et al. 2017). However, this arbitrary choice implies that all the indicators are considered equally important, which ignores the preferences and knowledge of decision makers or experts. With the capacity of handling conflicting decision situations, multi-criteria decision analysis (MCDA) has been considered a promising tool to aid weighting in LCIA and/or interpretation of LCA or SLCA results. Multi-criteria decision analysis (or multi-criteria decision-making) is an umbrella term for a set of methods enabling comparison of multiple alternatives based on pre-established criteria. MCDA methods using outranking approaches (Rogers and Seager 2009; Prado-Lopez et al. 2014; Domingues et al. 2015) and additive aggregation approaches (Miettinen and Hamalainen 1997; Myllyviita et al. 2012; Dias et al. 2016) have been applied to life cycle studies to rank, select or categorize products based on their environmental and/or social impacts. Relevant stakeholders or experts are often surveyed to collect the preferences and trade-offs for all the indicators. Equal importance of all the members in a group decision-making setting is commonly taken as an implicit assumption. Other studies are found applying stochastic weights to generate robust conclusions based on LCA results, without considering the preferences of decision makers (Dias et al. 2016). *As pointed out from the results of a recent survey conducted among LCA practitioners (Pizzol et al. 2017), further development is needed to improve uncertainty and robustness of weighting in life cycle studies.*

1.2 Research questions and objectives

This thesis aims to answer the overarching question: *how sustainable is sugarcane production in Brazil, in the context of increasing adoption of mechanical harvesting?* In this respect, life cycle environmental and social impacts of sugarcane production with a focus on comparing manual and mechanical harvesting will be assessed. Life cycle assessment and social life cycle assessment are valuable tools when assessing the environmental and social impacts of a product supply chain. However, both methods have limitations and room for improvements. This study has identified and applied the most relevant life cycle approaches to assess the environmental and social sustainability of sugarcane production, and contributed to methodological developments of LCA and SLCA, anchoring on the comparative analysis of manual and mechanical harvesting.

Deriving from the overarching question and the gaps in the state of the art identified in the previous section, three sub-questions and the related objectives were formulated and defined:

Sub-question No.1*: What are the global and local environmental impacts of sugarcane production in Brazil, in the context of increasing use of mechanization?*

To answer this question, a comparative LCA study was developed to assess the environmental impacts of sugarcane production in Brazil with manual and mechanical harvesting. Alongside evaluating the life cycle environmental impacts on relevant indicators, health effects of particulate matter under both harvesting operations were compared, since this is one of the most important local impacts of sugarcane production. In order to do so, suitable approaches of evaluating health effects of particulate matter in the framework of LCA were identified and applied.

Sub-question No.2*: What are the social hotspots associated with sugarcane production in Brazil, considering increasing use of mechanization?*

An SLCA study was developed to screen the social hotspots of sugarcane production in Brazil, and social impacts of manual and mechanical harvesting were compared. SLCA is at the early stage of its development but evolving rapidly, and this study provided a comprehensive snapshot of the development of this new field and contributed to identify potential data sources and methodologies that can improve the results of an SLCA.

Sub-question No.3*: Facing the trade-offs between various environmental and social indicators, which harvesting operation is more preferable regarding its environmental and social sustainability?*

A multi-criteria decision analysis model was developed to improve uncertainty and robustness of weighting in life cycle studies, in order to support group decision-making based on LCA and SLCA results. The more preferable option between manual and mechanical harvesting in regard to environmental and social sustainability was identified.

1.3 Outline

This thesis consists of six chapters including this one.

Chapter 2 provides literature reviews on three methodological issues that underlie this research, including characterizing health effects of particulate matter in life cycle assessment, social life cycle assessment and application of multi-criteria decision analysis methods in life cycle studies.

In Chapter 3, a comparative LCA study of sugarcane production in Brazil with manual and mechanical harvesting is presented. Environmental impacts of both systems were compared at the mid-point and end-point levels. Health effects of particulate matter 2.5 ($PM_{2.5}$) of both systems were addressed as well, applying spatially differentiated characterization factors of $PM_{2.5}$ for Brazil.

Social impacts of sugarcane production with manual and mechanical harvesting are presented in Chapter 4. A screening SLCA was applied to identify the social hotspots of sugarcane production in Brazil. Social impacts were modelled in Social Hotspots Database and analyzed through content analysis of relevant literature. A comparison between social impacts of manual and mechanical harvesting is included.

Based on the findings of Chapter 3 and Chapter 4, Chapter 5 explores how to integrate value choices in LCA and SLCA to support decision-making in a robust manner. A novel multi-criteria decision analysis approach using stochastic weights was developed and applied to simulate combinations of various preferences in group decision-making. The preference levels of manual and mechanical harvesting were presented in regard to environmental (at the mid-point and end-point levels) and social impacts.

Chapter 6 draws the conclusions together by summarizing the key findings of this study. Limitations are discussed as well, followed by research contributions and recommendations provided for relevant stakeholders and insights for future research.

CHAPTER 2 STATE OF THE ART

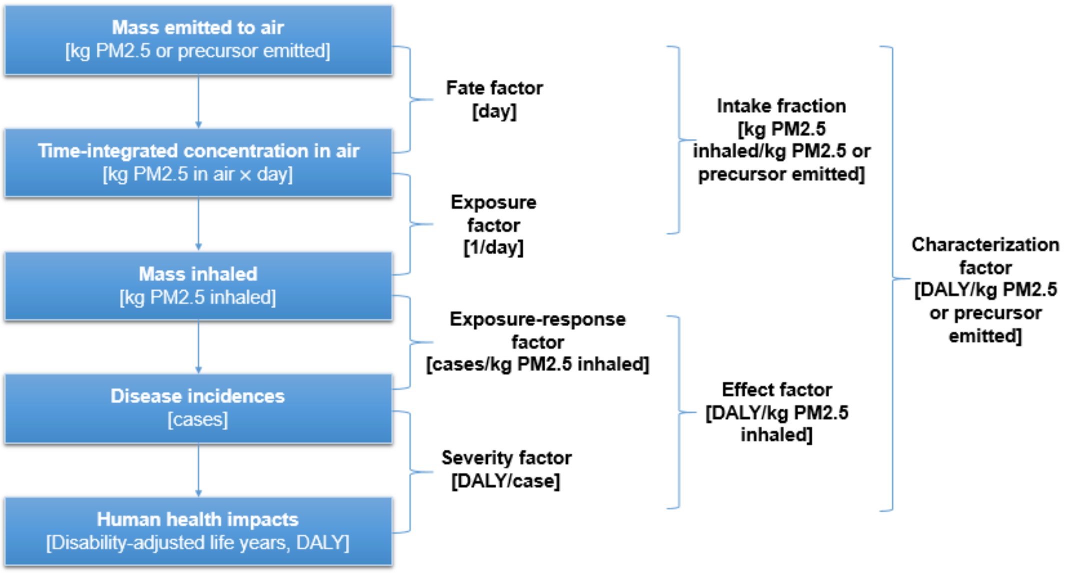
This chapter reviews the state-of-the-art of the three methodical issues this thesis will contribute to. Section 2.1 summarizes current knowledge and best practices on assessing health effects of particulate matter in life cycle assessment. A comprehensive overview of social life cycle assessment is included in Section 2.2. Section 2.3 reviews studies integrating multi-criteria decision analysis (MCDA) in life cycle studies, with a focus on agricultural sustainability.

2.1 Health effects of particulate matter in life cycle assessment

The methodological framework of life cycle assessment (LCA), according to two international standards ISO 14040 and ISO 14044 (2006), includes four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. After data on energy and material inputs and environmental releases are collected in LCI, the potential impacts are modelled and calculated for selected relevant categories in LCIA at the mid-point level (e.g. climate change, acidification, eutrophication, fossil depletion etc.), which can be further aggregated at the end-point level (e.g. human health, ecosystem services, resources depletion). Particulate matter (PM) is an important ambient pollutant contributing to health-related impacts. According to Lelieveld et al. (2015), outdoor air pollution, mostly by particulate matter (PM), was estimated to cause 3.3 million premature deaths per year worldwide, which number is projected to double by 2050 based on a business-as-usual emission scenario. PM has been widely recognized for its correlation with increased mortality and morbidity. A number of epidemiological studies showed that PM is related to heart disease, lung cancer, reduced life expectancy, asthma, and low birth weight (Arbex et al. 2007; Bell et al. 2008; Laden et al. 2000; Pope et al. 2002; Pope et al. 2009).

As pointed out in Notter (2015), characteristics of PM possess great complexity in regard to particle mass, particle size, chemical composition (organic and inorganic) and solubility. PM can be distinguished by formation sources (primary or secondary) and/or aerodynamic diameter. Primary PM refers to particles emitted directly; while secondary PM is formed through reactions to precursor substances including nitrogen oxides (NO_x), sulfur oxides (SO_x) and ammonia (NH_3). According to aerodynamic diameter, PM is categorized as respirable particles (PM_{10}, i.e. PM with aerodynamic diameter less than or equal to 10 μm), coarse particles ($PM_{10-2.5}$, i.e. a subset of PM_{10} with aerodynamic diameter ranging from 2.5 to 10 μm), fine particles ($PM_{2.5}$, i.e. a subset of PM_{10} with aerodynamic diameter less than or equal to 2.5 μm), and ultrafine particles (UFP, i.e. PM with aerodynamic diameter less than or equal to 100nm). Particles with different sizes behave very differently in the atmosphere, and the general rule is that with the increase of particle sizes, the amount of time the particle remains in the air decreases. $PM_{2.5}$ can remain airborne for long periods and travel hundreds of miles; while $PM_{10-2.5}$ tends to deposit on the ground in a much shorter time span after being emitted.

Fig. 2.1 shows a generic environmental mechanism of characterizing health effects of PM exposure in LCA. The general approach of linking the amount of PM emissions to health effect is as such: the amount of PM emission at an emission source (unit: kg $PM_{2.5}$ or precursor emitted) is firstly converted to PM ambient concentration via fate factor. Fate factors are determined by a number of conditions such as particle removal process (e.g. dry deposition, wet deposition and coagulation condensation), particle residence time, and height of emission source (e.g. high stack, low stack, ground level). Exposure factor is then calculated to estimate the amount of PM inhaled and retained in the lung considering population density. Exposure to particles is linked to its health effects (e.g. mortality and morbidity) by exposure-response factor. Exposure-response is cause and age specific and shapes of exposure-response curves for different causes vary. At last, various health effects can be converted to disability adjusted life years (DALY) by severity factor (Humbert et al. 2015).



* Adapted from Humbert et al. (2015)

Fig. 2.1 Cause-effect pathway of modelling health effects of particulate matter in LCA

This environmental mechanism can as well be expressed by Equation 2.1 (Fantke et al. 2015),

$$IS = m \times CF = m \times iF \times ERF \times SF \tag{2.1}$$

IS: impact score, usually expressed by DALY

m: the mass emitted of particulate matter

CF: characterization factor, expressed by DALY per mass emitted

iF: intake fraction

ERF: exposure-response factor

SF: severity factor

Intake fraction presents the fraction of the emission inhaled by the exposure population. For secondary PM, intake fraction is calculated by dividing the mass of secondary PM inhaled by the mass of precursors emitted. Exposure-response factor links the health effects to the affected population with the ambient PM concentration. Exposure-response factor is commonly derived from epidemiological studies and expressed by disease rate or risks per unit mass concentration. Severity factor is usually expressed by DALY per disease case or unit of risk. The product of intake fraction, exposure-response factor and severity factor represents the characterization factor (unit: DALY per mass emitted).

Health effects of PM are evaluated in most life cycle studies under the mid-point impact category of particulate matter/respiratory inorganics, respiratory effects or human toxicity, and attributable to the damage category of human health (Humbert et al. 2015). Differentiating characteristics of PM and emission sources is crucial in conducting a sound assessment of health effects of particulate matter in LCA. However, the widely applied impact assessment methods such as CML, ReCiPe and IMPACT 2002, do not differentiate the health effects of PM based on its size or the geographical characteristics of the source of emissions (ILCD 2011).

Global efforts have been carried out to provide recommendations and guidance on evaluating the health effects of PM in life cycle studies, such as the flagship project launched by the UNEP/SETAC Life Cycle Initiative (Fantke et al. 2015) and the study performed for the Joint Research Center of the European Commission (JRC) (Hauschild et al. 2013). Both projects have contributed to identifying the best practices for characterization modeling in LCA. Work of Humbert et al. (2011) on deriving PM intake fraction has been recognized as one of the best existing characterization models to date. The authors developed a set of intake fractions considering emission release height (high stack, low stack, ground level) and archetypal environment (indoor, outdoor: urban, rural, remote). Size and source type of PM emissions are also classified, including primary $PM_{10-2.5}$, primary $PM_{2.5}$, and secondary $PM_{2.5}$ with the precursors of SO_2, NO_x and NH_3.

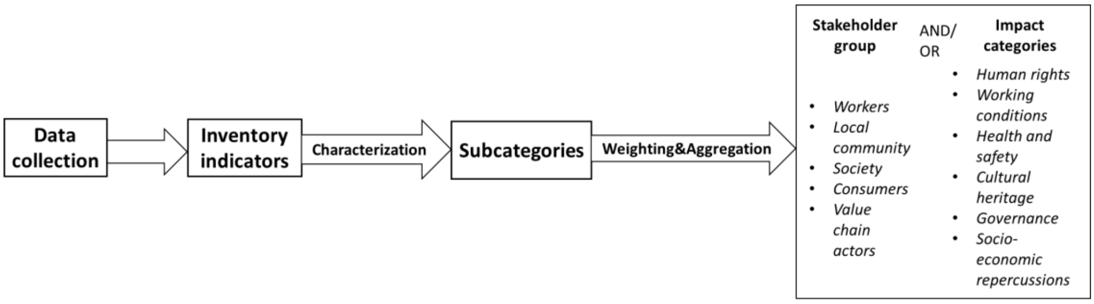
Compared to the development of iF, less consensus has been reached on the development of exposure-response assessment (Fantke et al. 2015). In most methods (Pope et al. 2002; WHO 2006; Van Zelm et al. 2008), a linear, no-threshold exposure-response curve is often assumed; however, when the concentration of PM is not within the range (~10-35 $\mu g/m_3$ for $PM_{2.5}$) of ambient PM concentration observed in the epidemiological studies often conducted in the European or American conditions, the linearity assumption may not hold (Burnett et al. 2014; Humbert et al. 2015; Lim et al. 2012). With respect to the health effects associated with PM exposure, the field is under development and more consensuses need to be achieved among the scientific community. Van Zelm et al. (2008) considered chronic and acute mortality, and acute respiratory and cardiovascular morbidity due to exposure to PM_{10}. Gronlund et al. (2015) accounts for cardiopulmonary and lung cancer mortality attributable to chronic exposure to $PM_{2.5}$. Humbert et al. (2010) also proposed a set of health effects should be considered and corresponding effect factors for PM_{10} and $PM_{2.5}$. Fantke et al. (2015) pointed out the potential of the Global Burden of Diseases (GBD) 2010 study as a starting point for calculating health effects of $PM_{2.5}$ exposure. $PM_{2.5}$ as one of the 67 risk factors in the GBD study is related to five adverse health effects, including ischemic heart disease (IHD), cerebrovascular disease (stroke), chronic obstructive pulmonary disease among adults (COPD), trachea, bronchus and lung cancer (LC), and lower respiratory infections among young (ALRI) (Lim et al. 2012).

2.2 Social life cycle assessment

Considering that social life cycle assessment (SLCA) is a relatively new research field, with a rapidly growing body of diverse topics and case studies published, this section provides an in-depth review of this emerging field. A social and socio-economic life cycle assessment is "a social impact `real and potential impacts´ assessment technique that aims to assess the social and socio-economic aspects of products and their positive and negative impacts along their life cycle encompassing extraction and processing of raw materials, manufacturing, distribution, use, re-use, maintenance, recycling and final disposal" (UNEP/SETAC 2009). The advantages of adopting a life cycle perspective include informing retailers and end-consumers about the positive and negative social impacts of the particular products they sell or buy, and preventing the shifting of negative social impacts from one life cycle stage to another, or from one social issue to another (Benoît and Vickery-Niederman 2010).

SLCA has a young history which evolved considerably in the last decade due to several milestone documents published by the UNEP/SETAC, providing a framework and guidance on conducting SLCA. In 2009, this group published the key document *Guidelines for Social Life Cycle Assessment of Products*, referred as the Guidelines below, serving as a framework for the method of SLCA (UNEP/SETAC 2009). To complement the Guidelines and support the development of SLCA case studies, UNEP/SETAC published *The Methodological Sheets for Subcategories in Social Life Cycle Assessment* in 2013 to clarify the concepts of subcategories, recommend data sources, and relate SLCA to existing relevant policies (UNEP/SETAC 2013). The framework proposed in the Guidelines is in line with the ISO 14040 and

14044 standards for life cycle assessment (LCA) with adaptations for social impacts. Therefore, SLCA follows the four iterative phases in LCA. A general framework of SLCA is shown in Fig. 2.2. The Guidelines stated that SLCA complements LCA with social and socio-economic aspects, and can be applied as a standalone tool or in combination with LCA.



* Adapted from the UNEP/SETAC guidelines (2009)

Fig. 2.2 General framework of social life cycle assessment based on the UNEP/SETAC approach

SLCA phases and related key issues in each phase will be discussed below. Recommendations on future research in SLCA will also be presented.

2.2.1 Goal and scope definition

The ultimate objective of conducting a SLCA is *to promote improvement of social conditions throughout the life cycle of a product.* For each study, a specific goal and scope should be stated. Key aspects considered in this phase are introduced here.

Functional Unit

The Guidelines suggested that defining a functional unit is fundamental but faces difficulties in presenting results due to the inclusion of qualitative and semi-qualitative data in SLCA. Social impacts related to a product are closely related to the conduct of the companies involved in the product chain (Dreyer et al. 2006). Hence, social impacts related to a supply chain are more dependent on the management of the related organizations rather than the function(s) of the product. Including a functional unit approach and a company perspective in the same SLCA framework may be contradictory (Zamagni et al. 2011). Zanchi et al. (2016) also emphasized the importance of taking an organizational view, and suggested that the frameworks and approaches of SLCA should be redefined to integrate social evaluation of organizational behaviors and product-oriented approaches. In most SLCA studies, functional units are not clearly defined. Besides the reasons mentioned above, difficulties of scaling inventory data on functional units may be another reason. Inventory data need to be quantitative in order to be scalable, and the underlying assumption is the arguable linear relations between indicators and functional units. For instance, if producing 1 million US dollars of a product is associated with 100 occupational injuries, the functional unit of 2 million US dollars' worth of this product is related to 200 occupational injuries (Wu et al. 2014).

System Boundaries

As pointed out by Lagarde and Macombe (2013), principles set to guide the design of product system and system boundaries are yet unclear. In the Guidelines, establishing system boundaries upon the settings of LCA is suggested. This point is supported by other researchers concerning the integration of SLCA results with LCA and/or life cycle costing (LCC) results to give a global sustainable view of a product (Kloepffer 2008). According to Dreyer et al. (2006), only the parts of an life cycle that the company performing the assessment can influence directly should be included.

Area of Protection

Inventory data are translated to the magnitude and significance of the potential social or environmental impacts of a product system in the phase of social life cycle impact assessment (SLCIA) or life cycle impact assessment (LCIA). The concept of area of protection describes on what entities the product system will have impact on; in other words, what are the entities we want to protect. In LCA, three areas of protection are mostly accepted including human health, natural resources, and natural environment (Dewulf et al. 2015). In SLCA, opinions on area of protection are generally concentrated on human well-being. The Guidelines suggested that according to the choice of the type of impact categories, the endpoint category could be human well-being or fairness of relationships. Another way of categorizing end-points includes human capital, cultural heritage and human well-being. Several authors also discussed other options on areas of protection. For instance, Dreyer et al. (2006) and Weidema (2006) proposed human dignity and well-being and human life and well-being respectively for SLCA as complementary to the existing area of protection of human health in LCA.

Subcategories

Subcategories are socially significant themes or attributes which compose the foundation of an SLCA assessment. Dreyer et al. (2006) suggested developing SLCA subcategories based on international agreements combined with local or country norms. Reitinger (2011) considered the classification of impact categories from the perspectives of philosophy and ended up with developing fairness and seven dimensions of human flourishing. However, after the publication of the Guidelines, the majority of case studies have selected and assessed the subcategories proposed by the UNEP/SETAC approach. The Guidelines classified subcategories according to the stakeholder groups (i.e. workers, local community, society, consumers and value chain actors) and the impact categories (i.e. human rights, working conditions, health and safety, cultural heritage, governance and socio-economic repercussions). Together considering international agreements such as conventions and treaties and best practices at the international level, 31 subcategories were included in the final list in the Guidelines (see Fig. 2.3). Subcategories related to the stakeholder group of workers are the ones mostly evaluated in the existing case studies (Wu et al. 2014). Based on the needs of a case study, the list of subcategories under evaluation can be adjusted. Two subcategories mostly added in the studies that are not covered in the Guidelines are education and training and social responsibility management systems (Benoît-Norris 2012).

Positive impacts

In LCA, the majority of impacts assessed are negative, except in few exceptions such as the avoided carbon emissions from carbon uptake through biomass cultivation. Meanwhile, the baseline of the product system under investigation is based on the implicit assumption that when production does not occur, no environmental impacts are generated. However, in SLCA, positive impacts are critical because the capability of improving social well-being is one of the strengths that make SLCA an appealing assessment tool to facilitate decision-making of relevant stakeholders. Cesare et al. (2016) analyzed the existing literature and reported on the status of inclusion of positive impacts in current SLCA studies. They concluded that around 25% of the case studies being analyzed considered positive impacts. Moreover, among the case studies published more recently (between 2016 and 2017), nearly 30% of the case studies included both positive and negative impacts.

Although the importance of the inclusion of positive impacts in SLCA is well acknowledged, consensus on using what method to identify and assess positive impacts is still lacking.

* Adapted from the UNEP/SETAC guidelines (2009)

Fig. 2.3 Subcategories recommended in the Guidelines by stakeholder groups

There is no unified definition of positive impacts in SLCA so far. In the Guidelines, positive impacts are considered as performances beyond compliance such as with laws, international agreements, and certification standards. Some researchers have perceived positive impacts as the absence of negative issues. For instance in Ciroth and Franze (2011), negative and positive impacts are assessed on a one-to-six scale (1: positive effect; 6: very negative effect). One example of positive impacts considered in this study is the absence of forced labour. However, other researchers disagreed upon this perception. Ekener et al. (2016) suggested reference points for assessing positive impacts depend on the goal and scope of the study. For a case-specific assessment, the regional general behavior should be considered as the reference, and all the subcategories should apply regionalized reference points for characterization; while for a generic assessment, relating the reference points to a generic framework such as ILO standards are more practical. Ekener et al. (2016) also proposed 13 subcategories presenting positive impacts and related indicators, out of which five subcategories are among the subcategories recommended in the Guidelines, including social benefits and social security, local employment, public commitment to sustainability issues, contribution to economic development and technological development.

2.2.2 Social life cycle inventory analysis

Social life cycle inventory (SLCI) analysis is the most time and resource consuming phase of a SLCA study where data are collected, similarly to environmental LCA. Depending on the goal of the study, different types of data are collected: if the goal of a study is to identify social hotspots or to analyze a generic product, generic data at country or country-sector level could be sufficient. However, if a specific product is analyzed for its related social impacts, site-specific data need to be collected because the conduct of a company can vary considerably from one to another even if they operate in the same region (Benoit-Norris 2013). Due to the nature of social impacts, qualitative and semi-qualitative indicators are more often used in SLCA compared to in LCA. In some cases, numeric information is not sufficient to reflect the status or has to be assessed with additional information. SLCA does not favor objective data over subjective data since objective data may introduce greater uncertainty (UNEP/SETAC 2009).

Steps of data collection

Thousands of processes can be involved in a supply chain, and it is unpractical to study all the processes. Prioritization of processes is necessary to determine which processes or organizations will be included in data collection. Cut-off criterion is usually applied to decide the system boundaries and where primary and secondary data are collected respectively. In SLCA, activity variable is often used to set cut-off criterion. An activity variable is a measure of process activity to represent the relative significance of each unit process in the product system. Worker-hours and value-added as activity variables have been recommended in the Guidelines and applied in several case studies (Ramirez et al. 2016; UNEP/SETAC 2009). Generic data is data that is not site or enterprise specific, and it can be collected through literature review or web search. Site-specific data can be gathered through document auditing (i.e. enterprise, authorities and NGOs documentation), interviews, questionnaires, and participatory evaluation. Data availability is considered to be a driving force for the development of SLCA, and creation of databases can ease the burden of data collection (Benoit-Norris 2013; Jørgensen 2013). The status of SLCA database development will be discussed in the following paragraph.

Database development

On the landscape of SLCA, two databases have been considered as the most up-to-date and comprehensive generic data sources, namely Social Hotspots Database (SHDB) and Product Social Impact Life Cycle Assessment (PSILCA). Both SHDB and PSILCA adopt an input-output approach; however, SHDB builds upon GTAP input-output database (GTAP 2017), while PSILCA is based on Eora Multi-region input-output database (Lenzen et al. 2012). Both databases allow users to model supply chains by country-specific sectors. SHDB covers 227 countries and 57 sectors for each country, and PSILCA includes 187 countries represented by a total of 15909 sectors. 23 subcategories are included in both databases based on the Guidelines. Subcategories are grouped by impact categories in SHDB but by stakeholder groups in PSILCA. 124 indicators are used to assess the social themes of interest in SHDB, and 88 qualitative and quantitative indicators are included in PSILCA. Worker-hour is adopted as activity variable in both databases to rank country-specific sectors within supply chains by labour intensity. Compared to SHDB in which only negative impacts are considered, PSILCA includes both negative and positive impacts (e.g. for indicators regarding fair salary and respect for indigenous rights). In SHDB, social indicators are characterized into 4 risk levels (low risk, medium risk, high risk and very high risk), and PSILCA adopts 6 risk level (no risk, very low risk, low risk, medium risk, high risk and very high risk). PSILCA appears to be more transparent in terms of data quality by reporting raw values of inventory indicators and assessment of data quality based on pedigree matrix. However, with a longer history of development, more case studies applying SHDB are available in the existing publications (Benoit-Norris et al. 2012; Ekener-Petersen et al. 2014; Zamani et al. 2016).

2.2.3 Social life cycle impact assessment

No specific social life cycle impact assessment (SLCIA) methods are recommended in the Guidelines. SLCIA is the most covered topic in the existing SLCA publications (Garrido et al. 2016). In general, there are two types of SLCIA methods developed as pointed out in the Guidelines and the Methodological Sheets, Type 1 SLCIA methods which use Performance Reference Points and Type 2 SLCIA methods which attempt to seek the causal-effect relations between indicators and social impacts. As stated in the Guidelines, "*Type 1 impact categories aggregate the results for the subcategories within a theme of interest to a stakeholder, e.g. Human Rights. Type 2 impact categories model the results for the subcategories that have a causal relationship defined on the criteria, e.g. Autonomy"*. With the booming of publications proposing and applying new impact assessment methods, a number of researchers have attempted to summarize the developments of SLCIA and sort out the similarities and differences in these impact assessment methods. Type 1 and Type 2 impact assessment methods will be summarized and discussed in the next sections, based on three review articles which are considered the most up-to-date and comprehensive among similar work (Chhipi-Shrestha et al. 2015; Garrido et al. 2016; Wu et al. 2014). In these three articles, all the authors acknowledged the difference of the adoption of causal relations in the two types of SLCIA methods. Wu et al. (2014) and Chhipi-Shrestha et al. (2015) emphasized the implementation of scoring system in Type 1 methods compared with Type 2 methods; however, Garrido et al. (2016) suggested that the most essential differences between the two types of methods are the reference points that are used and the types of data assessed. Garrido et al. (2016) further explained that the inventories in Type 1 methods aim to represent the negative or positive social performances of related organizations. The inventory data in Type 1 methods are characterized at the same point on the impact pathway, usually into risk levels regarding negative impacts and opportunity levels concerning positive impacts. However, the implicit causal chain that positive performances result in positive impacts has not been tested in SLCA literature so far. In Type 2 method, characterization models resemble the logic of characterization in Environmental LCA in which inventory data are aggregated into mid-point or end-point impact categories through causal relations. These two types of SLCIA methods are reviewed in details as below.

Type 1 SLCIA methods

In this type of methods, data collected in the inventory phase is compared with other information (e.g. internationally accepted level of minimum performance) to understand its magnitude and significance. This additional information is referred as Performance Reference Point. Type 1 SLCIA methods assess social performances of a product life cycle rather than potential social impacts. Causal-effect relationships regarding social impacts are often not simple enough or not known with enough precision to allow quantitative modeling (Parent et al. 2010). Wu et al. (2014) analyzed 13 articles adopting Type 1 methods considering the aspects of scoring scheme, aggregation level, weighting, geographical specification, product system specification and the scope of the case study. Chhipi-Shrestha et al. (2015) also summarized the studies adopting Type 1 methods and went one step further by classifying 11 selected case studies into three groups, namely checklist methods, scoring methods and the SHDB method. Garrido et al. (2016) conducted an in-depth review of case studies applying Type 1 SLCIA methods including a more comprehensive literature body of 32 articles, and discussed impact assessment methods according to the approaches of characterization and weighting.

Studies applying Type 1 SLCIA methods were selected and summarized in Table 2.1, representing a wide range of approaches. The inventory on social indicators are usually compared against international, national or sectoral norms or best practices, and then characterized on a binary or a four- to five-level scale. The scales typically contain the aspects of being in compliance with reference points, performing above or below reference points. Reference points are often not clearly stated in the study, and the criteria determining the scaling are implicit. Quantis (2012) and Ramirez et al. (2016) set good examples by stating reference points established for each social indicator explicitly and the criteria for the scale assessment. Ramirez et al. (2016) also considered the factors of the social, economic, and political contexts of the companies when proposing the scale: when social performance on a certain indicator is worse than Basic Requirement (i.e. reference point), the company located in a *positive context* (i.e. the context promotes social sustainability) is scored at a lower level (Level D) than when the company is operating in a *negative context* (i.e. challenging socio-economic context) (Level C). Efforts on establishing scientifically-sound reference points for characterization have been observed as well, mostly focusing on the subcategory of income and fair wage (Croes and Vermeulen 2016; Neugebauer et al. 2017). Other researchers adopted the reference points based on stakeholders′ or experts′ judgments (or expectations) (Aparcana and Salhofer 2013; Foolmaun and Ramjeeawon 2013; Manik et al. 2013). For instance, in Manik et al. (2013), the authors compared the perceived performances on 24 social indicators against the expected performances on the same indicators in a

SLCA case study of palm oil biodiesel in Indonisia. Another stream of studies applied the approach embedded in the Social Hotspots Database, which characterizes the risk level of a social indicator related to the range of values reported for the countries included in the database (Ekener-Petersen et al. 2014; Zamani et al. 2016).

The majority of SLCA studies applying Type 1 SLCIA methods characterized social performances at the subcategory level (Aparcana and Salhofer 2013; Dreyer et al. 2010; Ekener-Petersen et al. 2014; Franze and Ciroth 2011; Quantis 2012; Ramirez et al. 2016). Other studies aggregated social performances by impact category, life cycle phase, or to a single score (Ciroth and Franze 2011; Foolmaun and Ramjeeawon 2013; Manik et al. 2013; Traverso et al. 2016). Weighting is not conducted in a number of studies, especially when social performances are presented at the subcategory level. When weighting is carried out, four types of weighting approaches have been observed in the studies including equal weighting, weighting based on the worse performance for a given subcategory, weighting based on panel judgements, and weighting based on an activity variable (e.g. worker-hours). An increasing application of Multi-Criteria Decision Analysis methods in weighting and aggregation in SLCA has been observed, which will be further discussed in Section 2.3.2.

Table 2.1 Summary of SLCA studies applying Type 1 SLCIA methods

Case study	Product system	Country	Functional unit	Scope	Cut-off criterion	Stakeholder groups	Number of subcategories	Number of indicators	Characterization method	Reference point	Weighting	Aggregation level
Dreyer et al. 2010	five manufactu-ring companies and one knowledge company	Malaysia, Brazil, Croatia, Hungary, Israel, Denmark	Not specified	Gate to gate	Not specified	Workers	4	Not specified	Multi-criteria model	Assessment based on norms and socio-economic geographic-al context	No weighting	Subcategory
Ciroth and Franze 2011	Notebook laptop	Belgium	One notebook	Cradle to grave	Not specified	Workers, value chain actors, local community, society, consumers	30	88	Scoring-color based method: six performance levels (very good, good, satisfactory, inadequate, poor, very poor) and six impact levels (positive, light positive, indifferent, lightly negative, negative, very negative)	Assessment based on norms and best practices	Equal weighting	Impact categories
Franze and Ciroth 2011	Roses	Ecuador and Netherla-nds	A bouquet of roses with 20 caulis per spray	Gate to gate	Not specified	Workers, value chain actors, local community, society, consumers	19	21	Checklist method: 5-level impacts (positive, indifferent, lightly negative, negative, very negative)	Assessment based on norms and best practices	No weighting	Subcategory
Quantis 2012	Milk production	Canada	1kg fat and protein corrected milk from a Canadian farm, to the processing facility	Gate to gate	more than 1.5% of the total expendit-ures of the dairy farms	Worker, local community, society, value chain actors	21	28	Scoring method: 4-level performance level (risky, compliant, proactive, commited, 1-4 respectively)	Assessment based on norms and best practices	Equal weighting	Subcategory

Table 2.1 Summary of SLCA studies applying Type 1 SLCIA methods (continued)

Case study	Product system	Country	Functional unit	Scope	Cut-off criterion	Stakeholder groups	Number of subcategories	Number of indicators	Characterization method	Reference point	Weighting	Aggregation level
Ekener-Petersen and Finnved-en 2013	Laptop	Sweden	One laptop	Cradle to grave	Not specified	Workers, local community, society, value chain actors, consumers	30	61	4-level impacts assigned by quartiles; 4 activity levels; country-sector with higher impacts on indicators and larger activities is hotspot	Assessments based on how a performance is positioned with regard to a distribution of performances	based on the worse performance for a given subcategory	Subcategory
Foolma-un and Ramjee-awon 2013	PET bottles disposal techniq-ue	Mauritius	1 tonne of used PET bottles	Gate to grave	Not specified	Workers, society, local community	8	11	Scoring method: 5-level (0-4) by percentage to convert inventory to scores	Assessed based on stakeholder´s or expert´s judgment of companies´/sectors´complian-ce to societal expectations or norms	Equal weighting	Single score
Manik et al. 2013	Palm oil biodiesel	Indones-ia	Not specified	Cradle to gate	Not specified	Workers, local community, society, value chain actors	24	Not specified	Likert scale method: 7-point Likert scale, measuring the differences between social expectations and social perceptions	Assessed based on stakeholder´s or expert´s judgment of companies´/sectors´complian-ce to societal expectations or norms	based on stakeholder´s/ expert´s/us-er´s judgment of importance of issues	Single score
Ekener-Petersen et al. 2014	Oil, bio-ethanol, biodiesel	Russia, sweden, Nigeria, Brazil, US, France, Lithuania	Not specified	Gate to gate	Not specified	Workers, local community, society, value chain actors	22	137	SHDB method: 4-level risks (very high, high, medium, low) by quartile falls in; Social indicators with high and very high risks are counted	Assessments based on how a performance is positioned with regard to a distribution of performances	No weighting	Subcategory/ Impact category/Life cycle phase

Table 2.1 Summary of SLCA studies applying Type 1 SLCIA methods (continued)

Case study	Product system	Country	Functional unit	Scope	Cut-off criterion	Stakeholder groups	Number of subcategories	Number of indicators	Characterization method	Reference point	Weighting	Aggregation level
Haaster et al. 2016	Introduction of large-scale novel technologies (large-scale deployment of CCS in coal-fired power plants)	General (OECD Europe)	Case-dependent (1kWh electricity delivered to the grid)	Cradl to gate	Not specified	Worker, local community, society, value chain actors	11	Not specified	Quantitative indicator-aggregated by means of a weighted and normalized arithmetical mean; Qualitative indicator-not aggregated	Assessments based on norms and best practices	2 weight sets: Equal weights or experts´ opinion	Single score-quantitative indicators; Subcategory-qualitative
Ramirez et al. 2016	Natura´s cocoa soap	Brazil	the cocoa soap required to provide cleaning baths to a person over a year (i.e. 10 soaps of 150g)	Cradle to gate	>1% mass weighted by working hours	Worker, local community, society, value chain actors	25	Not specified	Scoring method: 4-level performance level (proactive performance beyond Basic Requirements, fulfillment of BR, non-fulfillment in a negative and positive context)	Assessments based on norms and socio-economic geographical context	No weighting	Subcategory
Traverso et al. 2016	a Run On Flat tire mounted on a BMW vehicle	General	a single tire with an average service life of a six-year period around 50,000 km	Cradle to gate	Not specified	Workers, customers, local communities	19	71	Checklist method: 3-level performance (good performance, reach the target, not reach the target)	Assessment based on norms and best practices	No weighting	Life cycle phase
Zamani et al. 2016	clothing consumption	Sweden	the production of 1 USD worth of clothing for Swedish consumption	Cradle to gate	country-sectors >2 % of the economic value	Workers, local community, society, value chain actors	Not specified	133	SHDB method: 4-level risks (very high, high, medium, low) by quartile falls in	Assessments based on how performance is positioned with regard to performance distribution	based on an activity variable (worker hours in this case)	indicator and country-sector

Type 2 SLCIA methods

As in LCA, Type 2 SLCIA methods use characterization models to represent impact pathways. Most of the case studies applying Type 2 SLCIA methods were published before the Guidelines (between 2006 and 2008). Impact pathway methods usually apply quantitative data, which are aggregated to a mid-point and/or end-point level through causal-effect chain modeling.

Table 2.2 summarized key references using impact pathway methods in SLCA studies. Some studies only explored single impact pathway focusing on one social issue, which in most cases is in regard to human health. Feschet et al. (2013) built *Preston pathway* which establishes the relation between life expectancy and income per capita. The pathway was applied to a case study of banana industry in Cameroon, and it was concluded that 200 000 tons export of bananas annually contributed to the increase of life expectancy at birth in Cameroon by five days over 20 years. The authors also pointed out four conditions to ensure the applicability of Preston pathway concerning the economic scale and the significance of the economic activity in the given country. Bocoum et al. (2015) extended the work of Feschet et al. (2013) and proposed *Wilkinson Pathway* which describes the relation between income inequality and health. The authors suggested that the effects of changes in income inequality on health differed between OECD and non-OECD countries. In both OECD and non-OECD countries, the variation in income inequality has a delayed effect to reflect on the variation in infant mortality rate; however, the impacts on OECD countries are much greater than in non-OECD countries. Hutchins and Sutherland (2008) and Norris (2006) also proposed pathways describing the relation between income level and health status.

Other studies using Type 2 SLCIA methods tried to model the casual relationships between indicators to multiple midpoint and/or endpoint categories. Most studies proposed frameworks rather than explicit pathways linking indicators to corresponding categories. Weidema (2006) proposed quality adjusted life years (QALY) quantifying the reduction of well-being covering six damage categories including life and longevity, health, autonomy, safety/security/and tranquility, equal opportunities, and participation and influence. Hunkeler (2006) used labour hours as an intermediate variable to link unit processes and social needs such as access to housing, healthcare, education and necessities. Labuschagne and Brent (2006) proposed Social Impact Indicators (SII) based on the method of Resource Impact Indicators (RII), and applied SII to three process industries. The authors suggested 21 mid-point categories, which were further aggregated to four end-point categories including internal human resources, external population, stakeholder participation, and macro-social performance.

Table 2.2 Summary of SLCA studies applying Type 2 SLCIA methods

Case study	Product system	Country	Functional unit	Scope	Cut-off criterion	Stakeholder groups	Number of Impact pathway(s)	Characterization method (casual relation)	Normalization/ Weighting	Aggregation level
Labuschagne and Brent 2006	General (3 examples - an open cast mine, a chemical facility, a fibre manufacturi-ng plant)	South Africa	one operational year of the asset	Gate to gate	Not specified	Workers, local community, society, value chain actors	Multiple	Proposed Social Impact Indicators (SII) based on the method of Resource Impact Indicator (RII)	A conventional distance-to-target normalization and weighting	Midpoint: 21; Endpoint: 4 (internal human resources, external population, stakeholder participation, macro-social performance
Hunkeler 2006	Detergent 1&2	Germany	1kg of detergent	Cradle to gate	Not specified	Workers	Multiple	Relating unit processes to employment hours, then converting to social needs	Equal weighting	Midpoint: not specified (exemplary categories - housing, health care, education, necessities)
Norris 2006	Global supply chain of Dutch electricity	Netherlands	Not specified	Cradle to gate	Not specified	Population in the country where the economic activity takes place	1	Relationship between life expectancy and GNP per capita	No	Endpoint: human health - mean life expectancy
Weidema 2006	General	General	Not specified	Gate to gate	Not specified	Not specified	Multiple	Biophysical and economic inventory results to social midpoint categories	Global normalization: monetization weighting	Midpoint: 6 (life and longevity, health, autonomy, safe/security/and tranquility, equal opportunities, participation and influence; Endpoint: human life and well-being

Table 2.2 Summary of SLCA studies applying Type 2 SLCIA methods (continued)

Case study	**Product system**	**Country**	**Functional unit**	**Scope**	**Cut-off criterion**	**Stakeholder groups**	**Number of Impact pathway(s)**	**Characterization method (casual relation)**	**Normalization/ Weighting**	**Aggregation level**
Hutchins and Sutherland 2008	General	General	Not specified	Gate to gate	Not specified	Population in the country where the economic activity takes place	1	Relationship between infant mortality and GDP per capita	No	Endpoint: human health - infant mortality rate
Feschet et al., 2013	General (case study: Banana industry)	General (case study: Cameroon)	Annual export of 200,000 t bananas	Gate to gate	Not specified	Population in the country where the economic activity takes place	1	Preston pathway: GDP per capita to life expectancy	No	Endpoint: human health-life expectancy at birth
Bocoum et al. 2015	General (case study: production of table wine)	General (case study: Fictional country C)	the provision of 40 million L of table wine per year over 20 years	Gate to gate	Not specified	Population in the country where the economic activity takes place	1	Wilkinson pathway: relationship between income inequality and health	No	Endpoint: human health - infant mortality rate

2.2.4 Alternative approaches and other issues in SLCA publications

SLCA is a rapidly evolving research field with different schools of thoughts on a wide range of topics. Alternative approaches of conducting SLCA and issues not covered above but worth noting are discussed in this section.

In regard to alternative approaches proposed in SLCA publications, Martínez-Blanco et al. (2015) proposed social-organizational LCA (SOLCA) integrating the frameworks of SLCA and organizational LCA. Pré-Sustainability lead the development of the framework of Roundtable for Product Social Metrics collaborating with industrial partners to develop two approaches of social impact assessment i.e. quantitative approach and scale-based approach (concerning qualitative data) (Fontes et al. 2016; Traverso et al. 2016). Mccabe and Halog (2016) proposed the integration of participatory systems thinking techniques from social science in SLCA practices. Weidema (2016) suggested the new method of social footprinting which is based on the idea of a streamlined SLCA that the majority of the processes are non-production specific processes and the inventory can be collected from national/sectoral statistics.

An increasing number of articles investigating the scientific grounding of SLCA have been published. Iofrida et al. (2016) discussed about the links between social research paradigms and the diversity of SLCA methods. The authors concluded that more than 70% of SLCA methods belong to interpretivism-oriented paradigm, while approximately 25% of the methods are based on post-positivist paradigm. Wu et al. (2015) applied statistic causal models, namely structural equation modeling to identify impact pathway, and used Bayesian networks to develop a hybrid model incorporating Type 1 and Type 2 SLCIA methods. Sakellariou (2016) explored the relation between engineering ideologies of sustainability in the application of SLCA. Grubert (2016) suggested the integration of social science research methods and theories in SLCA.

2.2.5 Concluding remarks and future research needs identified in SLCA

Section 2.2 reviewed the state-of-the-art development of social life cycle assessment. Researchers from various disciplines have contributed to the flourishing diversity of SLCA. Despite the considerable achievements of the field, a number of issues need to be further explored in the SLCA community. The list below is by no means and not intended to be an exhaustive list of research needs in SLCA.

- Despite scientific grounding of SLCA has been discussed in several publications, consensus on rigors of SLCA is lacking. Experts of social sciences are called for to collaborate with SLCA practitioners to examine the robustness of SLCA through social science theories.
- Social indicators and subcategories suggested in the Guideline and the Methodological Sheets have been widely adopted in SLCA case studies. However, as more urgent and relevant social issues vary among industries and regions. The needs of developing tailored indicators and subcategories with prioritization for country-sectors should be further discussed.
- As social performances or social impacts are closely related to the conducts of companies which can vary significantly even when belonging to the same country-sector, collecting high-quality site-specific data is considered crucial when conducting a SLCA study which goal is beyond hotspots identification. Marrying the knowledge of conducting surveys and interviews in social science with SLCA can facilitate data gathering. For instance, sharing questionnaire templates and experiences on conducting focus group studies will foreseeably improve the accessibility of SLCA.
- Collecting site-specific data can be very costly, therefore reliable generic database and robust cut-off criteria are the keys to identify social hotspots. There are lack of discussions and consensus on how to determine cut-off criteria in SLCA literature. The current SLCA databases include data on the country-sector level which often aggregate several sectors into one broad category; moreover, differences for social impacts due to technology developments are not considered. More accurate and up-to-date data need to be included in SLCA databases.
- There exists a great diversity in both Type 1 and Type 2 SLCIA methods. Standardization and harmonization are required to make SLCA more accessible to practitioners outside of the SLCA community. Type 1 and Type 2 SLCIA may be combined in practice, nevertheless explicit guidelines or case studies are needed.

- Consensus on determining functional unit, system boundary, methods of weighting and aggregation, and characterization of qualitative and semi-quantitative indicators are still lacking.
- Inclusion of positive impacts in SLCA is important for evaluating social impacts of supply chains in a comprehensive manner. Indicators, characterization methods and aggregation with negative impacts need to be further discussed.

2.3 Application of Multi-Criteria Decision Analysis (MCDA) in life cycle studies

Multi-Criteria Decision Analysis (MCDA) offers a collection of methods to support comparison of different alternatives based on a set of evaluation criteria. In comparative life cycle studies, one product system often does not have better performances on all the categories. Weighting various impacts in life cycle impact assessment (LCIA) can support decision-making; however, the commonly used method of a simple weighted sum is considered to be controversial. In light of the arguable practices of weighting in life cycle studies, ISO standards suggest that normalization, aggregation and weighting are optional LCIA steps (ISO14044 2006). With the capacity of handling conflicting decision situations, MCDA has been considered a promising tool to aid the aggregation of different environmental indicators in a scientifically sound manner. Application of MCDA in life cycle studies can be dated back to 1990s (Miettinen and Hamalainen 1997); however, there is no consensus on how MCDA methods can be integrated in life cycle studies partially due to the diversity of the MCDA field itself (Benoit and Rousseaux 2003).

Since the early attempts of integrating MCDA in life cycle studies (Miettinen and Hamalainen 1997; Benetto et al. 2008), a large body of literature has been published in the research area. In this section, the focus is given to life cycle studies related to agricultural products (including bioproducts) considering the subject of interest of this dissertation (i.e. sugarcane). Application of MCDA methods in LCA studies is reviewed in Section 2.3.1, followed by a review of application of MCDA methods in SLCA and LCSA in Section 2.3.2.

2.3.1 Application of MCDA methods in LCA studies of agricultural products

A desktop research of publications between 1997 and 2017 applying multi-criteria methods and LCA was conducted on Google Scholar, Web of Science, ScienceDirect and Research Gate. Key words *life cycle assessment, LCA, multi-criteria, multicriteria, multiple criteria, MCDA, MCDM* and *MCA* were used in the search. 108 studies were identified in this phase. Eighteen studies are relevant with agricultural products (or bioproducts) and included in the final analysis (see Table 2.3). The selected articles have covered the subjects in three main categories: a) food (poultry, wine, riparian vegetation, and sugar); b) industrial processes of bioproducts (biochar facilities, soda pulp, and wood products); and c) bioenergy (biodiesel, lignocellulosic bioenergy, algae biogas and flex-fuel). The number of alternatives and environmental criteria assessed differ largely by case. Various LCIA methods have been applied, with CML being the most adopted (4 out of 18). The objective of applying MCDA in LCA studies is dominantly to facilitate weighting.

Two categories of MCDA methods were identified in the review: a) the outranking approaches (e.g. ELECTRE TRI, PROMETHEE and SMAA-TY), and b) the additive model approaches (e.g. AHP, SMAA, and SMART). The outranking approaches are based on comparisons between pairs of options to verify whether one alternative is at least as good as another alternative. In outranking methods, small differences between alternatives can be considered indifferent, and considerable differences over a certain extent do not bring additional value for one alternative to be preferred (Roy 1991). The additive model approaches follow the general format of synthesizing the information in a unique overall value, which is a weighted sum of its value on each criterion (Dias et al. 2016).

Castellini et al. (2012) compared the environmental impacts of three poultry production systems applying the impact assessment method of Eco-indicator 99, together with economic, social and quality indicators. Outranking method ELECTRE I was used to compare production systems. Information of priorities of various indicators was collected through surveying relevant stakeholder groups including scientists, consumers and producers. Kralisch et al. (2013) adopted outranking method PROMETHEE II to rank the environmental impacts of 18 biodiesel production systems. The authors assessed nine mid-point impact categories of CML, and assumed equal weights on all the categories. The analytic hierarchy process (AHP) is the most applied MCDA method in the selected articles (7 out of 18). AHP uses a series of pair-wise comparisons to determine the relative weights of the criteria or indicators, with the total of all weights adding up to 100% (Saaty 1980). Doderer and Kleynhans (2014), Lipuscek et al. (2010), Narayanan et al. (2007) and Pastare et al. (2014) consulted experts´ opinions to calculate the weights by AHP. In Ahmed et al. (2012) and Dinh et al. (2009), the values of pair-wise comparisons were decided by authors, while Hermann et al. (2007) explored three sets of weights regarding various importance levels of environmental criteria up to the perspective considered (global, national or regional). Other additive model approaches such as SMART, VIKOR and distance-to-target have also been found in the articles facilitating the weighting and aggregation in LCA (Falcone et al. 2016; Myllyviita et al. 2012; Perimenis et al. 2011; Recchia et al. 2010; Reeb et al. 2016; Zhou et al. 2007). The aforementioned case studies required the value judgment information of decision makers regarding the importance of each criterion, which is often gathered through surveys to experts or stakeholders. Several articles used MCDA methods applying stochastic weights to support the interpretation of LCA results when complete information about weights is lacking. Rogers and Seager (2009) adopted outranking approaches using stochastic weights to decide the possibilities of each alternative positioned preferably in the ranking. Dias et al. (2016) compared four product systems of rapeseed biodiesel regarding six impact categories using an additive model approach with stochastic weights. The results were then analyzed with Variable Interdependent Parameter Analysis to assess the robustness of the rankings.

Table 2.3 Summary of LCA studies of agricultural products applying Multi-Criteria Decision Analysis methods

Reference	Objective issue	Alternatives	Criteria	LCIA method	MCDA method	If used weights in MCDA	Sensitivity analysis	Category of MCDA method
Hermann et al. 2007	Eucalyptus-based Soda pulp industry	Thai pulp sector	GWP, AP, EP, POF, HTP	CML	AHP	Yes	Yes	Additive model
Narayanan et al. 2007	Bio-diesel production	soy bean, rape seed oil, sunflower oil, beef tallow	Environmental (land usage, water usage), economic, safety, system specific	Unclear	AHP	Yes	No	Additive model, distance to target
Zhou et al. 2007	Fuels	conventional gasoline, conventional diesel oil, compressed natural gas, M85, E85, E100	Life cycle cost, GWP, net energy, non-renewable depletion potential	IPCC	1. equal weights; 2. priority given to one indicator at a time	Yes	Yes	Additive model
Dinh et al. 2009	Biodiesel production	jatropha, algae, palm oil, rapeseed, soybean	Environment (GHG, water, land use), economic, safety, fuel performance, raw material performance	Unclear	AHP	Yes	No	Additive model
Rogers et al. 2009	Transportation fuels	gasoline (GAS), lowsulfur diesel (LSD), 100% soy-biodiesel (BD100), electric vehicle (EV), and 85% corn-based ethanol (EtOH)	fossil fuel depletion, global warming potential, eutrophication, photochemical ozone formation, acidification, air pollution	TRACI	SMAA (based on outranking PROMETHEE)	No	Yes	Outranking
Lipuscek et al. 2010	Wood products	Wood product in Slovenia	Solid wastes, emissions to waters, waste air, energy emissions	Unclear	AHP	Yes	No	Additive model
Recchia et al. 2010	Riparian vegetation	10 scenarios considering different working yard characteristics and yard mechanization	Cumulated Energy Requirement; GHG; Atmospheric emissions (Carbon monoxide, Nitrogen Oxides (NO_x), Particulate, Sulfur dioxide (SO_2))	Unclear	Four-level A to D weighting	Yes	No	Additive model

Table 2.3 Summary of LCA studies of agricultural products applying Multi-Criteria Decision Analysis methods (continued)

Reference	Objective issue	Alternatives	Criteria	LCIA method	MCDA method	If used weights in MCDA	Sensitivity analysis	Category of MCDA method
Perimenis et al. 2011	Biodiesel from rapeseed in Germany	Rapeseed biodiesel in Germany	8 indicators covering environmental (GHG, primary energy demand), technical, economic, social	Unclear	Group Decision Support Systems (pair-wise comparison point based)	Yes	No	Additive model
Ahmed et al. 2012	various locations for pyrolysis biochar facilities	9 feedstocks: straw, sawmill residues, forestry residue chips, softwood-small round wood, C&D waste wood, sewage sludge, garden and green waste, food waste, distilleries grain waste	8 proximity to different land uses (arable cereal, horticulture, woodland, grassland, rural settlements) andcurrent wood-fuel suppliers; proximity to major roads; and slope of 'sink' land.	carbon abatement	AHP	Yes	No	Additive model
Castellini et al. 2012	Poultry production systems	3 systems: Organic, Conventional, Organic-plus	4 dimensions (economic, social, environmental, quality)/24 indicators	Eco-indicator 99	ELECTRE I	Yes	No	Outranking
Cucek et al. 2012	Biomass and bioenergy supply chains	Combination of various biomass types, technology options and byproducts	6 indicators: Carbon footprint, Energy footprint, water footprint, water pollution footprint, food-to-energy footprint, land footprint	Unclear	Mixed-integer nonlinear programming model (MINLP)	No	No	Optimization
Myllyviita et al. 2012	biomass production chains	4 biodiesel or pulp product systems with biomass productions in Asia or Finland	14 indicators from ReCiPe category and expert´s identified criteria (e.g. Biodiversity)	Unclear	SMART	Yes	No	Additive model
Kralisch et al. 2013	Biodiesel production	18 biodiesel production processes	GWP, ADP, ODP, POCP, AP, EP, Land use, HTP and Terrestrial Eco-toxicity Potential (TETP)	CML	PROMETHEE II	No	No	Outranking
Doderer & Kleynhans 2014	Lignocellulosic bioenergy systems	37 scenarios of agricultural operations, transportation and technologies	13 indicators: Environment (ADP, AP, EP, GWP, POCP); Financial-economic; Socio-economic	CML 2001	AHP	Yes	No	Additive model (distance to target)

Table 2.3 Summary of LCA studies of agricultural products applying Multi-Criteria Decision Analysis methods (continued)

Reference	Objective issue	Alternatives	Criteria	LCIA method	MCDA method	If used weights in MCDA	Sensitivity analysis	Category of MCDA method
Pastare et al. 2014	Macro-algae for biogas production	9 scenarios considering feedstock, cultivation media and place and harvesting technology	12 indicators covering environment (ecosystem quality, climate change, human health, resource depletion), technical, social, economic	IMPACT 2002+	AHP, TOPSIS	Yes	Yes	Additive model
Dias et al. 2016	Biodiesel from rapeseed	3 produced in Europe and 1 in North America	GW; AD; Ac; Eu; OLD;PD	CML	SMAA (based on additive aggregation); VIP(Variable Interdependent Parameters Analysis)	No (no single weight vector was specified, but accepted ratios between weights)	Yes	Additive model
Falcone et al. 2016	Wine production	Combination of two cropping systems and two training systems	LCA (GWP, ODP, POCP, AP, EP, NRF); LCC(Net present value, initial investment cost, life cost unit, labour per production unit, life total return unit, life net return unit)	EPD 2008	VIKOR	Yes	Yes	Additive model
Reeb et al. 2016	Bio-based sugar feedstock	18 feedstocks	Biomass cost, environmental preference (GWP, AD, EP, Ecotoxicity, OD, POF, Carcinogenics, non-carcinogenics, respiratory effects), sugar yield, transport distance, harvestable months	TRACI	1. unweighted scoring method; 2. weighted, rank-order distributed scoring method; 3. weighted, raw value distributed scoring method	Yes	Yes	Additive model

2.3.2 Application of MCDA in SLCA or LCSA studies of agricultural products

A desktop research of publications between 1997 and 2017 applying multi-criteria methods in SLCA or LCSA studies was conducted on Google Scholar, Web of Science, ScienceDirect and Research Gate. Key words *social life cycle assessment, SLCA, life cycle sustainability assessment, LCSA, multi-criteria, multicriteria, multiple criteria, MCDA, MCDM* and *MCA* were used in the search. 13 studies were identified, among which seven are related to agricultural products (including bioproducts), as summarized in Table 2.4. Agricultural products have been assessed covering the categories of biofuels (e.g. biodiesel, bioethanol), industrial bioproducts (e.g. biomethane, bicycle frame) and food (e.g. citrus). Various MCDA methods (i.e. value function, TOPSIS, MCBB, AHP) have been applied to the selected SLCA and LCSA studies with three streams of objectives: a) ranking selected product systems; b) selecting the most promising alternative among all the alternatives considered; and c) handling uncertainties due to subjective judgements.

De Luca et al. (2015) and Ren et al. (2015) applied AHP-based approaches to a SLCA study of citrus farming and a LCSA study of bioethanol in China respectively. De Luca et al. (2015) compared social impacts of nine citrus farming systems considering various farming locations and techniques on 19 criteria related to eight social issues for the stakeholder groups of workers, local communities and society. Pair-wise comparisons were conducted by relevant stakeholders through focus group to determine the importance of each criterion, social issue and stakeholder group respectively. The aggregated results were used in the weighting process of LCIA. In Ren et al. (2015), pair-wise comparisons were carried out at the level of sustainability dimensions (i.e. environmental, social and economic) and among selected criteria in each dimension. After obtaining weight for each criterion through AHP, the authors went one-step further by applying another MCDA method, VIKOR, to rank three bioethanol production options in China. MCDA method has also been identified in the articles to handle uncertainty issues in SLCA studies applying performance reference point approaches. Carmo et al. (2017a) identified two sources of uncertainties in Type 1 SLCA studies resulting from scoring choices and weighting factors. Unlike in traditional SLCA studies which often assume linear value function in the characterization of inventory indicators, the authors established customized value function for each indicator based on expert judgements considering the complexity of social issues of interests. Weights of social criteria were firstly surveyed among SLCA experts individually, and then stochastic weights were applied to account for the value judgements of all the stakeholders. First-rank possibilities of each alternative were finally calculated regarding the stakeholder dimension to facilitate the interpretation of SLCA results. Other authors used MCDA methods to facilitate ranking and selection of product systems based on SLCA or LCSA results. Karklina et al. (2015) applied a distance-to-target approach TOPSIS to rank seven biomethane production and distribution systems based on their performances on five social criteria (i.e. employment, standard of living, environmental protection, rational use of resources, and security of energy supply). Suwelack and Wüst (2015) developed a method named Multi Criteria Based Benchmarking (MCBB) to rank three biomass conversion systems against seven criteria of environmental, social and economic impacts, in which equal weight was assumed to each dimension and criterion. Results based on LCSA analysis and ranked by MCBB were then visualized by advanced radar plots to improve the transparency and communication of LCSA results.

Table 2.4 Summary of SLCA and LCSA studies of agricultural products applying Multi-Criteria Decision Analysis methods

Reference	Objective issue	Alternatives	Criteria	MCDA method	If used weights in MCDA	Purpose of MCDA	Sensitivity analysis	Category of MCDA method
De Luca et al. 2015	Citrus farming in Southern Italy	9 combination of 3 main agricultural areas and 3 principal techniques of cultivation	Contribution to economic development, environmental impacts, area reputation, use of IT and local knowledge, use of local natural resources, equal opportunities, fair working conditions, health and safety working conditions.	AHP (pairwise comparison at three levels: category, subcategory, stakeholder)	Yes	Weighting	No	Additive model
Karklina et al. 2015	Biomethane production and distribution	Biogas to heat; biogas to CHP; Biomethane with grid injection to heat; Biomethane with grid injection to CHP; Biomethane with grid injection to transport; Biomethane directly to transport; Natural gas.	Employment, standard of living, environmental protection, rational use of resources, security of energy supply	TOPSIS	Yes	Ranking	No	Distance to target
Ren et al. 2015	bioethanol in China	wheat-based; corn-based; cassava-based	LCA(4); SLCA(3); LCC(1)	AHP (pairwise comparison between aspects of sustainability and criteria in each aspect) +VIKOR	Yes	Weighting (AHP) and ranking (VIKOR)	1) Equal importance 2) one dominant criteria, with the remaining of equal importance	Additive model
Suwelack et al. 2015	biomass conversion systems	3 biomass conversion systems	Job created, increased rural development, natural land use, GWP, Fossil resource depletion, production costs, specific investment	Multi Criteria Based Benchmarking	Yes	Ranking and visualization of the results	No	Additive model
Carmo et al. 2017a	biodiesel	soya biodiesel in Argentina; palm oil biodiesel in Malaysia; soya biodiesel in the US; wasted oil biodiesel from Quebec.	SLCA: 3 stakeholder dimensions and 11 subcategories	Value function, stochastic weights	Yes	Uncertainty in weighting	Yes	Additive model
Carmo et al. 2017b	biodiesel	4 biodiesel suppliers	SLCA: 3 stakeholder dimensions and 11 subcategories	Value function, average numerical weights	Yes	Uncertainty in weighting	Yes (comparing to linear value function)	Additive model

CHAPTER 3 ENVIRONMENTAL AND HEALTH IMPACTS

3.1 Introduction

Health effect of particulate matter is an important local impact associated with sugarcane production in Brazil, whereas it has not been addressed in the existing LCA studies of sugarcane or sugarcane products. Fine particulate matter ($PM_{2.5}$) contributes the most to the health effects associated with particulate matter emissions among all sizes (e.g. PM_{10}, $PM_{10-2.5}$, $PM_{2.5}$) (Humbert 2010). Discussions about characterizing health effects of $PM_{2.5}$ are on the rise in the LCA community (Fantke et al. 2015; Gronlund et al. 2015; Humbert et al. 2011). However, few studies were published adopting regional characterization factors (CF) for $PM_{2.5}$ for regions outside of Europe and the United States. An LCA of sugarcane production in Brazil incorporating health effects from $PM_{2.5}$ exposure calculated with regional characterization factors is needed, because it can quantify the magnitude of health benefits of replacing manual by mechanical harvesting, and contribute to the assessment of health effects of $PM_{2.5}$ in LCA practices.

This chapter compares the life cycle environmental and health impacts of manual and mechanical sugarcane harvesting in Brazil considering fine particulate matter emissions. The health effects associated with $PM_{2.5}$ emissions were assessed using characterization factors that differentiate geographical features of emission sources and consider different burdens of disease. Characterization factors of primary and secondary $PM_{2.5}$ for Brazil were calculated and implemented. The results of this chapter can provide incentives to accelerate the mechanization of sugarcane harvesting in areas with lower mechanization rate concerning the magnitude of public health benefits. These results can also contribute to further studies comparing potential benefits of sugarcane culture with alternative crops and guide better decision-making at regional development level. Characterization factors of $PM_{2.5}$ calculated in this study may also be applied to future studies regarding health effects of $PM_{2.5}$ in the Brazilian context. Materials and methods are discussed in Section 3.2. Results are presented in Section 3.3, and the concluding remarks can be found in Section 3.4.

3.2 Materials and methods

3.2.1 Life cycle model and inventory

A comparative cradle-to-gate life cycle assessment (LCA) was conducted, addressing sugarcane cultivation, harvesting and transportation in the center-south region of Brazil. Two sugarcane product systems were investigated and compared: one harvested manually with pre-harvest burning and the other in which this operation occurs mechanically without pre-harvest burning. The functional unit chosen is 1 tonne of sugarcane at the distillery. A simplified diagram of the product system is shown in Fig. 3.1. A life cycle inventory based on the database of Brazilian Bioethanol Science and Technology Laboratory (CTBE) was collected and implemented (Bonomi et al. 2016). Detailed inventory presented by functional unit were included in Appendix 1. The inventory includes average data representing current technologies and operations of manual and mechanical sugarcane harvesting in the centre-south region of Brazil. The sugarcane yield per hectare of manual harvesting system is slightly higher than in mechanical harvesting. It is because in manual harvesting, sugarcane sets are semi-mechanically planted requiring 12 tonne setts per hectare, while in mechanical harvesting the planting process is fully mechanized, requiring 20 tonne setts per hectare to compensate for inefficiency of the planting machine (CONAB 2011). Transport of raw materials and final products was also included in the product system. The average transportation distance of sugarcane stalks from the field to the mill is assumed as 25 km (Chagas et al. 2016). Production and field emissions of raw materials including organic and inorganic fertilizers, agrochemicals, diesel used in agricultural machineries were also considered. Vinasse, the liquid effluent of ethanol distillation, boiler ashes and filter cake, were used together with inorganic fertilizer (urea, SSP, and KCl) to supply the nutritional requirements of the sugarcane culture. The emissions of transporting vinasse from the industrial plant to the field (25km), and operations of pumping, storage and aspersion were included. Capital goods including harvesters, tractors and agricultural machineries were also accounted for.

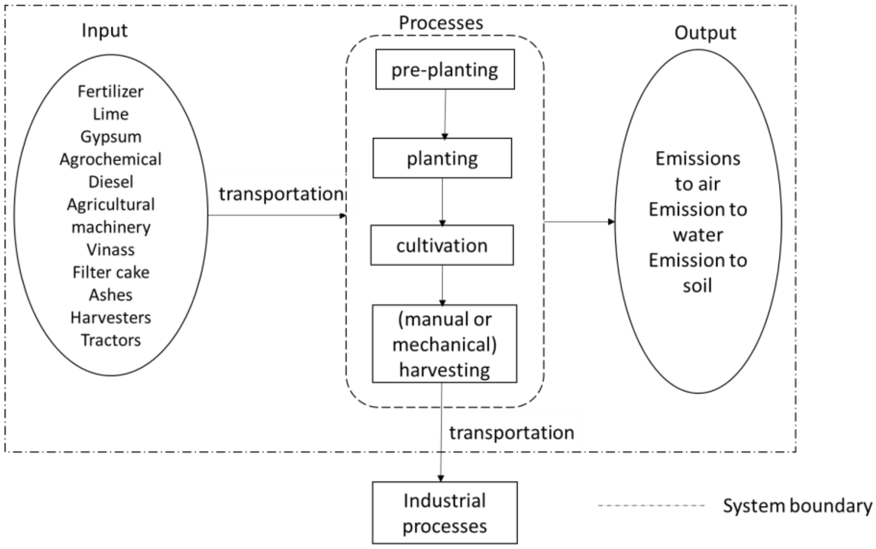


Fig. 3.1 A simplified diagram of the sugarcane product system

Regarding estimations of field emissions, for inorganic N fertilizer, 30% of the total N applied as urea was considered to be emitted as ammonia, and 1% of the ammonia was converted as N_2O. 1% of the total N applied directly emitted as N_2O, and 0.75% of the nitrogen leached were assumed to be emitted as N_2O (Costa 2003; Nemecek et al. 2007). Estimations of emissions from organic fertilizers (vinasse and filter cake) and sugarcane residues (straw and roots) followed IPCC (2006), emission factor for direct and indirect N_2O emissions was established as 1.22%, nitrogen content was assumed as 0.595 kgN/m_3 for vinasse and 12.5 kgN/tonne for filter cake (Macedo 2007; Chagas et al. 2016). We assumed 4.77 gN/kg of sugarcane straw and 5.1 gN/kg of sugarcane roots, with a root : shoot ratio (defined as the weight of all biomass below the ground surface divided by the weight of all biomass above the ground surface, on a dry basis) of 0.2 (Smith et al. 2005; Hassuani 2005). Quantification of climate change impacts followed the concept of neutral biogenic carbon, thus emissions of biogenic CO_2 from burning sugarcane residues and straw, as well as the capture of CO_2 by sugarcane were not accounted for. Emission factors of sugarcane straw (leaves and tops) burning were based on GREET (2009) and França et al. (2012). Details of assumptions and emission factors applied are in Appendix 2.

Sugarcane residues left on the ground from mechanical harvesting may result in an increase in soil organic carbon thus reducing CO_2 emissions depending on the level of soil carbon saturation of sugarcane fields. Carbon accumulation rates ranging from 1.1 – 1.5 tonne C/ha/year in sugarcane fields in São Paulo at the time span of 4 – 16 years and the soil depth of 20 – 60 cm have been reported (Carvalho et al. 2013; Cerri et al. 2011; Galdos et al. 2009; Segnini et al. 2013). Research on integrating soil organic carbon sequestration (SOC) in LCA is on the rise, but there is lack of consensus on how to proceed at the methodological level (Bosco et al. 2013; Brandão et al. 2013; Petersen et al. 2013). We calculated SOC following the IPCC guidelines (IPCC 2006). The IPCC method is based on the assumptions that soil carbon stock in a certain field will be saturated at some point, and soil carbon changes over time are linear. The default values of the time dependence of stock change and the soil depth in the IPCC method are 20 years and 30 cm respectively. The lands currently adopting mechanical harvesting of sugarcane have mostly experienced the transition from manual harvesting with pre-harvest burning, which was a dominant agricultural practice of sugarcane sector throughout Brazil for decades. To understand the contribution of SOC on climate change, two SOC scenarios were considered in mechanical harvesting without pre-harvesting burning of straw: (i) soil carbon saturated (no SOC increase); and (ii) SOC saturated in a 20-year span. The two SOC scenarios were selected because they represent the extreme scenarios for soil carbon change when a sugarcane field changes from manual to mechanical harvesting. In the second scenario, a total of 5.2 tonne of carbon was sequestrated per hectare in 20 years, considering conditions of sugarcane plantation in Brazil (temperature zone: tropical moist; soil type: low activity clay) (IPCC 2006). This scenario projects an average rate of 260 kg carbon sequestered per hectare per year from the sugarcane residues. Detailed assumptions and calculations of soil organic carbon change can be found in Box 1.

Box 1 Calculation of soil carbon changes transferring from manual to mechanical harvesting

Location: São Paulo

Temperature zone: Tropical moist

Soil type: Low activity clay

SOC_{REF} = 47 tC/ha

Mechanical harvesting product system (with residues)

$F_{LU\_residue}$ = 0.48 (*long-term cultivated*) $F_{MG\_residue}$ = 1.15 (*reduced tillage*)

$F_{I\_resiude}$ = 1 (*medium input*)

According to IPCC *Equation 2.25* in calculating annual change in organic carbon stocks in mineral soils,

$SOC_{residue} = 47 \times 0.48 \times 1.15 \times 1 = 25.94$ tC/ha

Manual harvesting product system (without residues)

$F_{LU\_noresidue}$ = 0.48 (*long-term cultivated*) $F_{MG\_noresidue}$ = 1 (*full tillage*)

$F_{I\_noresiude}$ = 0.92 (*low input*)

$SOC_{noresidue} = 47 \times 0.48 \times 1 \times 0.92 = 20.75$ tC/ha

Thus,

Soil carbon sequestrated = 5.19 tC/ha

Soil carbon sequestrated at a 20 year perspective:

5.19 tC ha^{-1}/20 year = 259.5 kgC $ha^{-1}yr^{-1}$

CO_2 reduction: 259.5 × 44 / 12 = 951.5 kgCO_2 $ha^{-1}yr^{-1}$

Per functional unit, avoided CO_2 is - 11.75 kgCO_2/t cane.

3.2.2 Life cycle impact assessment extended with health effects of $PM_{2.5}$

Life cycle impact assessment (LCIA) was carried out for ReCiPe mid-point impacts (climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, and fossil depletion) and end-point damage categories (human health, ecosystem and resources) (Goedkoop et al. 2013). Hierarchist perspective was adopted since it is the default one in ReCiPe and follows the most common policy principles with regards to time-frame and other issues. ReCiPe method was chosen among other LCIA methods due to its feature of consistent use of midpoints and endpoints in the same environmental mechanism (ILCD 2011), and because it is a widely used method. Impact categories were selected considering the importance of environmental issues for sugarcane production. Water depletion was not addressed because water needs of sugarcane cultivation in the centre-south of Brazil mostly relied on rainfall with no rainwater storage, and there are no expected differences on water needs between manual and mechanical product systems. To characterize the health effects of fine particulate matter in LCIA, models based on Humbert et al. (2011) and Gronlund et al. (2015) were applied. Two groups of characterization factors for $PM_{2.5}$ were calculated for Brazil, as described below.

We have first calculated intake fractions for Latin America based on methods implemented in Humbert et al. (2011). Secondly, we calculated two groups of effect factors considering different burdens of disease: the first group adopted the dose-response factors estimated by Gronlund et al. (2015) and the severity factors calculated based on Global Burden of Disease for Brazil (WHO 2004); while the second group followed Humbert (2010).We chose these two groups of effect factors because they represent the latest methods of exposure-response assessment in the literature; meanwhile, it is worth noting how the magnitude of effect factors vary depending on the burdens of disease considered. Finally, the intake fractions were multiplied with the two groups of effect factors respectively to generate the characterization factors.

Table 3.1 Intake fraction (iF) of primary $PM_{2.5}$ and secondary $PM_{2.5}$ (ppm - parts per million, representing mg PM inhaled per kg PM emitted) for Latin America calculated based on the recommended values and methods by Humbert et al. (2011)

Pollutant and stack height	Urban	Rural	Remote	Population-weighted average
Primary $PM_{2.5}$				
high-stack	13	0.48	0.1	5.6
low-stack	17	0.58	0.1	7.3
ground-level	49	1.1	0.1	20.7
emission-weighted average	29	0.75	0.1	12
Secondary $PM_{2.5}$				
SO_2	0.99	0.79	0.11	0.86
NO_x	0.2	0.17	0.02	0.18
NH_3	1.7	1.7	0.23	1.7

We calculated intake fractions of primary and secondary $PM_{2.5}$ for Latin America (Table 3.1) based on the emission-weighted average iF recommended for Latin America and the methods to differentiate the intake fractions based on emission heights and population densities from Humbert et al. (2011). Equations and values used for calculation can be found in Appendix 3. For secondary $PM_{2.5}$, stack height has limited importance in affecting iF. Distance from the affected population to emission locations is a critical factor influencing the magnitude of the health effects of $PM_{2.5.}$ When distance to the affected population is unknown, population-weighted iF can be employed, which is a weighted sum of iF for urban, rural and remote with its corresponding fraction of population in the region. In Brazil, the distances between sugarcane fields and populated areas varied significantly from one place to another. For instance, according to CANASAT, a project developed by National Institute for Space Research (INPE) aiming at mapping the sugarcane cultivation and harvest activities in São Paulo State, some municipalities such as Ribeirão Preto are closely surrounded by sugarcane plantation, while other municipalities are hundreds of kilometers away. Due to this reason, CFs calculated using population-weighted iF was applied to characterize the health effects.

Table 3.2 Parameters and effect factors applied to calculate CFs considering cardiopulmonary diseases and lung cancer

	Cardiopulmonary				Lung cancer	Total
	IHD[a]	Stroke	COPD[b]	Total death	LC[c]	
Death[e] (thousands)	140.8	129.2	50.5	320.5	22.3	342.8
DALY[d, f] (thousands)	1427	1279	796	3502	223	3725
Severity factor (DALY/death)	10.1	9.9	15.8	10.9	10	10.9
Exposure-response factor[g] (death/kg $PM_{2.5}$ inhaled)				3.9	0.35	4.2
Effect factor (DALY/kg $PM_{2.5}$ inhaled)				42.6	3.5	45.6

[a]: Ischemic heart disease; [b]: Chronic obstructive pulmonary disease; [c]: Lung cancer; [d]: Disability adjusted life years; [e,f]: Data from WHO Global Burden of Disease 2004 statistics; [g]: (Gronlund et al. 2015)

Regarding effect factors, the first group (Table 3.2) was calculated for Brazil based on Gronlund et al. (2013). Mortalities due to cardiopulmonary diseases and lung cancer were considered, and the total effect factor is 45.6 DALY/kg $PM_{2.5}$ inhaled. Data of Global Burden of Disease for Brazil were collected and implemented. Ischemic heart disease, cerebrovascular disease and chronic obstructive pulmonary disease were considered under cardiopulmonary disease (GBD disease code: W107, W108, W112 respectively). For lung cancer, the analysis took into account trachea, bronchus and lung cancer (GBD disease code: W067). The second set of effect factors were calculated based on the values proposed in Humbert (2010). A wider range of diseases were considered including chronic mortality, acute respiratory and cardiovascular morbidity, chronic bronchitis for children and adults, asthma attacks for children and adults and restricted activity days. Assuming $PM_{2.5}$ is 1.67 times as toxic as PM_{10} (European Commission 2005), the effect factor for $PM_{2.5}$ was calculated to be 137 DALY/kg $PM_{2.5}$ inhaled. For clarification, CF calculated with effect factor considering cardiovascular diseases and lung cancer is referred as Cardio.& Lung, and CF calculated with effect factor based on Humber (2010) is referred as Humbert.

Two groups of CFs of $PM_{2.5}$ calculated are presented in Table 3.3. Inventory of primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors of all the unit processes were then aggregated and multiplied with the relevant CFs according to different sources and emission heights. Heights of $PM_{2.5}$ emissions from production of raw materials such as fertilizers, pesticides and diesel were unknown, thus emission-weighted CFs were applied. $PM_{2.5}$ emissions from transportation and field emissions from fertilizer use and residue burning are considered to be at the ground level, and CFs at the ground level were used. A sensitivity analysis was conducted to discuss the influence of distance between emission sources and population (urban, rural and remote) on health impacts.

Table 3.3 Two groups of CFs (DALY/kg $PM_{2.5}$ or $PM_{2.5}$ precursors emitted) of $PM_{2.5}$

Pollutant and stack height	CFs considering cardiopulmonary diseases and lung cancer (Cardio.& Lung)				CFs considering a wider range of diseases (Humbert)			
	Urban	Rural	Remote	Population-weighted	Urban	Rural	Remote	Population-weighted
Primary $PM_{2.5}$								
High stack	5.93E-04	2.19E-05	4.56E-06	2.56E-04	1.78E-03	6.58E-05	1.37E-05	7.67E-04
Low stack	7.76E-04	2.65E-05	4.56E-06	3.33E-04	2.33E-03	7.95E-05	1.37E-05	1.00E-03
Ground level	2.24E-03	5.02E-05	4.56E-06	9.45E-04	6.71E-03	1.51E-04	1.37E-05	2.84E-03
Emission-weighted average	1.32E-03	3.42E-05	4.56E-06	5.48E-04	3.97E-03	1.03E-04	1.37E-05	1.64E-03
Secondary $PM_{2.5}$								
SO_2	4.52E-05	3.61E-05	5.02E-06	3.92E-05	1.36E-04	1.08E-04	1.51E-05	1.18E-04
NO_x	9.13E-06	7.76E-06	9.13E-07	8.21E-06	2.74E-05	2.33E-05	2.74E-06	2.47E-05
NH_3	7.76E-05	7.76E-05	1.05E-05	7.76E-05	2.33E-04	2.33E-04	3.15E-05	2.33E-04

3.3 Results and discussion

3.3.1 Mid-point impacts

Table 3.4 showed LCA results at the mid-point level and relative difference (Δ) between two systems. Mechanical harvesting had much lower impacts for photochemical oxidant formation (Δ = - 88%) and particulate matter formation (Δ = - 61%). Manual harvesting presented slightly better performances on fossil depletion, ozone depletion and terrestrial acidification (Δ = 17% to Δ = 19%). Differences of two product systems on freshwater eutrophication and human toxicity were very small (Δ <5%). The contributions for impacts from different processes were detailed in Fig. 3.2, and results for each mid-point impact category were described in the following paragraphs.

Table 3.4 Mid-point Life Cycle Impact Assessment (per tonne of sugarcane)

Impact category	Unit	Manual harvesting product system (A)	Mechanical harvesting product system (B)	Relative Difference (Δ = (B-A)/A)
Fossil depletion	kg oil eq	6.66	7.80	+ 17.1%
Ozone depletion	kg CFC-11 eq	1.47E-06	1.75E-06	+ 19%
Terrestrial acidification	kg SO_2 eq	1.34	1.57	+ 17.2%
Freshwater eutrophication	kg P eq	1.90E-03	1.99E-03	+ 4.7%
Human toxicity	kg 1,4-DB eq	4.22	4.38	+ 3.8%
Photochemical oxidant formation	kg NMVOC	6.83E-01	8.05E-02	- 88.2%
Particulate matter formation	kg PM_{10} eq	5.76E-01	2.24E-01	- 61.1%

Fossil depletion: Mechanical harvesting lead to 17% higher impacts on fossil depletion than manual harvesting. Diesel use in the sugarcane fields was related with 25% and 28% of the impacts in the manual and mechanical harvesting systems respectively, followed by diesel production and fertilizer production as main contributors on this impact category. Among fertilizer production, nitrogen fertilizer was responsible for more than 75% of the impacts resulting from fertilizer production. The worse performance of mechanical harvesting in this category is mainly due to the higher use of fertilizer and diesel compared to manual harvesting. Higher use of potassium in mechanical harvesting system is related to the lower recycling rate of this nutrient when sugarcane straw is not burnt. Similarly, higher use of nitrogen is explained by the need of additional amount to make up for the decreased efficiency of this fertilizer when applied over the straw mulch.

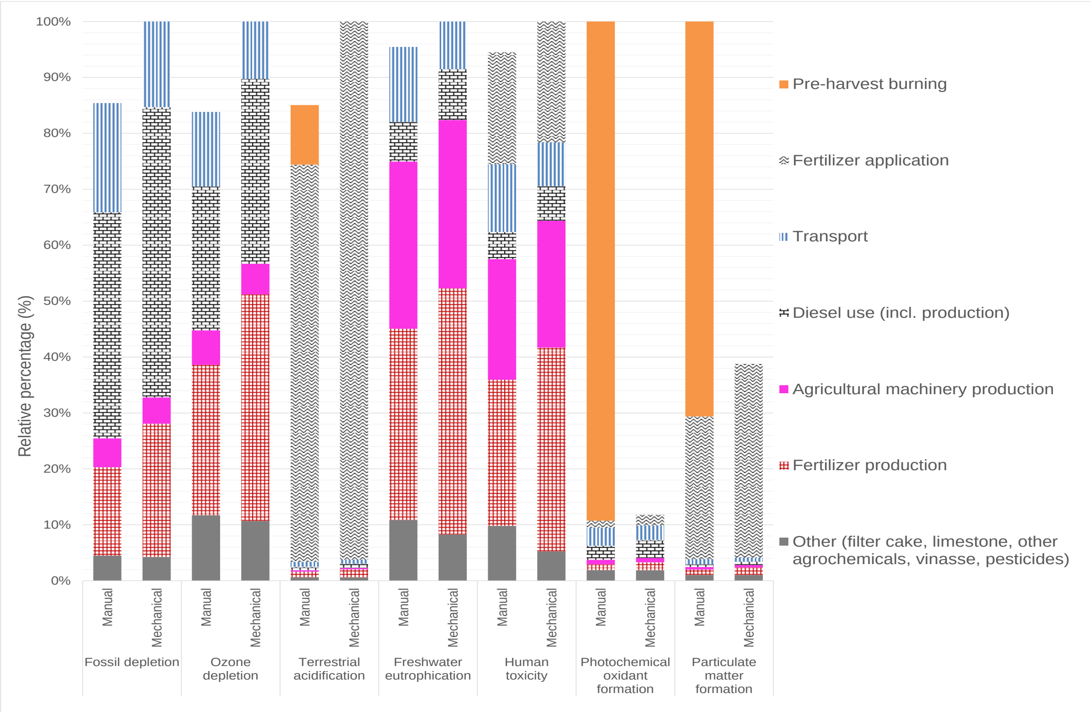


Fig. 3.2 Relative LCA results at the mid-point level

Ozone depletion: Mechanical harvesting system had 19% higher impacts due to higher inputs of diesel and fertilizer. Production of nitrogen fertilizer was the largest contributor for both systems, accounting for 34% of the impacts for the mechanical harvesting system, and 25% for manual harvesting.

Terrestrial acidification: Manual harvesting had 17% lower impacts on terrestrial acidification than mechanical harvesting. Fertilizer field emissions contributed the most mainly due to emissions of ammonia, accounting for 83% and 96% of the impacts respectively for the manual and mechanical harvesting systems. For the manual harvesting system, sugarcane residue burning was another main contributor on this category, presenting 13% of impacts. It is worth mentioning that ammonia emitted from fertilizer use was calculated based on the IPCC method assuming the same soil conditions and NH_3 emission factor for both systems, which is a simplification that we acknowledge may be revised with future data and models.

However, it is important to mention that a higher amount of nitrogen fertilizer (and consequently higher emissions from NH_3 volatilization) is used in mechanized harvesting systems for compensating higher nitrogen volatilization losses due to fertilization in the presence of sugarcane straw on the soil.

Freshwater eutrophication: The difference between two systems was less pronounced on this category. Production of nitrogen and phosphate fertilizers accounted for approximately one third of the impacts; while production of capital goods including agricultural machinery, tractors and harvesters represented another one third.

Human toxicity: Difference of two product systems on this impact category was unclear. For both harvesting systems, the processes that presented the highest impacts for human toxicity were fertilizer production and field application. Production of capital goods was another major source of impacts for this category, representing 22-23% of the impacts for both systems.

Photochemical oxidant formation: Manual harvesting had much higher impacts than mechanical harvesting due to emissions of carbon monoxide and nitrogen oxides from pre-harvest burning. For mechanical harvesting, around 46% of the impacts occurred in the sugarcane field from fertilizer use, diesel burning, and vinasse application.

Particulate matter formation: Mechanical harvesting appeared to have 61% less impacts, while 90% of the impacts came from the field emissions of ammonia due to fertilizer use. However, fertilizer use only contributed to 25% of the impact in the manual harvesting system. $PM_{2.5}$ emissions from pre-harvest burning were the largest source, accounting for 70% of the impacts.

3.3.1.1 Climate change considering two SOC scenarios

Figure 3.3 compared climate change impacts of manual and mechanical harvesting systems considering the two scenarios of soil carbon sequestration (SOC) previously mentioned: (i) soil carbon saturated (no SOC increase); and (ii) SOC saturated at a time span of 20 years. Manual harvesting resulted in 38.3 $kgCO_{2eq}$/tonne sugarcane. Changing the harvesting operation to a mechanized system led to an increase of 6% on climate change impacts when not considering the contribution of SOC, whilst a decrease of nearly 25% is observed when considering SOC.

Fertilizer application was the largest contributor on climate change in all the scenarios, accounting for approximately 55% of the total impact in the mechanical harvesting system without SOC, and 40% in the manual harvesting system. Diesel burning in agricultural operations was another important contributor to climate change, representing 12% and 10% of the total for mechanical (no SOC) and manual harvesting systems, respectively. GHG emissions from pre-harvest burning corresponded to 18% of the total GHG emissions of the manual harvesting system. In both scenarios, more than 70% of the impacts occurred in the sugarcane field, mainly due to the emissions of N_2O and CO_2.

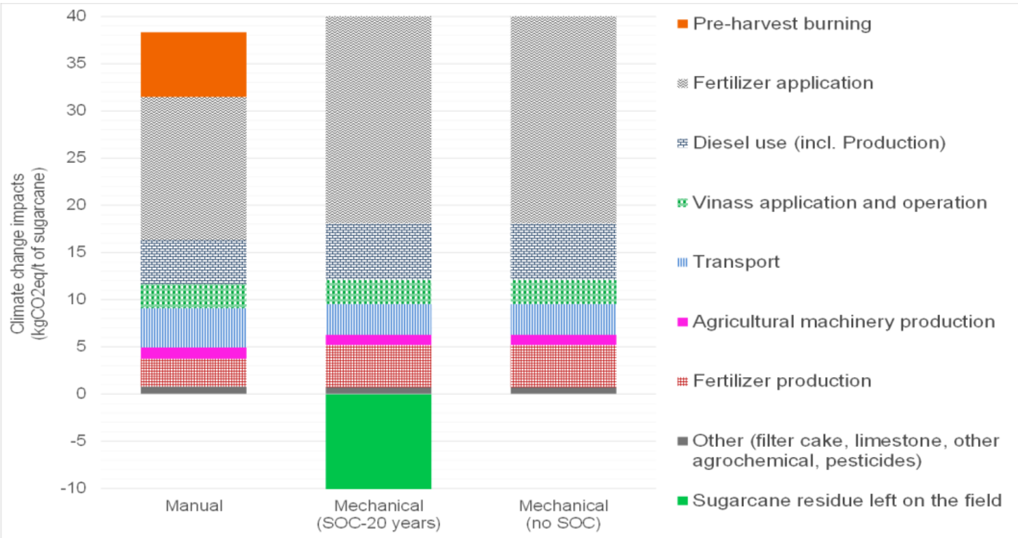


Fig. 3.3 Impacts on climate change considering different SOC sequestration scenario

3.3.2 End-point impacts

Environmental impacts at damage (end-point) level were presented in Fig 3.4. Mechanical harvesting had lower impacts (Δ = -43% to Δ = -51%) on human health for both SOC scenarios compared to manual harvesting. This is mainly due to the elimination of pre-harvest burning practices. On the other hand, because of higher fertilizer and diesel use, mechanical harvesting had higher impacts on resources increasing by 17%. However, as pointed out in the LCIA literature (e.g. ILCD 2011), there is important uncertainty associated with end-point results, which should be taken into consideration when discussing LCA results. Regarding the impacts on ecosystems, the difference between manual and mechanical harvesting is unclear, although when considering SOC increase, it may suggest a slightly lower impact of mechanical harvesting system.

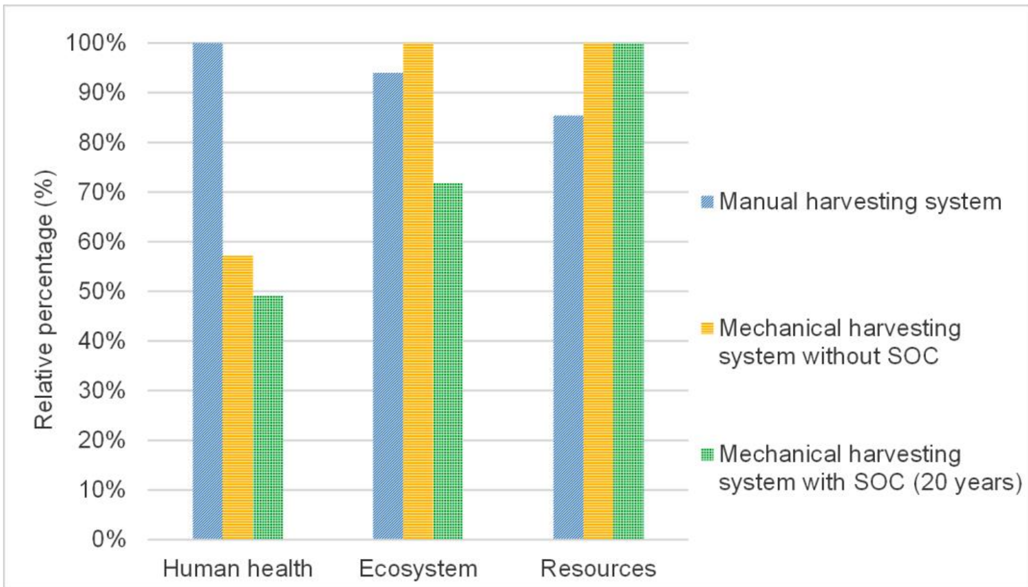


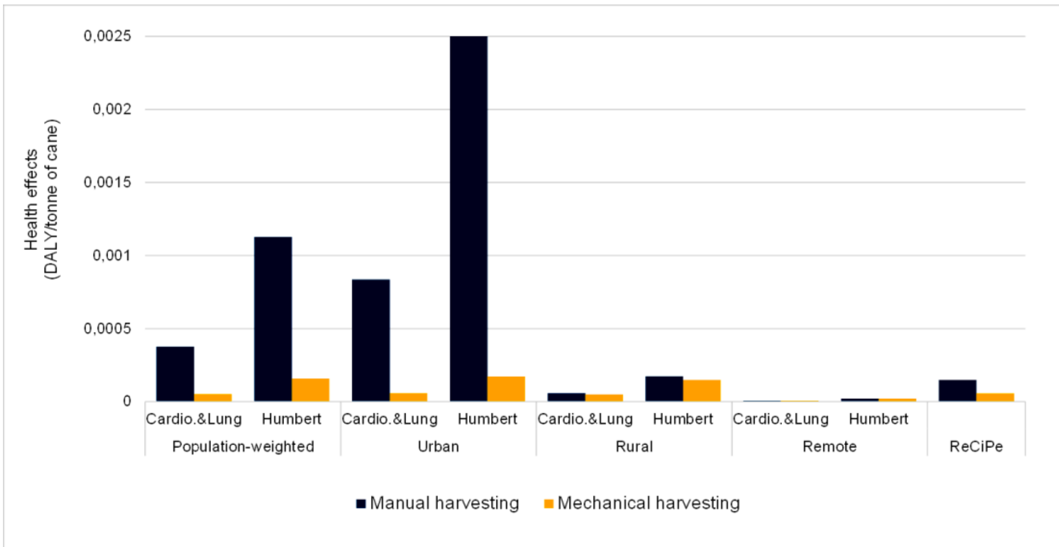
Fig. 3.4 LCA results at the end-point level

3.3.3 Health effects of $PM_{2.5}$

Fig 3.5 compares the health effects of $PM_{2.5}$ of manual and mechanical harvesting, calculated with population-weighted CFs together with a sensitivity analysis for different population densities (urban, rural and remote) and applying ReCiPe. The results show that population density is a key factor when assessing the health effects of $PM_{2.5}$. Health effects for manual harvesting in urban and population-weighted conditions were much larger than for rural and remote conditions. Mechanical harvesting showed lower health impacts than manual harvesting in all conditions, but important differences were only observed when applying urban and population-weighted CFs. Comparing our results with those calculated using ReCiPe, it shows ReCiPe underestimates health effects for population-weighted condition (1.5-6.6 timers lower), whilst showing comparable results with rural condition.

With regards to the two groups of CFs considering different burdens of disease, when applying population-weighted CFs, producing one tonne of sugarcane in manual harvesting resulted in a loss of 3.7×10^{-4} DALY and 1.1×10^{-3} DALY respectively due to the different burdens of disease considered in the CFs. When a wider range of diseases was considered, health effects were two times higher than when only considering cardiovascular diseases and lung cancer. This difference highlighted the needs for more transparency and consensus regarding effect factors when characterizing health effects of $PM_{2.5}$.

Health effects of mechanical harvesting do not vary with population density as much as manual harvesting, because more than 90% of the health effects are due to secondary $PM_{2.5}$ from NH_3 associated with fertilizer field application; while for manual harvesting, primary $PM_{2.5}$ contributed the most to health effects. The CFs of NH_3 calculated in this study were much smaller than the CFs of primary $PM_{2.5}$, and fairly comparable with CF of NH_3 in ReCiPe. The CFs of primary $PM_{2.5}$ calculated were higher than the one in ReCiPe. When applying population-weighted CFs, manual harvesting presented six times higher health effects of $PM_{2.5}$ than mechanical harvesting regardless the effect factors chosen. To put it in perspective, from 2005 to 2014 (data for the harvest season of 2006/2007 were missing) and considering population-weighted CFs, if the sugarcane harvested mechanically without pre-harvest burning were harvested manually with pre-harvest burning, it would have resulted in a potential loss of 479 000 - 1 440 000 DALYs. Considering average life expectancy of Brazil in 2014, this is equivalent to 6 438 - 19 355 life losses.



*Cardio.&Lung stands for health effects considering cardiopulmonary diseases and lung cancer
*Humbert stands for health effects considering a wider range of diseases based on Humbert et al. (2010)

Fig. 3.5 Health effects associated with $PM_{2.5}$ emissions considering various population densities

3.3.4 Comparison with previous studies and limitations

Macedo et al. (2008) found higher energy consumption with increasing percentage of mechanical harvesting, and this is in consensus with our findings on fossil depletion. Galdos et al. (2013) used generic characterization factors from Ecoindicator 99 for particulate matter to assess the health impacts, without differentiating emission sources, specifying burdens of disease and including effects of secondary $PM_{2.5}$ from precursor SO_2. Chagas et al. (2016) compared six sugarcane bioethanol production systems and concluded similar findings of increased impacts on eutrophication, ozone depletion and human toxicity, and lower impacts on photochemical oxidant formation comparing mechanical to manual harvesting system. However, health effects and SOC scenarios were not evaluated, and higher acidification and global warming impacts from manual harvesting were found, due to different choices on emission factors of sugarcane burning. Factors for generic agricultural residues burning from GREET (2009) were adopted, while in this study we employed emission factors for sugarcane burning based on laboratory experiments (França et al. 2012). Chagas et al. (2016) carried out an uncertainty analysis, based on a similar inventory (also from CTBE database), to assess how parameter uncertainty affects economic and environmental impacts, and reported relatively low standard deviations (SD) of ethanol GHG (SD from 20 to 23 g CO_2 eq/L for a mean value of 518 to 478 gCO_2 eq/L). Thus, this type of parameter uncertainty is not expected to affect the ranking of product systems in this study. Regarding the limitations, characterization of health effects of $PM_{2.5}$ was based on exposure-response factors from Gronlund et al. (2015) calculated for the USA, and intake fractions were calculated for the scale of Latin America, due to lack of specific data for Brazil.

3.4 Concluding remarks

This chapter compared the life cycle environmental and health impacts of sugarcane produced with manual and mechanical harvesting in Brazil. The results showed that the transition from manual to mechanical sugarcane harvesting systems in Brazil clearly reduces impacts on photochemical oxidant formation and particulate matter formation, mainly due to the elimination of pre-harvest burning practices. However, mechanical harvesting may increase the impacts on fossil depletion, ozone depletion, and terrestrial acidification resulting from higher use of fertilizer and diesel. Differences of impacts on freshwater eutrophication and human toxicity were not significant. In terms of climate change, the difference between two systems depended on the soil organic carbon sequestration scenario considered. When considering soil carbon increase at a 20-year time span, reduction of CO_2 emissions offset the contribution from higher use of diesel and fertilizers, and mechanical harvesting showed lower impacts on climate change. However, when not considering the contribution of soil carbon sequestration, the difference between manual and mechanical harvesting systems was small. At the end-point level, manual harvesting presented higher impacts on human health, but lower impacts on resources. The health effects of $PM_{2.5}$ vary considerably with population density. Changing from manual to mechanical harvesting close to urban areas leads to a drastic reduction of impacts, while for rural and remote areas, reductions are less important. When considering average population density, health effects of $PM_{2.5}$ of manual harvesting were approximately six times higher than mechanical harvesting. Health effects of $PM_{2.5}$ calculated with ReCiPe are much lower and may underestimate the effects of primary $PM_{2.5}$ emissions.

CHAPTER 4 SCREENING SOCIAL HOTSPOTS

4.1 Introduction

Assessments of social impacts of sugarcane production in Brazil have been mainly focusing on issues related to workers, without considering other relevant stakeholders. In addition, only one study (Souza et al. 2016) was identified considering the full life cycle of sugarcane, whereas only potential impacts within the Brazilian economy were accounted for. A social life cycle assessment of sugarcane production in Brazil can evaluate social impacts of sugarcane supply chain in Brazil considering all relevant stakeholders and covering the full life cycle. However, a typical product system can contain over a thousand unit processes; thus it is not practical to collect site-specific data at every organization along a supply chain, especially considering the increasing globalization of supply chains (Benoit-Norris et al. 2012). Application of a database can ease the burdens of data collection in SLCA significantly by revealing where in the supply chain attention should be focused.

Social Hotspots Database (SHDB) is one of the first databases in SLCA which can be utilized as a screening or prioritization tool. SHDB models the product life cycle based on global economic input-output data, and it can identify social risks or opportunities along the supply chains and the unit processes (i.e. country-specific-sectors in SHDB) where site-specific data need to be collected. Data in SHDB are collected at country-sector level; however, due to the aggregation of the data, SHDB is not suitable to differentiate the social impacts of homogeneous sectors (for instance, chemicals, plastics and rubber are aggregated into the same sector in SHDB) or different technologies in the same sector. Once the social hotspots are identified by using tools like SHDB, a systematic analysis of the existing publications related to the social impacts of key country-sector(s) can improve the quality of the results of a screening SLCA study by identifying the most relevant social themes, and both negative and positive impacts.

This chapter identifies social hotspots of sugarcane production in Brazil applying a novel approach of integrating SHDB approach and a systematic analysis of relevant literature. The results of this chapter can provide information for policy-making in Brazil aiming at improving social sustainability of sugarcane sector. The approach developed in this chapter can improve the quality of the results of future screening SLCA studies. Materials and methods are discussed in Section 4.2; while results are presented in Section 4.3, and conclusions are drawn in Section 4.4.

4.2 Materials and methods

The Social Hotspots Database (SHDB), with its in-built input-output model, was used to carry out a screening SLCA of cradle-to-gate production of sugarcane in Brazil, to identify the associated social hotspots. Overridingly, the social impacts arise within the sector itself. The dominant country and sector identified in this way, i.e. sugarcane sector in Brazil, was then examined in more depth by applying systematic content analysis to the relevant literature, to explore the effectiveness of using content analysis to enhance the results obtained from a generic database.

4.2.1 Characterization of social impacts in Social Hotspots Database (SHDB)

The Social Hotspots Database (SHDB) comprises three components: social theme tables, input-output model and worker-hour model (Benoit-Norris et al. 2012a&b; Benoit-Norris et al. 2013). As shown in Table 4.1, SHDB groups social indicators into five categories, namely Labour rights and decent work, Health and safety, Human rights, Governance, and Community infrastructure. Each category covers a range of relevant social themes, with one or more indicators to measure the risk level of each theme for a country-sector, including 22 themes and 124 indicators in total. The assessment framework of SHDB for a country-sector from impact category to inventory indicator is shown in Fig. 4.1. Four risk levels are defined (low, medium, high, and very high) for each indicator of a country-sector. For each theme, the risk level is defined with reference to the range of values reported for the countries included in the database. For instance, for the poverty indicator, percentage of people living under 2$/day, the characterization rule of <2%=low risk, 2-

10%=medium risk, 10-15%=high risk, >50%=very high risk is used. However, the basis for assigning the risk levels is not transparent. In the absence of further information, the same risk levels have been used in this article as in SHDB. For some indicators, such as forced labour, the risk level is determined by whether there is evidence of forced labour and the number of sources of that evidence. This approach has been developed further in this work by using systematic content analysis, as set out in Section 4.2.2.

The SHDB uses a global input-output model derived from the Global Trade Analysis Project (GTAP) (2017) to model product supply chains, covering economic data of 227 countries and 57 sectors. The economic data for a country-sector is then translated into its labour intensity through a worker-hour model. The total worker-hours of a country-sector are calculated by dividing the total payment of wages to workers (using data from the GTAP model) with wage rate data for that country-sector. As worker-hours represent the level of labour involvement of a country-sector in a supply chain, worker-hours can also be used to set cut-off criteria to establish the system boundary that includes the most relevant country-sectors for a product system (Ramirez et al. 2016). An initial analysis using SHDB showed that more than a thousand country-sectors in total are related to sugarcane production in Brazil. An initial cut-off criterion was defined to include only country-sectors contributing more than 1% of the total worker-hours associated with sugarcane life cycle in Brazil.

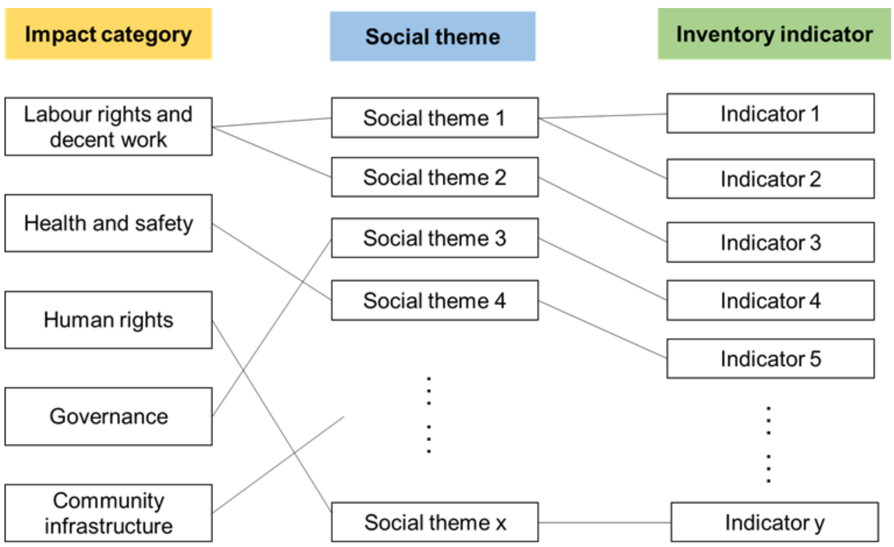


Fig. 4.1 Assessment framework of Social Hotspots Database for a country-sector

Table 4.1 Impact categories and related social themes included in Social Hotspots Database

Impact categories	Social themes
Labour rights and decent work	- Child labour - Forced labour - Excessive working time - Wage assessment - Poverty - Migrant labour - Freedom of association - Unemployment - Labour laws
Health and safety	- Injuries and fatalities - Toxics and hazards
Human rights	- Indigenous rights - High conflicts - Gender equity - Human health issues
Governance	- Legal systems - Corruptions
Community infrastructure	- Hospital beds - Drinking water - Sanitation - Children out of school - Smallholder vs. commercial farms

In the SHDB approach (Benoit-Norris et al. 2012a), the scores for the different social themes within each social category are aggregated into a Social Hotspots Index (SHI), defined by Equation 4.1. The risk levels (R) are translated into indices using the values low risk = 0, medium risk = 1, high risk = 2, and very high risk = 3. Equal weights have been assigned to the social themes in several SLCA case studies (Garrido et al. 2016), and this approach was adopted in this study due to the lack of information on value choices of decision makers. SHI is unit-less and its value varies from 0 to 1. Regardless of the number of indicators in an impact category, the larger is the value of SHI, the higher are the potential impacts in that category for a country-sector.

$$\mathrm{SHIcat} = \sum_{T=1}^{n}(\mathrm{Ravg} \times \mathrm{WT}) / \sum_{T=1}^{n}(\mathrm{Rmax} \times \mathrm{WT}) \qquad (4.1)$$

SHIcat: Social Hotspots Index for a category (e.g. labour rights, governance, etc.)
T: Social themes (e.g. child labour, freedom of association rights, etc.)
n: Number of themes within a category
Ravg: Average risk across the theme
Rmax: Maximum risk for a theme
WT: Weight assigned to the theme

In this chapter, Impact Scores (IS) were also developed to aggregate the social impacts within each category for each of the country-sectors included in the product system. As shown in Equation 4.2, a weighted sum approach was employed, considering both the overall risk levels and the contribution to labour intensity of a country-sector. Impact Score is a unitless index varying from 0 to 1, with higher values representing higher potential impacts in the category.

$$\mathrm{IS} = \sum_{\mathrm{m}=1}^{\mathrm{K}} \mathrm{SHIcat} \times \mathrm{WH\%} \qquad (4.2)$$

IS: Impact score; overall impacts on an impact category considering all the country-sectors
m: a country-sector
K: Number of country-sectors included in the system boundary
WH%: percentage of worker hours out of total worker hours for each country-sector

4.2.2 Content analysis

To enhance the results of the screening SLCA using a generic database, content analysis was applied to identify the social impacts of sugarcane production in Brazil by analyzing relevant publications. Content analysis refers to a family of approaches or techniques for studying and/or retrieving meaningful information from text(s) in a systematic manner based on explicit rules of coding (Stemler 2001; Zhang & Wildemuth 2009). The development of content analysis in the scientific arena can be dated to 1920s/30s, with an initial emphasis on quantitative textual analysis such as counting explicit text elements. However, this quantitative approach has been criticized for oversimplified or distorted quantification due to, for instance, inability to consider the cultural components of the context, multiple meanings of words, and multiple expressions for the same meaning. Qualitative content analysis has been developed to overcome these concerns: beyond merely counting words, it emphasizes an integrated view of texts and their specific contexts, and enables subjective but scientific and reproducible inferences to be drawn (Mayring 2014; Zhang & Wildemuth 2009). Quantitative and qualitative content analysis can be combined, and this combined approach has been applied here: frequency analysis was conducted and reported, and a careful hand-coding of the content of the literature was carried out based on the set of categories determined in this work. The process of content analysis was conducted following the steps described below.

Step 1: Formulation of issue or problem. This analysis addresses the objective of the work by determining which themes are most documented in recent publications relevant to the social impacts of sugarcane production in Brazil.

Step 2: Selection of the material to be analyzed. Web-based research was used to identify relevant documents by searching Web of Science, Google and Google scholar using the keywords *"social impacts", "social sustainability", "corporate social responsibility", "sugarcane"*, and *"Brazil"*. Documents published in English between 2000 and 2016 were included in the search. In total, 38 articles were considered relevant for content analysis: 21 journal articles, 7 grey papers and reports, 7 conference presentations, 2 NGO reports and 1 book chapter.

Step 3: Establishment of a set of categories. The set of categories included in a content analysis can be generated inductively (i.e. categories emerge from the material samples) or deductively (i.e. categories are predefined based on social theories or social findings). The set of categories used in this work, shown in Table 4.2, was established deductively based on the social themes recommended in the UNEP/SETAC Guidelines.

Step 4: Definition of categories and analysis units. The social themes making up each category were defined in accordance with the approach adopted in SHDB (Benoit-Norris et al. 2013; UNEP/SETAC 2013). Social themes were used as the coding units for the content analysis. This approach emphasizes the expression of an idea (e.g. the concept of fair salary) rather than the occurrence of the exact words (e.g. “fair salary” or its synonyms).

Step 5: *Coding.* The material samples were hand-coded in the software NVivo according to the established set of categories (NVivo 2017).

Step 6: Analyzing the coded data. The coding data were analyzed to identify the social themes referred to most frequently in the samples. The frequencies of the social themes within each category were aggregated to give the total frequencies of the categories.

Step 7: Reporting on the findings. Key findings on each social theme were summarized and reported in a descriptive paragraph with identification of key references; these results are discussed in Section 4.3.2.

4.2.3 Defining social hotspots

There is a lack of consensus in the SLCA community on the methodology of defining social hotspots. Following an approach adopted in published studies (Ekener-Petersen et al. 2014; Zamani et al. 2016), the social themes giving rise to the greatest concerns, i.e. the social hotspots indicated by the SHDB, were determined by summing the numbers of indicators with high and very high risks. A similar approach was adopted for the content analysis: the social impact themes arising most frequently in the coded samples were considered the social hotspots. It should be noted that this simple approach of counting indicators or themes may bias the identification of hotspots towards categories with a higher number of indicators. The Social Hotspots Index (SHI), introduced in Section 4.2.1, is defined to avoid this bias.

Table 4.2 Categories adopted in content analysis

Impact categories	Coding themes
Labour rights and decent work	- Child labour - Forced labour - Working hours - Fair Salary - Freedom of association and collective bargaining - Social benefits and social security - Delocalization and migration - Local employment - Contribution to economic development
Health and safety	- Occupational health and safety - Safe and healthy living conditions
Human rights	- Equal opportunities and discrimination - Cultural heritage* - Respect of indigenous rights - Secure living conditions - Respect of intellectual property rights*
Governance	- Public commitments to sustainability issues* - Prevention and mitigation of armed conflicts* - Technology development* - Corruption - Promoting social responsibility*
Community infrastructure	- Access to material resources - Access to immaterial resources - Community engagement* - Fair competition - Supplier relationships*

*Social themes additional to those in Social Hotspots Database, based on recommendations from the UNEP/SETAC Guidelines (UNEP/SETAC 2009).

4.3 Results

4.3.1 Life cycle social impacts of sugarcane production in Brazil and social hotspots identified from SHDB

Table 4.3 shows the country-sectors remaining after applying the cut-off criterion based on contribution to total worker-hours associated with the sugarcane life cycle (see Section 4.2.1). The two sectors contributing least are both concerned with animal husbandry in Brazil: Bovine cattle, sheep and goats, & horses; and Animal products. From the information in SHDB, 1 USD of Brazilian sugarcane output is related with the inputs of 0.017 USD of Animal products and 0.011 USD of Bovine cattle, sheep and goats, & horses in Brazil. It is not clear what connects these two sectors with the Brazilian sugarcane sector: SHDB uses an economic input-output model so that the connections between sectors are not obvious, as they are in process-based SLCA. The connection may be indirect, via first-tier suppliers to the sugarcane sector. In view of the lack of transparency over the relationship with these two sectors and their relatively small contributions to the total worker-hours, the cut-off criterion was revised to 1.5%. This leaves only the Brazilian Commerce and Business service sectors as relevant to the Brazilian sugarcane sector.

Table 4.3 Country-sectors included after applying cut-off criterion of 1% and their shares of worker hours

Country-Specific-Sector	Share out of total worker hours (%)
Sugarcane, sugar beet (Brazil)	85%
Commerce (Brazil)	2.2%
Business services (Brazil)	1.9%
Bovine cattle, sheep and goats, horses (Brazil)	1.2%
Animal products (Brazil)	1.2%

Table 4.4 presents the values of the Social Hotspots Index (SHI) for the five impact categories for these three connected sectors. Health and safety and labour rights and decent work have higher potential social impacts compared with the other impact categories. Within each impact category the value of the SHI is similar across the three sectors, because all the sectors are located in Brazil and the SHDB uses social data at the country level when data at the sector level are not available (Benoit-Norris et al. 2013): close examination of the SHDB handbook revealed that, of 124 indicators, only 18 are based on data at the sector level.

Table 4.4 Social Hotspots Index (SHI) of country-sectors in each impact category

	Community Infrastructure	Governance	Health and safety	Human rights	Labour Rights and Decent Work
Sugar cane, sugar beet (Brazil)	0.36	0.33	0.50	0.40	0.45
Commerce (Brazil)	0.39	0.33	0.50	0.39	0.40
Business services (Brazil)	0.39	0.33	0.50	0.34	0.29

Fig. 4.2 shows the Impact Scores of the sugarcane life cycle, aggregated across the country-sectors considering risk levels and contribution to labour intensity according to Equation 4.2. The sugarcane sector in Brazil is the dominant contributor to social impacts due to its dominance in labour intensity.

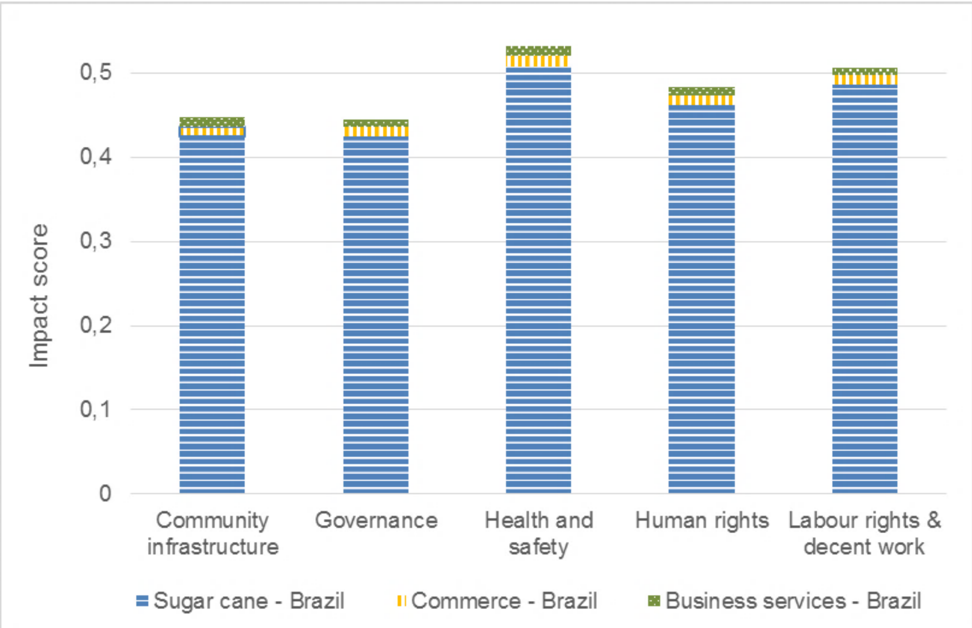


Fig. 4.2 Aggregated Impact Scores of three country-sectors by impact category

Using the approach to determining social hotspots described in Section 4.2.3, Table 4.5 shows the indicators with high and very high risks in the sugarcane sector in Brazil, whilst Table 4.6 ranks them to show the principal Social Hotspots. In total, 37 indicators are identified with high or very high risks related to 15 social themes. Occupational toxics & hazards and human health due to communicable diseases are the social themes with the greatest concerns, followed by high conflict zones and migrant workers. Among the 15 social hotspots identified by SHDB, nine are also identified by content analysis, as discussed in the next section.

Table 4.5 Indicators with high and very high risk levels in sugarcane sector in Brazil identified in SHDB

Social theme	Impact Category	Risk level	Indicators
Access to Hospital Beds	Community infrastructure	High risk	- Risk that there are too few hospital beds to support population
Smallholder v. Commercial Farms	Community infrastructure	High risk	- Characterization of large land holdings
Legal system	Governance	Very high risk	- Characterization of CIRI Independent Judiciary
		High risk	- Characterization of BTI Rule of Law
Occupational Injuries & Deaths	Health and safety	Very high risk	- Risk of fatal injury by sector
		High risk	- Risk of non-fatal injuries by sector
Occupational Toxics & Hazards	Health and safety	High risk	- Risk of loss of life by airborne particulates in occupation - Risk of loss of life years by asthma due to airborne particulates in occupation - Risk of loss of life years by chronic obstructive pulmonary disease due to airborne particulates in occupation - Risk of loss of life years by mesothelioma due to occupation - Risk of loss of life years by silicosis due to airborne particulates in occupation
Human Health (Communicable Diseases)	Human rights	Very high risk	- Risk of HIV - Risk of malaria
		High risk	- Risk of Dengue Fever - Risk of Leprosy - Risk of Tuberculosis
Indigenous Rights	Human rights	Very high risk	- Risk that indigenous people are negatively impacted at sector level
Gender Equity	Human rights	High risk	- Characterization of GGG - Characterization of GII
Labour Laws	Governance	High risk	- Risk that Country does not ratify ILO conventions by Sector

Table 4.5 Indicators with high and very high risk levels in sugarcane sector in Brazil identified in SHDB (continued)

Social themes	Social category	Risk level	Indicators
Freedom of Association, Collective Bargaining, and Right to Strike	Labour rights and decent work	High risk	- Risk that a country lacks or does not enforce Freedom of Association rights
Migrant Workers	Labour rights and decent work	High risk	- Risk that a country has not ratified international conventions or set up policies for immigrants[b]
High Conflict Zones	Human rights	High risk	- Characterization of Heidelberg Barometer[a] - Overall Risk for High Conflict- increased if risk exists at sector level
Human Health (Non-communicable Diseases) and other health risks	Human rights	High risk	- Risk of dying from Malignant neoplasms - Risk of Obesity (BMI = 30 kg/m^2), Aged 15+,Females
Child Labour	Labour rights and decent work	Very high risk	- Risk of Child Labour in sector, Female - Risk of Child Labour in sector, Male - Risk of Child Labour in sector, Total
Forced Labour	Labour rights and decent work	Very high risk	- Risk of Forced Labour by Sector
		High risk	- Risk of Forced Labour in Country according to Qualitative Sources
Wage Assessment	Labour rights and decent work	Very high risk	- Risk of Sector Ave Wage being lower than Country's Minimum Wage - Risk of Sector Ave Wage being lower than Country's Non-poverty Guideline

[a]The Heidelberg Barometer has three sub-indicators, counted separately here: i) number of conflicts; ii) maximum intensity of conflicts; and iii) change in conflicts.

[b] Risk that a country has not ratified international conventions or set up policies for immigrants has four sub-indicators, counted separately here: i) policy regarding the integration of non-citizens; ii) ratification of ILO convention No. 97 on migration for Employment 1949; iii) ratification of ILO convention No. 143 on migrant workers 1975; and iv) ratification of international convention on the protection of rights of migrant workers and their families, NY 18 Dec 1990.

Table 4.6 Social hotspots identified by Social Hotspots Database (SHDB) and the numbers of indicators with high and very high risk levels

No.	Social themes	Impact category	High risk	Very high risk	Sum	Content analysis (Y- Yes; N-No)
1	Occupational Toxics & Hazards	Health and safety	5	0	5	Y
2	Human Health - Communicable Diseases	Human rights	3	2	5	N
3	High Conflict Zones	Human rights	4	0	4	N
4	Migrant Workers	Labour rights and decent work	4	0	4	Y
5	Child Labour	Labour rights and decent work	0	3	3	N
6	Legal System	Governance	1	1	2	N
7	Occupational Injuries & Deaths	Health and safety	1	1	2	Y
8	Gender Equity	Human rights	2	0	2	Y
9	Human Health - Non-communicable Diseases and other health risks	Human rights	2	0	2	Y
10	Forced Labour	Labour rights and decent work	1	1	2	Y
11	Wage Assessment	Labour rights and decent work	0	2	2	Y
12	Smallholder v. Commercial Farms	Community infrastructure	1	0	1	Y
13	Indigenous Rights	Human rights	0	1	1	N
14	Freedom of Association, Collective Bargaining, and Right to Strike	Labour rights and decent work	1	0	1	Y
15	Labour Laws	Governance	1	0	1	N

4.3.2 Social hotspots identified by content analysis

Content analysis identified in total 22 social themes in the text samples examined. The social themes mentioned most frequently (coding frequency > 10 times), i.e. social hotspots, are shown in Fig. 4.3. By impact category, social themes related to labour rights and decent work arise most frequently in the coded texts, followed by health and safety. Nine social themes are identified as social hotspots both in content analysis and in SHDB, including occupational health and safety, fair salary, social benefits and social security, access to material resources, delocalization and migration, forced labour, safe and healthy living conditions, freedom of association and collective bargaining, and equal opportunity and discrimination. Local employment emerges as a social hotspot from the content analysis, but not from the SHDB because the database only includes data aggregated at the country level and characterized as medium risk. Public commitment to sustainability issues and contribution to economic development are identified as social hotspots in content analysis, but these two social themes are not included in SHDB.

Table 4.7 presents the key findings for each social hotspot based on content analysis. The results of content analysis suggest that the sugarcane sector in Brazil is well-regulated with active collaborations between governments and the industry association with the focuses on reducing environmental impacts through eliminating pre-harvest burning and improving working conditions of sugarcane field workers. Despite the positive overview at the sectoral level, social impacts of different organizations vary due to their different conducts. For instance, for the social hotspots of social benefits and social security, access to material resources and freedom of association and collective bargaining, evidences of both positive and negative conducts are identified. Moreover, although in SLCA, good management is often considered as evidence of lower impact (Dreyer et al. 2006; Ramirez et al 2016), the findings on occupational health and safety run counter to this assumption: even if adequate protection equipment is provided to manual sugarcane cutters, the nature of the job may still put a heavy and unavoidable toll on workers´ long-term health and safety.

No.	Social Theme	Impact Category	No. of related samples	Coding Frequency (times)
1	Occupational health and safety	Health and safety	17	52
2	Local employment	Labour rights and decent work	19	35
3	Fair salary	Labour rights and decent work	14	31
4	Social benefits and social security	Labour rights and decent work	15	31
5	Access to material resources	Community infrastructure	10	19
6	Delocalization and migration	Labour rights and decent work	11	15
7	Forced labor	Labour rights and decent work	8	14
8	Contribution to economic development	Labour rights and decent work	10	14
9	Public commitment to sustainability issues	Governance	5	13
10	Equal opportunity and discrimination	Human rights	8	13
11	Safe and healthy living conditions	Health and safety	7	11
12	Freedom of association and collective bargaining	Labour rights and decent work	4	10

Identified as social hotspots in SHDB as well

Included but not identified as social hotspots in SHDB

Not included in SHDB

Fig. 4.3 Social themes identified most frequently with their coding frequencies

Table 4.7 Inventories of social hotspots identified in content analysis

Social theme	Inventory
Health and safety	a) Sugarcane workers agree that they are exposed to high health risks due to agrochemicals use (Lehtonen 2010); b) Heavy workload: Cutting cane is a repetitive task, and workers often have to work under high temperature. Wounds caused by exhaustion, fatigue, spinal diseases, and high psychological stress are reported. Injuries and death records due to exhaustion are reported too (Junior et al. 2012; Luz et al. 2012; Priuli et al. 2014; Rocha et al. 2010); c) Pre-harvest burning is reported to be related to the increase of respiratory diseases, cardiovascular diseases, cancer and renal dysfunction (Santos et al. 2015); d) Requirements for protection equipment are considered well-regulated and implemented (Hermele 2011a; Rocha et al. 2010).
Local employment	a) Increasing mechanization rate of sugarcane harvesting is causing job loss, especially for low-schooling and unskilled workers (Guilhoto et al. 2002; Smeets et al. 2008; Macedo 2007; Moraes 2007; Moraes et al. 2015; Walter et al. 2011; Hall et al. 2009; Lehtonen 2010; ELLA 2012; Duarte et al. 2013; Viana and Perez 2013); b) Governments and the industry association have established training programs for the replaced workers (Amaral 2011); c) Demand for skilled labour as drivers, mechanics and technicians have increased (Duarte et al. 2013; Moraes 2007).

Table 4.7 (continued)

Social theme	Inventory
Fair salary	a) Sugarcane cutters were paid by productivity, and this payment method may lead to exhaustion due to heavy workload (Smeets et al. 2008; Martinelli and Filoso 2008; Walter et al. 2011; Hermele 2011a; Xavier et al. 2011; Luz et al. 2012; Duarte et al. 2013); b) Payment of workers in sugarcane industry in Brazil is documented to be well above minimum wages - two to three times of the minimum wage at the harvesting season (Smeets et al. 2008; Goldemberg et al. 2008; Walter et al. 2011; Rocha et al. 2010; Hermele 2011a); c) Income of workers in the centre-south of Brazil is reported to be higher than the North-Northeast region (Macedo 2007).
Social benefits and social security	a) The number of formal workers has increased over the past decade. Sugarcane sector has a high rate of formal workers, reaching more than 80%. The centre-south region provided more formal jobs than the North-Northeast region (Smeets et al. 2008; Macedo 2007; Moraes 2007; Martinelli and Filoso 2008; Walter et al. 2011; Moraes 2011; Viana and Perez 2013); b) Social benefits provided by sugarcane companies varied from one to another, but most of the companies are reported to comply with the regulations (Macedo 2007; Goldemberg et al. 2008; Walter et al. 2011; Hall et al. 2009).
Access to material resources	a) The area of sugarcane cultivation has increased considerably (Chaddad 2010; Xavier et al. 2011); b) Large producers occupy approximately 75% of the land, and the number of smallholder farmers has been declining (Goldemberg et al. 2008; Smeets et al. 2008); c) Agro-ecological zoning regulation has protected rainforest, wetland and "cerrado" (tropical savanna ecoregion of Brazil) (Chaddad 2010); d) Most of the companies provide accommodations for non-local workers, but poor housing and transportation conditions have been reported for migrant workers (Walter et al. 2011; Rocha et al. 2010); e) Most of the companies provide school, nursery centers and day care for workers and their children (Smeets et al. 2008; Walter et al. 2011).
Forced labour	Cases of slavery labour are found in the literature (Smeets et al. 2008; Walter et al. 2011; Lehtonen 2010; Hermele 2011a; McGrath 2013).
Delocalization and migration	A large number of sugarcane workers are migrant workers from the north-northeast to the centre-south of Brazil to work at the harvesting seasons. They are mostly young males with low schooling, who are reported to have few job opportunities in their original regions. Poor living conditions are reported for these migrant workers (Macedo 2007; Moraes 2008; Moraes et al. 2015; Walter et al. 2011; Hall et al. 2009; Lehtonen 2010; Hermele 2011a; Junior et al. 2012; Duarte et al. 2013).
Public commitment of sustainability issues	Brazilian Sugarcane Industry Association (UNICA) has been actively engaged with government and international organizations to shape regulations, such as establishing the agreements of Green Protocol and National Commitment to Improve Working Conditions for Sugarcane Workers. UNICA has also proactively encouraged and helped members to improve their sustainability practices through sustainability reporting and certification following the frameworks of BONSUCRO, Global Bioenergy Partnership (GBEP) and Global Reporting Initiative (GRI). UNICA is one of the first agro-industry unions worldwide who has published GRI reports (Chaddad 2010; Hermele 2011b; Viana and Perez 2013; UNICA 2010; Moraes et al. 2015).

Table 4.7 (continued)

Social theme	Inventory
Contribution to economic developments	Sugarcane industry contributes significantly to the income of agro-business in Brazil and provides job opportunities at a relatively low cost. The municipalities with sugarcane production are reported to have better socio-economic indicators than municipalities without sugarcane production (Macedo 2007; Goldemberg et al. 2008;Walter et al. 2011; Chaddad 2010; Martinelli et al. 2011; Duarte et al. 2013; Machado et al. 2016).
Freedom of association and collective bargaining	Regulations and legal systems in Brazil ensure that workers have the rights for freedom of association and collective bargaining. Some authors have reported the active engagement of labour unions, while others found evidences of violations of labour regulations among migrant workers (Hermele 2011a; Macedo 2007; Martinelli and Filoso 2008; Moraes 2007).
Safe and healthy living conditions	Sugarcane pre-harvest burning emits a number of air pollutants. Particularly, the associated particulate matter emissions are reported to result in increasing health risks related to respiratory diseases in communities close to sugarcane plantations (Arbex et al. 2007; Arbex et al. 2000; Du et al. 2016; Du et al. 2017a; Duarte et al. 2013; ELLA 2012; Martinelli & Filoso 2008; Uriarte et al. 2009).
Equal opportunity and discrimination	a) Very few females work as sugarcane cutters due to heavy workload. Cases have been reported that women are required to be sterilized to obtain the job (Hermele 2011a; Junior et al. 2012; Moraes et al. 2015; Smeets et al. 2008); b) With the increasing rate of mechanization, workers with low schooling are the most vulnerable population to lose their jobs; meanwhile, the number of female workers is expected to increase (Chaddad 2010; Duarte et al. 2013; Goldemberg et al. 2008; Moraes et al. 2015).

The results of content analysis have also shed light on the important differences in social impacts between different operations within the sugarcane sector. Harvesting is identified as the most labour intensive process. The transition from manual to mechanical harvesting, which is especially rapid in the centre-south region, changes the impacts associated with each social hotspot. Fig. 4.4 compares manual and mechanical harvesting on the social themes where their social impacts differ. Mechanical harvesting has lower impacts in most social themes except for local employment and access to material resources, illustrating the widespread tension between labour intensity and machine use. For manual harvesting, the social theme with the highest potential impact is occupational health and safety. Exhaustion, back pain, occupational injuries due to fatigue, and high psychological stress have been reported among sugarcane cutters (Priuli et al. 2014; Rocha et al. 2010). This is resulted from the pressure on sugarcane cutters to achieve high productivity: productivity of sugarcane cutters has increased from 6 tons/day to 12 tons/day in the past decades in order to be competitive with the productivity of mechanical harvesting. High risk associated with a fair salary for manual harvesters also contributes to the concern over health and safety: manual sugarcane cutters are usually paid by productivity rather than a fixed wage and this often motivates them to work beyond their physical limits. The high impacts of delocalization and migration of manual harvesters are related to the evidence of lacking decent living conditions, sanitation and nutritionally adequate food for seasonal migrant workers (Luz et al. 2012).

Compared to manual harvesting, mechanical harvesting has both negative and positive impacts on local employment. One mechanical harvester can replace 80 to 100 manual workers. As estimated by UNICA, in the state of São Paulo alone, 82200 manual sugarcane field workers face potential job loss (Guilhoto et al. 2002; Duarte et al. 2013; Moraes et al. 2015). On the other hand, mechanical harvesting is expected to improve working conditions, average salary and gender equity in the sugarcane sector in Brazil. These findings are consistent with those of Souza et al. (2016), who concluded that manual harvesting leads to creation of more employment while mechanical harvesting results in a lower level of occupational accidents, higher average wages and more participation of female workers.

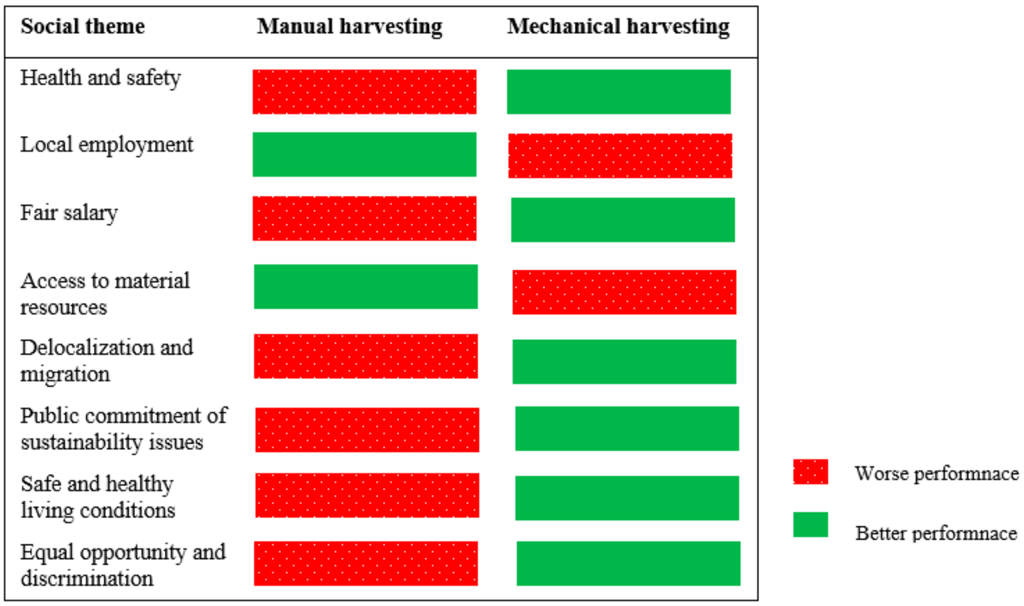


Fig. 4.4 Comparison of social impacts of manual and mechanical sugarcane harvesting by social theme

4.3.3 Comparing the results of SHDB and content analysis

SHDB and content analysis identified 15 and 12 social hotspots respectively in the sugarcane sector in Brazil, with 60% of the social hotspots identified in SHDB confirmed by the content analysis. This confirms that SHDB is a useful tool to identify social risks associated with a country-sector. However, at the moment, SHDB has limited ability to distinguish between social impacts arising in different sectors in the same country or associated with different practices within the same country-sector, whereas content analysis gives a much richer picture of the impacts and the consequences of changes in the product system. In this specific example, there are large differences in social impacts between manual and mechanical harvesting (see Section 4.3.2) but these differences are not captured in SHDB in its current form. However, in future studies, with better input-output data and sectoral impact inventories, the product systems and impacts of manual and mechanical harvesting may be differentiated.

The limitations of SHDB can be overcome by combining it with content analysis. Unlike SHDB, which only assesses negative impacts, content analysis is able to identify positive impacts, such as the industrial association´s endeavor to promote public commitment to sustainability issues and the impacts of increasing mechanical harvesting in increasing average salaries. In addition, content analysis can facilitate data collection for foreground processes and provide more comprehensive understanding of the sectoral context, enabling better judgements on the status and cause of social impacts. Content analysis can further benefit the design of data collection materials such as questionnaires and interviews if site-specific data collection will be conducted. However, it is worth noting that obtaining in-depth information through content analysis is at the cost of requiring more time for gathering and analyzing literature.

4.4 Concluding remarks

This chapter reports a screening SLCA to identify the social hotspots related to sugarcane production in Brazil. Social impacts are modelled using the Social Hotspots Database (SHDB) and analyzed through content analysis of relevant literature. The sugarcane sector in Brazil is the dominant country-sector contributing to the overall social impacts of sugarcane life cycle in Brazil, with other sectors representing nugatory contributions to working hours and hence to social impacts. The SHDB identifies Health and safety and Labour rights and decent work as the most significant impact categories. Social hotspots of sugarcane sector in Brazil identified in both SHDB and content analysis include health and safety, fair salary, social benefits and social security, access to material resources, delocalization and migration, forced labour, safe and healthy living conditions, freedom of association and collective bargaining, and equal opportunity and discrimination. Comparing the results of both approaches shows that SHDB is effective for identifying social impacts at the country level but is less effective at the sector level due to the aggregation of the data. However, integrated use of content analysis with SHDB can improve the quality of inventory data for foreground processes considering the magnitude and cause of the social impacts and the impacts of different operations. Content analysis can also identify positive impacts which are not included in SHDB. We recommend a combination of content analysis with SHDB to improve the quality of the results of a screening SLCA.

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CHAPTER 5 INTEGRATING MCDA WITH LCA AND SLCA

5.1 Introduction

Presenting LCA and SLCA results by environmental category and social theme provides information on the environmental and social impacts of a product. However, considering trade-offs among several alternatives on multiple indicators can be difficult for decision makers to determine which alternative is the preferable one among all. Weighting indicators and aggregating impacts on all the indicators into a single score is a common practice in life cycle studies to support decision-making, in spite of being a controversial topic in LCA. As stated in ISO14044 (2006), "weighting shall not be used in LCA studies intended to be used in comparative assertions intended to be disclosed to the public". The most used weighting approach in LCIA is allocating equal weights to all the indicators (Huppes and van Oers 2011). This approach implies the arbitrary choice of considering same weight to each indicator, which fails to account for decision makers´ and experts´ preference and knowledge.

As reviewed in Section 2.3, multi-criteria decision analysis (MCDA) has been increasingly applied in life cycle studies to aggregate LCA or SLCA results. Dias et al. (2016) adopted stochastic weights in an additive aggregation model with partial preference information. This approach does not depend on arbitrary choices of weights and identifies robust conclusions; however, it does not utilize decision makers and experts´ preferences and knowledge. Other studies based on additive aggregation approaches often collect decision makers or experts´ preferences by survey, and the final weight of an indicator is usually calculated by averaging the weights given to that indicator by all the experts or stakeholders surveyed (Doderer and Kleynhans 2014; Lipuscek et al. 2010; Narayanan et al. 2007; Pastare et al. 2014). This approach ignores the different levels of interests and familiarities to the topic of each indicator among group decision makers. A robust additive aggregation approach of group decision-making based on LCA and/or SLCA results is lacking (Keeney et al. 1975; Dyer and Sarin 1979), which takes into account preferences and knowledge of decision makers or experts, but acknowledges that weights allocated to decision makers in group decision-making are often unknown (Sarabando et al. 2017).

This chapter describes a novel MCDA approach in the LCIA phase to support decision-making based on comparative LCA and SLCA results, which utilizes decision makers´ preference information while taking into account the different levels of interests and familiarities of decision makers on each indicator: for this research, comparing sugarcane production in Brazil with manual and mechanical harvesting (Du et al. 2017a&b). The feature distinguishing the additive MCDA approach developed in this chapter from previous studies is the adoption of stochastic weights accounting for group decision makers´ value choices. Instead of assigning equal importance to preferences of all the decision makers, stochastic weights analysis is implemented to explore all the possible combinations when no distinctions are made among the weights assigned to the opinions of different decision makers (all are treated equally, but without assuming equal weights). The advantage of integrating stochastic weights analysis with preference information is to generate robust results reflecting all the possible tradeoffs in aggregating the preference information of all the decision makers.

The MCDA approach developed in this chapter can be applied to future comparative life cycle studies. The findings of this chapter also shed light on the advantages of including both mid-point and end-point categories in an LCA. Section 5.2 details the methods applied in this chapter, and the results are presented in Section 5.3. Concluding remarks are included in Section 5.4.

5.2 Methods

5.2.1 MCDA approach: an additive model with stochastic weights

A novel multi-criteria decision analysis approach based on additive aggregation has been developed and applied to compare the overall environmental and social impacts of manual and mechanical sugarcane harvesting in Brazil. The overall impact of an alternative (a product system) a_i, denotedI (a_i , w), is calculated by Equation 5.1, which is a weighted sum of its impact on indicator j (i.e. $I_j(a_i)$) considering the corresponding weight w_j. All the weights are non-negative and the sum of all weights is equal to 1 (Equation 5.2).

$$I\,(a_i\,,w) = \sum_{j=1}^{n} w_j\, I_j\,(a_i) = w_1\, I_1\,(a_i) + \cdots + w_j\, I_j\,(a_i) + \cdots + w_n\, I_n\,(a_i) \qquad (5.1)$$

$$w_1, w_2 \ldots . w_n \geq 0 \; and \; \sum_{j=1}^{n} w_j = 1 \qquad (5.2)$$

w: a vector of weights for all the indicators, (w_1, w_2, …., w_n)
a_i: an alternative, in this case, the sugarcane product system with manual or mechanical harvesting
w_j: the weight of indicator j, in this case, mid-point impact category, end-point damage category or social theme respectively
I_j (a_i): the normalized value of alternative a_i on indicator j
n: the total number of indicators

The weight of indicator j, w_j, is calculated by Eq. (5.3) and (5.4), in which μ_p represents the weight assigned to the preference of decision maker *p* when calculating the weight of the indicators. μ_p is computed based on Monte Carlo simulation in the software @Risk 7.5, considering a uniform distribution over the unit simplex defined by Eq. (5.4), according to the process described in Butler et al. (1997). All the weights assigned to decision makers are non-negative and the sum of all the weights equals 1.

$$w_j = \sum_{p=1}^{m} \mu_p\, w_{jp} = \mu_1\, w_{j1} + \mu_2\, w_{j2} + \cdots + \mu_m\, w_{jm} \qquad (5.3)$$

$$\mu_1, \ldots, \mu_m \geq 0 \text{ and } \sum_{p=1}^{m} \mu_p = 1 \qquad (5.4)$$

p: decision maker
m: the total number of decision makers
w_{jp}: the weight of indicator j assigned by decision maker p
μ_p: the stochastic weight assigned to decision maker p.

It is worth mentioning that each vector of weights assigned to decision makers, (μ_1,…, μ_m), will correspond to a vector of indicator weights (w_1, w_2 … w_n) that is a convex combination of the indicator weights provided by the decision makers. This resulting vector of indicator weights can then be seen as a mix of the inputs provided by different decision makers. When all the individual weight vectors satisfy (5.2), then equation (5.3) and (5.4) guarantee that the resulting vector (w_1, w_2 … w_n) also satisfies (5.2).

In order to collect preference information of relevant decision makers, a survey was conducted to gather experts′ opinions on their value choices for eight mid-point environmental indicators, three end-point environmental indicators, and eight social indicators. The survey material can be found in Appendix 4. To obtain survey responses that represent values of informed decision makers, only experienced Brazilian LCA researchers and practitioners (more than 5-year experience in LCA) with knowledge of the sugarcane sector in Brazil were invited to answer the survey. In total, 26 surveys were sent out with 7 responses received (response rate 27%). The survey participants were asked to give a weight (between 0 and 100) to each environmental or social indicator considering both the context of sugarcane production in Brazil and the magnitude and significance of the change on impact changing from manual to mechanical harvesting (information provided with the questionnaire). All the weights given in the same aspect summed up to 100. The characterized values of mid-point and end-point environmental impacts and a summary of social performances on each social indicator in regard to manual and mechanical harvesting were provided to the participants. One example of survey instruction, regarding mid-point environmental impacts, reads as "*Considering i) the context of sugarcane production in Brazil, and ii) importance of changes on impacts from manual to mechanical harvesting (e.g. on Climate Change, reducing emissions from 38 kgCO2 eq/t of sugarcane to 29 kgCO2 eq/t of sugarcane), please assign weights (0-100 points) to the mid-point indicators below. All the weights assigned should be summed up to 100 points.*"

It is worth noting that w_j represents the importance of the change of the impact on indicator j comparing mechanical harvesting to manual harvesting, instead of the importance of the indicator j itself. On the other hand, μ_p simulates the weight assigned to decision maker p, when setting the weights for each indicator.

5.2.2 VIP Analysis

VIP (Variable Interdependent Parameter) Analysis is based on additive aggregation model of value functions. It does not require the decision makers to indicate precise values as criteria weights, and it can be used to generate robust conclusions using every accepted combination of weights. VIP Analysis has the ability to find the most extreme values with respect to the differences between the overall results of two alternatives (Dias and Climaco 2000). The value difference between two alternatives a_i and a_j can be defined by Eq. 5.5, where D^{max} (a_i,a_j) and D^{min} (a_i,a_j) indicate the highest and lowest values of D (a_i,a_j), respectively.

$$D\ (a_i,a_j) = \{ I(a_i, w) - I(a_j, w) : w \in W\} \qquad (5.5)$$

In the above equation, $w \in W$ represents the set of all the indicator weights that corresponds to convex combinations of weights assigned by the different decision makers (Fig. 5.1). When D (a_i, a_j) is negative, this means that a_i has lower impacts than a_j, since only negative impacts are considered in the life cycle studies and the objectives are to minimize them. Likewise, a_i presents higher impacts than a_j when D (a_i, a_j) is positive. Applying the additive model with stochastic weights described in Section 5.2.1 and VIP Analysis together can provide complementary outputs: the former can indicate the probability that one alternative is better than the other, while the latter reveals how much better or worse can one alternative be over the other.

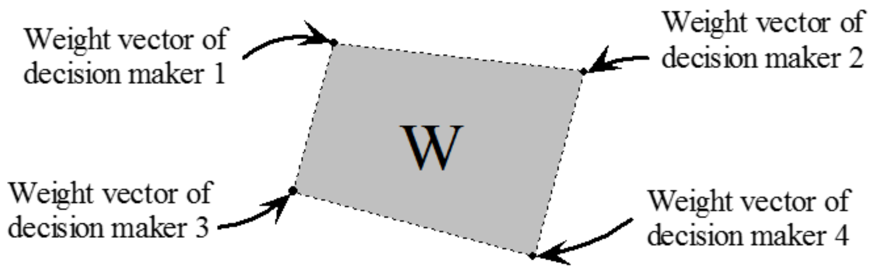

Fig. 5.1 An example of a weight space that represents the set of all the indicator weights that corresponds to convex combinations of weights assigned by four different decision makers

5.2.3 Normalization of LCA and SLCA results

Normalization is an optional step in LCA, which is applied after characterization of environmental impacts to mid-point and/or end-point indicators. Because characterized LCIA results are expressed in various units for various indicators, normalization can convert the results into commensurable measures or reveal the magnitude of impacts (Dias et al. 2016; Myllyvitta et al. 2014). Normalization can be conducted externally or internally. External normalization relates the characterized scores of a product system to a reference value, i.e. indicator results for a reference area or a reference scenario (Myllyvitta et al. 2014; Domingues et al. 2015). In internal normalization, characterized values are not related to external reference values but values of alternatives under assessment. Two extreme values, i.e. minimum and maximum values are often considered in internal normalization. When applying MCDA approaches, internal normalization is more commonly used, for instance in multi-attribute value theory (MAVT) and analytic hierarchy process (AHP). This chapter deploys internal normalization following Eq. 5.6, in order to match the way that indicator weights are elicited (comparing the magnitude of the difference between the manual and the mechanical systems). Because only two alternatives are compared in this chapter, the normalized values of two alternatives on all the indicators are either 0 or 1.

$$I_j\ (a_i) = \frac{I_j^o\ (a_i) - I_{j,min}^o}{I_{j,max}^o - I_{j,min}^o} \qquad (5.6)$$

$I_j^o\ (a_i)$: characterized value of alternative a_i on indicator j, in the original units (before normalization).
$I_{j,min}^o = \min_i\{I_j^o\ (a_i)\}$: the best performance on indicator j
$I_{j,max}^o = \max_i\{I_j^o\ (a_i)\}$: the worst performance on indicator j

Despite internal normalization is the most relevant approach to this chapter, it is worth mentioning that adding a new alternative may result in changes on the relative positions of original alternatives due to the rank reversal problem (Norris 2001; Dias and Domingues 2014). If a new alternative is added with any of its impacts being higher than the previous maximum or lower than the previous minimum, then the survey would have to be repeated considering the new (wider) difference magnitudes.

For social impacts, the assessment of this research (see Chapter 4) is based on qualitative data. For the purpose of comparison, qualitative results of each indicator are quantified by a binary scoring rule: better performance of an alternative is assigned a 0, and worse performance of an alternative is assigned a 1, based on experts′ judgments. This quantification option for social indicators is aligned with the normalization option for environmental indicators.

5.2.4 Sensitivity analysis

In order to test the robustness of the results concerning the choice of decision makers, a sensitivity analysis is conducted adopting the one-at-a-time (OAT) approach. Answers of one decision maker are removed at a time. The results are then compared with each other to evaluate the effect of this decision maker´s preference on the overall output. This approach can effectively identify the outliers among samples. The OAT approach has been criticized for its limitation on detecting interactions between input variables (Czitrom 1999); because the survey is conducted independently, this limitation is not relevant to this chapter.

5.3 Results

5.3.1 Comparing environmental impacts at the mid-point

The characterized values of mid-point impacts of manual and mechanical harvesting (see Chapter 3) are normalized by Eq. 5.6, and the normalized values are shown in Table 5.1. Since the goal regarding environmental impacts is to minimize it, a normalized value zero represents a better performance between the two alternatives, and one represents a worse performance.

Table 5.1 Normalized mid-point LCA results of manual and mechanical harvesting

Impact category	Manual harvesting	Mechanical harvesting	Difference Δ= Value(manual)- Value(mechanical)
Climate change	1	0	1
Fossil depletion	0	1	-1
Ozone depletion	0	1	-1
Terrestrial acidification	0	1	-1
Freshwater eutrophication	0	1	-1
Human toxicity	0	1	-1
Photochemical oxidant formation	1	0	1
Particulate matter formation	1	0	1

The survey results of weights of mid-point indicators are shown in Table 5.2. The values are divided by 100 in the final analysis so that all the weights sum up to 1. The weight vector representing the weights assigned to decision makers for each indicator (μ_1, μ_2, … μ_7) are simulated for 100 000 iterations. Since the objective is to compare manual and mechanical harvesting systems, the results of interest are the differences between the overall results of two alternatives. As shown in Fig. 5.2, obtained by performing a Monte Carlo simulation, the overall impact of the manual system is more likely to be lower than the overall impact of the mechanical system. The manual system is preferred to the mechanical system in 67% of the cases. Following the VIP Analysis approach, the minimum and the maximum values, respectively -0.26 and 0.50, indicate that despite the manual system has a higher possibility to win, the advantage at best of the manual system (0.26, i.e. the symmetric value of the minimum) is less than the advantage at best of the mechanical system (0.50) (these are exact values, which constitute a wider interval than the interval estimated by the Monte Carlo simulation).

Table 5.2 Survey results of weights of mid-point indicators

Impact category	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
Climate change	25	40	50	15.1	23	25	15
Fossil depletion	20	20	20	13.2	20	22.5	13
Ozone depletion	2.5	10	5	9.4	1	17.5	8
Terrestrial acidification	10	5	0	11.3	20	5	11
Freshwater eutrophication	2.5	10	0	9.4	4	5	11
Human toxicity	20	0	0	14.2	18	5	15
Photochemical oxidant formation	5	10	5	13.2	8	5	12
Particulate matter formation	15	5	20	14.2	6	15	15

Based on these results, there is no clear conclusion about which system is more preferable: for some weights vectors it is the manual system, for other weights vectors it is the mechanical system. The manual system is preferred for a fairly large majority (67%) of the weight vectors, but on the other hand the mechanical system can potentially beat the manual system by a larger margin than the reverse.

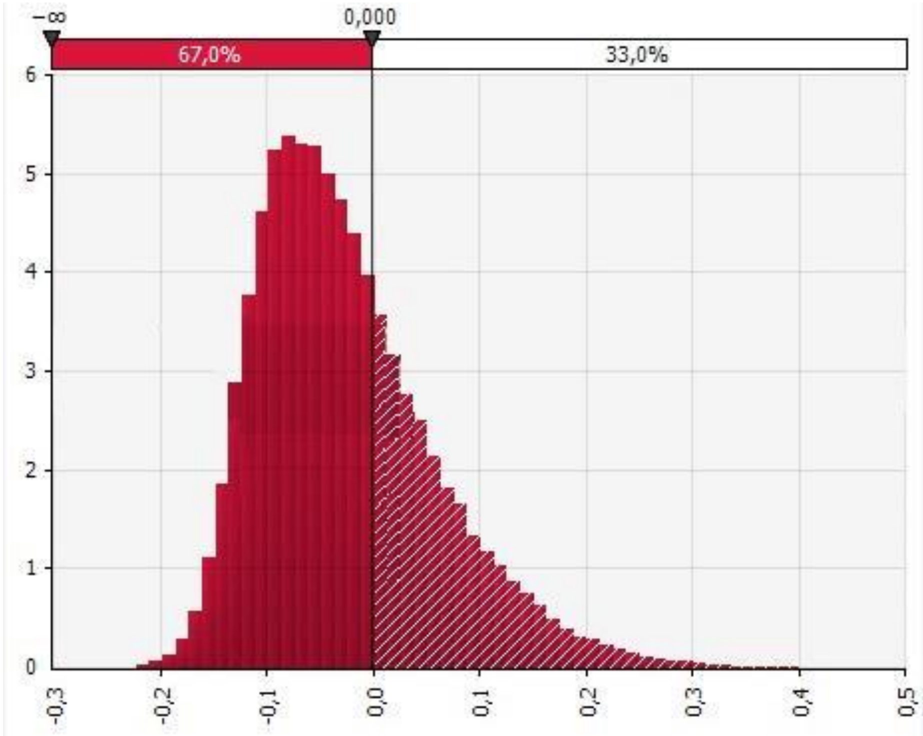

Fig. 5.2 Simulated results of overall differences (Manual-Mechanical) for mid-point impacts

Sensitivity analysis

The robustness of the previous results is assessed concerning whether a single participant might have a large influence on the results. One sample is removed at a time, reducing the number of samples to 6. Table 5.3 shows the results of sensitivity analysis regarding mid-point indicators based on Monte Carlo simulation and VIP analysis. Regardless of which sample is removed, the manual system is more likely to be preferred to the mechanical system (all the differences are negative for more than 50% of the simulated weights). However, when removing sample 3, the result is overwhelmingly in favor of the manual system (in 99% of the cases), winning by a margin of 0.26 at best, and losing in the worst case by a relatively small margin of 0.10. This is because sample 3 provides the highest weights on climate change (50%) and particulate matter formation (20%) among all the samples, and the manual harvesting system possesses worse performances on these indicators. When removing sample 5, the probability of the mechanical system being preferred increases to 49.7% (nearly 50%), and the advantage at best of the mechanical system is almost three times of the advantage of the manual system at best. In the cases of removing other samples (i.e. sample 1, 2, 4, 6 or 7), the probability of the manual system winning over the mechanical system ranges between 56.8% and 73.2%, and the margins in the manual system´s worst cases are always larger than the margins of its best cases.

Table 5.3 Sensitivity analysis of mid-point impacts considering the influence of a single sample

	Without Sample1	Without Sample2	Without Sample3	Without Sample4	Without Sample5	Without Sample6	Without Sample7	Original Overall
Minimum (VIP analysis)	-0.26	-0.26	-0.26	-0.26	-0.16	-0.26	-0.26	-0.26
Maximum (VIP analysis)	0.50	0.50	0.10	0.50	0.50	0.50	0.50	0.50
Mean	-0.01	-0.04	-0.11	-0.00	0.02	-0.01	-0.00	-0.02
Std Dev	0.09	0.09	0.04	0.09	0.09	0.09	0.09	0.08
% of Value (manual) -Value (mechanical)<0	60.6	73.2	98.9	57.4	50.3	60.6	56.8	67

5.3.2 Comparing environmental impacts at the end-point

Table 5.4 presents the normalized LCA results of end-point impacts of the manual and mechanical systems (see the characterized values in Chapter 3), in which zero indicates better performance on the indicator, and one indicates worse performance.

Table 5.5 shows the weights of end-point indicators given by seven samples. The values are as well divided by 100 in the final analysis, and the weights vectors indicating the decision maker weights (μ_1, μ_2, ..., μ_7) are simulated for 100 000 iterations. Results of differences between the manual and the mechanical systems at the end-point are shown in Fig. 5.3. It is clear that in regard to end-point indicator, the manual system is always less preferred than the mechanical system, with the smallest margin of 0.20 (putting all the weight in sample 3), and the largest margin of 0.80 (putting all the weight in sample 5).

Table 5.4 Normalized end-point LCA results of the manual and mechanical systems

Damage category	Manual harvesting	Mechanical harvesting	Difference Δ= Value(manual)-Value(mechanical)
Damage to human health	1	0	1
Damage to ecosystem diversity	1	0	1
Damage to resource availability	0	1	-1

Table 5.5 Survey results of weights of end-point damage categories

Damage category	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
Damage to human health	30	30	40	35	50	40	40
Damage to ecosystem diversity	50	40	20	33	40	30	30
Damage to resource availability	20	30	40	33	10	30	30

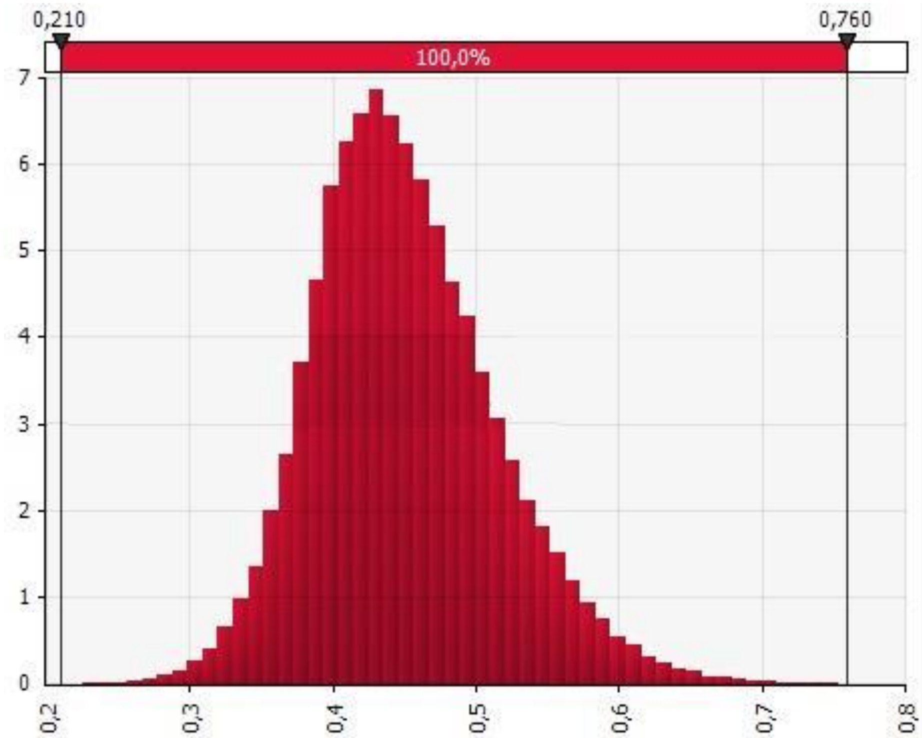

Fig. 5.3 Simulated results of overall differences (Manual-Mechanical) for end-point impacts

Sensitivity analysis

Table 5.6 presents the results of sensitivity analysis of end-point impacts of the manual and mechanical harvesting systems. The mechanical system always has lower impacts than the manual system, no matter which sample is removed. The mechanical system possesses the smallest advantages in the range of [0.20, 0.35], and the largest advantages of [0.60, 0.80]. No particular sample has a large influence on the overall conclusions.

Comparing to the LCA results at the mid-point, the results at the end-point are more robust and in favor of the mechanical system, which appears to be contradictory with the conclusions that can be drawn based on the mid-point indicators. It is even possible to note that removing sample 3 benefits the manual system and removing sample 5 benefits the mechanical system when considering the mid-point analysis. However, considering the end-point analysis the contrary occurs (although not putting into question the robust conclusion of the mechanical system's superiority in the latter case).

Table 5.6 Sensitivity analysis of end-point impacts considering the influence of a single sample

	Without Sample1	Without Sample2	Without Sample3	Without Sample4	Without Sample5	Without Sample6	Without Sample7	Original Overall
Minimum (VIP analysis)	0.20	0.20	0.35	0.20	0.20	0.20	0.20	0.20
Maximum (VIP analysis)	0.80	0.80	0.80	0.80	0.60	0.80	0.80	0.80
Mean	0.43	0.46	0.49	0.47	0.39	0.46	0.46	0.45
Std Dev	0.07	0.07	0.06	0.07	0.04	0.07	0.07	0.06
% of Value (manual) - Value (mechanical)<0	0	0	0	0	0	0	0	0

The results of this chapter are consistent with the general perception that aggregating the LCA results at the end-point may ease the process of resolving trade-offs across indicators for decision makers (Bare et al. 2000). It is also important to bear in mind the higher uncertainties of end-point results compared to the mid-point. The apparent differences we demonstrate in this chapter when performing multi-criteria decision analysis using mid-point and end-point indicators suggest including both mid-point and end-point indicators in LCA is beneficial for informing decision-making. However, more research is needed to understand how mid-point and end-point can be included in a framework in a consistent manner, and how results at two levels can be integrated to support decision-making.

5.3.3 Comparing social impacts by social themes

Quantification of social impacts of the manual and mechanical systems by social themes is presented in Table 5.7 (zero is better and one is worse; also, see qualitative results in Chapter 4). Table 5.8 presents the weights provided by experts on eight social indicators (divided by 100 in the final analysis).

The weights vectors of the weights assigned to decision makers are simulated for 100 000 iterations, and the simulated results of the differences for overall social impacts between the manual and mechanical systems are shown in Fig. 5.4. The differences between the social impacts of the manual and mechanical systems (manual subtracts mechanical) are always positive, suggesting that the mechanical system clearly has lower overall impacts than the manual system. The advantages of the mechanical system are quite large, falling in the range of [0.40, 0.80].

Table 5.7 Quantitative SLCA results of the manual and mechanical systems by social themes

Subcategory	Manual harvesting	Mechanical harvesting	Difference Δ= Value(manual)-Value(mechanical)
Health and safety	1	0	1
Local employment	0	1	-1
Fair salary	1	0	1
Access to material resources	0	1	-1
Delocalization and migration	1	0	1
Public commitment to sustainability issues	1	0	1
Safe and healthy living conditions	1	0	1
Equal opportunity and discrimination	1	0	1

Table 5.8 Survey results of weights of relevant social subcategories

Social issues	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
Health and safety	15	20	20	14.5	30	25	16
Local employment	5	20	20	13.5	5	22.5	16
Fair salary	25	20	20	10	20	17.5	14
Access to material resources	5	5	10	10	5	2.5	8
Delocalization and migration	25	10	0	10	0	12.5	12
Public commitment of sustainability issues	5	10	0	12	25	7.5	10
Safe and healthy living conditions	10	5	20	15	10	7.5	16
Equal opportunity and discrimination	10	10	10	15	5	5	8

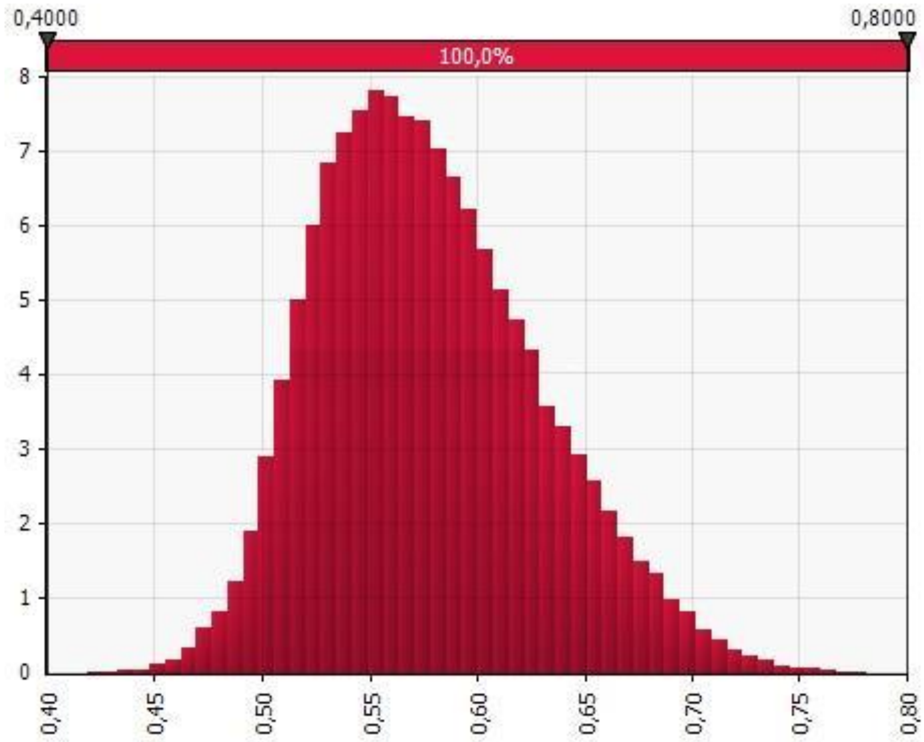

Fig. 5.4 Simulated results of overall differences (Manual-Mechanical) for social impacts

Sensitivity analysis

Table 5.9 summarizes the results of sensitivity analysis of social impacts of the manual and mechanical systems by removing one sample at a time. The conclusions are consistently and overwhelmingly in favor of the mechanical system regardless which sample is removed. The margins of advantages in all the cases are very close to each other, with differences less than 0.1.

Table 5.9 Sensitivity analysis of social impacts considering the influence of a single sample

	Without Sample1	Without Sample2	Without Sample3	Without Sample4	Without Sample5	Without Sample6	Without Sample7	Original Overall
Minimum (VIP analysis)	0.40	0.40	0.50	0.40	0.40	0.40	0.40	0.40
Maximum (VIP analysis)	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Mean	0.541	0.591	0.608	0.587	0.541	0.591	0.588	0.578
Std Dev	0.0466	0.0579	0.0516	0.0590	0.0464	0.0582	0.0587	0.0517
% of Value (manual) -Value (mechanical)<0	0	0	0	0	0	0	0	0

5.4 Concluding remarks

This chapter develops a novel MCDA approach in the LCIA phase to support group decision-making based on comparative LCA and/or SLCA results. This approach was applied to a comparative study of sugarcane production with manual and mechanical harvesting. Brazilian LCA experts were surveyed to collect their value choices of mid-point and end-point environmental indicators and social indicators. Instead of assuming equal importance of all the members in group decision-making, this chapter adopts stochastic weights to explore all the possible combinations of weights assigned to decision makers. Sensitivity analysis is conducted to test the robustness of the results. The results show consistently that mechanical harvesting has lower environmental impacts at the end-point and lower social impacts. However, the results of the environmental impacts at the mid-point are less robust and clear: manual harvesting appears to be more likely to have lower impacts than mechanical harvesting; whereas the advantage of mechanical harvesting can be greater than the advantage of manual harvesting in some cases. The contradictory findings at the mid-point and end-point from this study confirmed the perceptions from previous studies that aggregating LCA results at the end-point has the benefit of easing decision-making. However, taking into account the higher uncertainties of end-point results, we suggest that both mid-point and end-point results should be provided to decision-makers when comparing environmental impacts of different product life cycles. The MCDA approach developed in this chapter can be adopted in future comparative LCA and/or SLCA studies to support decision-making by utilizing experts′ or stakeholders′ preference information while improving the robustness of the comparison(s).

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CHAPTER 6 CONCLUSIONS

6.1 Summary of the thesis

This thesis addressed the overarching question of how sustainable sugarcane production is in Brazil, in the context of increasing adoption of mechanical harvesting. Life cycle environmental impacts with a focus on health effects of particulate matter and social impacts of sugarcane production with manual and mechanical harvesting were assessed applying life cycle assessment and social life cycle assessment (Chapter 3 and Chapter 4). A multi-criteria decision analysis model was developed to support robust decision-making based on LCA and SLCA results (Chapter 5).

This section summarizes and discusses the key findings of this thesis, following the framework of the three sub- research questions presented in Section 1.2. Limitations and future research needs are discussed in Section 6.2, followed by main research contributions (Section 6.3) and recommendations (Section 6.4).

1) What are the global and local environmental impacts of sugarcane production in Brazil, in the context of increasing use of mechanization?

Chapter 3 presented a comparative life cycle assessment of sugarcane production with manual and mechanical harvesting. The results highlighted higher impacts of manual harvesting on the mid-point categories of photochemical oxidant formation and particulate matter formation and the end-point category of human health; while mechanical harvesting showed higher impacts on fossil depletion, ozone depletion and terrestrial acidification (mid-point), as well as resources use (end-point). The results demonstrated the importance of considering soil carbon in calculating the Climate Change impact. Comparing to manual harvesting, mechanical harvesting has 6% higher impacts when not considering the contribution of soil carbon sequestration, but it has 25% lower impacts when considering soil carbon sequestration over a 20-year time span.

The research provided important insights on differentiating population densities when assessing the health effects of particulate matter emissions associated with manual and mechanical harvesting. Changing from manual to mechanical harvesting resulted in 93% lower health effects close to urban areas, whereas only a reduction of 15% and 5% for rural and remote areas respectively.

2) What are the social hotspots associated with sugarcane production in Brazil, considering increasing use of mechanization?

In Chapter 4, life cycle social impacts of sugarcane production in Brazil were first assessed using a generic database based on an input-out model; the results were then improved through a systematic analysis of relevant literatures. The results highlighted the dominant contribution of the sugarcane sector in Brazil in the overall social impacts of sugarcane life cycle. The social issues of the sugarcane sector in Brazil raising the greatest concerns were identified, including i) health and safety, ii) fair salary, iii) social benefits and social security, iv) access to material resources, v) delocalization and migration, vi) forced labour, vii) safe and healthy living conditions, viii) freedom of association and collective bargaining and ix) equal opportunity and discrimination.

Social impacts of manual and mechanical harvesting largely differ from each other. Mechanical harvesting has lower negative impacts on majority of the social themes, except for local employment and access to material resources. Manual harvesting has higher negative impacts on occupational health and safety, fair salary, migrant labour, safe and healthy living conditions and social equity. The research has also demonstrated that an integrated use of content analysis can overcome the limitations of generic databases by identifying both negative and positive impacts and differentiating operations within the same sector.

3) Facing the trade-offs on various environmental and social indicators, which harvesting operation is more preferable regarding its environmental and social sustainability?

Chapter 5 compared the overall life cycle environmental and social impacts of sugarcane production with manual and mechanical harvesting applying a novel additive multi-criteria decision analysis approach. Robustness of weighting in LCA and SLCA was improved by considering all the possible combinations of the weights assigned to each of the decision makers in a group, in this case, Brazilian LCA and SLCA experts. Sensitivity analysis was also conducted to examine if any of these decision makers had major impact on the conclusions.

The results highlighted the impacts of reporting LCA results at the mid-point and end-point levels on decision-making. Mechanical harvesting was clearly preferred to manual harvesting when considering end-point environmental indicators; whereas the difference between manual and mechanical harvesting at the mid-point level was less pronounced. At the mid-point level, manual harvesting appears to be more likely to have lower environmental impacts; however, the advantage of mechanical harvesting can be greater than the advantage of manual harvesting in some cases. Regarding social impacts, mechanical harvesting showed lower negative impacts than manual harvesting.

6.2 Limitations and topics for future research

Limitations of this research are discussed in this section; when relevant, topics for future research related to limitations are also included.

First of all, as pointed out in Chapter 3, parameter uncertainties in the inventory (e.g. productivity, fertilizer, diesel etc.) are not expected to affect the conclusions based on LCA results. Other sources of uncertainties due to data quality and characterization models could be improved in future work. For instance, impacts on terrestrial acidification come mostly from NH_3 emissions for both manual and mechanical harvesting systems. Due to lack of data on soil condition, the quantification of these NH_3 emissions are based on assumptions from the IPCC (2006). However, pre-harvest burning may considerably change the soil condition, which will require different emission factors of NH_3 emissions for both systems. In addition, the characterization factors of $PM_{2.5}$ calculated used the exposure-response factor based on the American condition and the intake fractions for the region of Latin America, the calculations of characterization factors can be updated when data for exposure-response factors and intake fractions of Brazil are available.

Secondly, only the land use scenario of changing from manual to mechanical harvesting was investigated, without considering moving from forested land, other crops, or other soil management systems to mechanical harvesting of sugarcane. This choice is due to the trend that sugarcane expansion has been mainly related to the use of previous pasture lands instead of forested land (e.g. prohibition of agricultural use through the regulation *AgroEcological Zoning*) and other crop lands (Seabra et al. 2011). With the rapid expansion of sugarcane areas in Brazil, this assumption needs to be revisited with updated data, and other land use scenarios may need to be included in the environmental impacts analysis.

Thirdly, due to lack of information on uncertainties of data included in Social Hotspots Database, uncertainty of screening SLCA results was not assessed. When this study was conducted, social LCA database PSILCA was not available; however, PSILCA possesses the features of SHDB and has included uncertainty information in the inventory. Social impacts of sugarcane production can be modelled in PSILCA and compared with the results from this study in future work.

Another limitation regarding the assessment of social impacts is that social impacts of sugarcane production in different regions of Brazil were not differentiated. However, social impacts of sugarcane production in the north-northeast and the centre-south of Brazil may be different due to economic developments, regional policies, financial incentives and local cultures.

Regarding the results of multi-criteria decision analysis model, presenting results of environmental impacts at the mid-point and the end-point levels can strongly affect decision-making: as shown in Chapter 5, mechanical harvesting is clearly better than manual harvesting considering end-point indicators; whereas the best alternative is unclear when considering mid-point indicators. The factors that led to this difference may include the difficulties of the task (e.g. weighting three indicators instead of eight), influence of media exposure and political agenda (e.g. climate change), and projection of preference on a certain alternative when assigning weights. Surveys or interviewers with relevant decision makers will be needed to confirm the reasons for different results of MCDA.

Lastly, the MCDA analysis in this research did not consider constraints on the weights assigned to the preferences of certain decision makers (for instance, the weight assigned to the preference of decision maker A cannot be lower than 0.05; or the weight assigned to the importance of decision maker A cannot be more than two times higher than decision maker B). When more information of preferences and knowledge of decision makers is available, the MCDA model can be further developed considering explicit weighting constraints.

Besides the limitations and the relevant future research topics mentioned above, two other aspects can be further explored in the future. One is to include life-cycle cost analysis (LCC) of manual and mechanical harvesting of sugarcane to assess the economic impacts of the two systems. The other is to integrate the results from LCA, SLCA and LCC in the framework of life cycle sustainability assessment (LCSA) to understand the overall sustainability impacts of different harvesting operations and the trade-offs among the three dimensions of sustainability.

6.3 Research contributions

This research makes methodological contributions to the developments of LCA and SLCA on three research topics: i) regional characterization of health effects of particulate matter, ii) improving quality of the results of screening SLCA, and iii) improving uncertainty and robustness of weighting in LCIA and SLCIA.

The results and findings demonstrated the importance of applying spatially-differentiated characterization factors when assessing health effects of particulate matter in LCA, and the need for more research on effect factors. The characterization factors of primary and secondary $PM_{2.5}$ calculated in this thesis can be applied to future LCA studies in the Brazilian context to more accurately quantify health effects by differentiating emission sources and emission heights. The considerable differences between the results applying the characterization factors calculated in this work and the ReCiPe method suggest that the ReCiPe method may underestimate the health effects of particulate matter, particularly for primary particulate matter.

The novel approach of an integrated use of generic SLCA databases and content analysis can be applied in future studies to improve the results of a screening SLCA. This approach has the advantages of identifying both negative and positive social impacts, and differentiating social impacts of different operations in the same sector.

The MCDA approach developed in this study takes into account both decision-makers′ preference information and importance levels of decision makers.

This approach can be applied in the weighting process of future LCA and SLCA studies to improve the uncertainty and robustness of group decision-making based on LCA and SLCA results.

Most of the research in this PhD thesis is based on the following articles published or submitted.

1. (***Chapter 3***) Du C, Kulay L, Cavalett O, Dias L, Freire F (2017a) "Life cycle assessment addressing health effects of particulate matter of mechanical versus manual sugarcane harvesting in Brazil". *International Journal of Life Cycle Assessment*. doi: 10.1007/s11367-017-1334-7.

2. (***Chapter 4***) Du C, Ugaya C, Freire F, Dias L, Clift R (2017b) "Enhancing the results of screening SLCA: a case study of sugarcane production in Brazil". (submitted)

3. (***Chapter 5***) Du C, Dias L, Freire F (2017c) "Improving weighting in comparative LCA and SLCA: a case study of sugarcane production in Brazil". (submitted)

In addition, articles related to this study published in conference proceedings are listed below:

4. Du C, Kulay L, Freire F, Luis D (2016) "Environmental sustainability and impacts on public health of bioethanol in Brazil". *22nd Intl. Sustainable Development Research Society Conference Proceedings*, Lisbon, Portugal.

5. Du C, Kulay L, Freire F, Dias L (2015) "Social sustainability of sugarcane production in Brazil". *Energy for Sustainability 2015 Conference Proceedings – Designing for People and the Planet*, Coimbra, Portugal.

6. Du C, Freire F, Dias L (2014) "Overview of social life-cycle assessment". *2014 [avniR] Conference Proceedings - Life Cycle in Practice*, Lille, France.

6.4 Recommendations

According to the results of this thesis, the following recommendations are hereby made:

To policy makers and sugarcane market players

i) Concerning its damage on public health, pre-harvest burning of sugarcane fields should only be performed in rural or remote areas if performed at all.

ii) Fertilizers and diesel use are the biggest contributors to the environmental impacts of sugarcane production in Brazil. Operations to increase use efficiency such as removing sugarcane residues on the fields before applying fertilizers should be considered. Possibilities of using biodiesel in agricultural machineries should as well be investigated.

iii) Mechanical harvesting of sugarcane should be accelerated especially in areas with lower mechanization levels such as North-Northeast of Brazil, because it can not only reduce environmental impacts, but also generate positive social impacts of increasing average income, improving social equality and fair salary.

iv) Mechanization can result in job loss especially for workers with lower education and lower skill levels. Government and the industry association should create more training programs like RenovAção to prepare the vulnerable labour groups with skills required for the positions for mechanical harvesting, such as drivers, technicians and mechanics, or skills to work in other sectors.

To LCA and SLCA practitioners

v) Height and location of an emission source of particulate matter can largely influence the magnitude of health effects. Thus, spatially-differentiated characterization factors of particulate matter should be applied when they are available.

vi) Systematic analysis of publications should be conducted to complement with modeling social impacts in generic databases, which will strongly improve data quality and identify both negative and positive social impacts.

vii) The pros and cons of presenting mid-point and end-point LCA results to decision-makers should be borne in mind when comparing environmental impacts of different products or scenarios.

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APPENDIX 1 Life cycle inventory for two sugarcane production systems (per tonne of sugarcane), including cultivation, harvesting and transportation from field to industry

	Unit	Manual harvesting	Mechanical harvesting	
Inputs[a]				
Vinasse	m3	0.88	0.88	
Filter cake	kg	7.95	7.95	
Urea, as N	kg	0.74	1.18	
Single superphosphate, as P_2O_5	kg	0.15	0.16	
Potassium chloride, as K2O	kg	1.0	1.21	
Limestone	kg	4.84	4.94	
Gypsum	kg	2.42	2.47	
Pesticide unspecified	g	3.7	3.3	
Glyphosate	g	3.1	3.2	
Diuron	g	1.2	1.2	
Carbofuran	g	5.1	0	
Harvester, production	kg	0	0.055	
Tractor, production	kg	0.097	0.063	
Agricultural machinery, production	kg	0.15	0.12	
Diesel, farm operation	kg	1.22	1.57	
Diesel, sugarcane transportation[b]	kg	0.80	0.58	
Diesel, input transportation[c]	kg	0.10	0.11	
Diesel, vinasse transportation[b]	kg	0.20	0.20	
Emission to air[d]				
Dinitrogen monoxide	g	39.9	62.1	Fertilizer, residues (vinasse, filtercake, straw and roots) and soil amendments field emissions
Ammonia	g	454.2	615.1	
Nitrogen oxides	g	8.4	13.0	
CO2, fossil	kg	3.29	4.03	
VOC	kg	0.95	0	Straw burning (only apply to manual harvesting system)
Nitrogen oxides	kg	0.2	0	
$PM_{2.5}$	kg	0.35	0	
Sulfur oxides	kg	0.05	0	
Dinitrogen monoxide	kg	0.01	0	
Methane	kg	0.13	0	
Carbon monoxide, biogenic	kg	8.81	0	
Emissions to water (groundwater)[e]				
Nitrate	kg	1.67	2.64	Fertilizer and residues (vinasse, filtercake, straw and roots)
Emissions to water (river)[f]				
Carbofuran	g	0.076	0	
Diuron	g	0.018	0.018	
Fiproni	g	0.007	0	

Glyphosate	g	0.047	0.048	Pesticides
Hexazinone	g	0.005	0.005	
Pesticides, unspecified	g	0.025	0.026	
Tebuthiuron	g	0.018	0.019	
Emissions to soil[e,f]				
Zinc	g	0.26	0.26	Emissions of tire (machinery)
Lead	g	0.04	0.04	
Cadmium	g	0.01	0.01	
Cadmium	g	0.005	0.005	Fertilizers
Copper	g	0.09	0.1	
Zinc	g	0.31	0.36	
Lead	g	0.11	0.11	
Nickel	g	0.05	0.06	
Chromium	g	0.1	0.11	
Carbofuran	g	5.01	0	Pesticides
Diuron	g	1.16	1.19	
Fiproni	g	0.48	0	
Glyphosate	g	3.09	3.15	
Hexazinone	g	0.34	0.35	
Imazapic	g	1.67	1.7	
Tebuthiuron	g	1.19	1.22	

a. Inputs and outputs were based on data from Brazilian Bioethanol Science and Technology Laboratory (CTBE), which represents the average technology and agricultural operations in the centre-south of Brazil. (Bonomi et al. 2016)
b. For sugarcane and vinasse transportation, it was considered a transport distance of 25 km between field and mill.
c. Inputs included are seed cane, limestone, gypsum, fertilizers and agrochemicals, and filter cake.
d. Breakdowns of emission sources and assumptions can be found in Appendix 2.
e. It was assumed that 5% of the total nitrogen applied as urea or as ammonia leach to groundwater, being converted into nitrate. All the heavy metals contained in mineral fertilizers, limestone and gypsum were considered as emissions to soil (Trivelin and Franco 2011; Renouf et al 2010).
f. 98.5% of pesticides were considered to be emitted to agricultural soil and 1.5% to superficial water (Renouf et al 2010).

APPENDIX 2 Emission factors applied to calculate sugarcane field emissions to air

Emission	Unit	Emission factor
Diesel combustion in agricultural machinery[a]		
Carbon dioxide, fossil	kg/kg diesel	3.14
Carbon monoxide, fossil	kg/kg diesel	1.14E-02
Dinitrogen monoxide	kg/kg diesel	1.20E-04
Heat, waste	MJ/kg diesel	45.58
Methane, fossil	kg/kg diesel	1.61E-04
Nickel	kg/kg diesel	7.05E-08
Fertilizer field emissions[b]		
Ammonia	kg/kg fertilizer	3.60E-01
Nitrogen oxides	kg/kg fertilizer	4.40E-03
Dinitrogen monoxide	kg/kg fertilizer	2.10E-02
Carbon dioxide, fossil	kg/kg fertilizer	1.58
Vinasse field emissions[c]		
Nitrogen oxides	kg/m^3 vinasse	3.00E-03
Dinitrogen monoxide	kg/m^3 vinasse	1.40E-02
Filter cake field emissions[c]		
Nitrogen oxides	kg/kg filter cake	5.05E-05
Dinitrogen monoxide	kg/kg filter cake	2.41E-04
Sugarcane straw[d]		
Nitrogen oxides	kg/t straw	2.70E-03
Dinitrogen monoxide	kg/t straw	1.27E-02
Sugarcane roots[d]		
Nitrogen oxides	kg/t roots	0.01
Dinitrogen monoxide	kg/t roots	0.05
Limestone[b]		
Carbon dioxide, fossil	kg/limestone	0.48
Sugarcane burning before manual harvesting[e]		
VOC	kg/t residues	7
Nitrogen oxides	kg/t residues	1.5
$PM_{2.5}$	kg/t residues	2.6
Sulfur oxides	kg/t residues	0.4
Dinitrogen monoxide	kg/t residues	0.1
Methane	kg/t residues	0.93
Carbon monoxide, biogenic	kg/t residues	65

a. Based on data from Nemecheck et al. 2007, with updates to represent Brazilian conditions.
b. 30% of the total N applied as urea was considered to be emitted as ammonia, and 1% of the ammonia was converted as N2O. 1% of the total N applied directly emitted as N2O, and 0.75% of the nitrogen leached were assumed to be emitted as N2O. All carbon content in urea and limestone is emitted as carbon dioxide (Costa 2003; Nemecek et al. 2007; IPCC 2006).

c. 1.225% of N in vinasse and filter cake is converted to direct and indirect N_2O emissions (IPCC 2006). Nitrogen content was assumed as 0.595 kgN/m^3 for vinasse and 12.5 kgN/tonne for filter cake (Macedo 2007; Chagas et al. 2016).
d. Direct and indirect N_2O emissions are considered based on the IPCC method (IPCC 2006). Nitrogen content in straw and roots is assumed as 4.77 gN/kg of sugarcane straw and 5.1 gN/kg of sugarcane roots (Smith et al. 2005; Hassuani 2005).
e. Emission factors for VOC and sulfur oxides are based on GREET (2009); and NO_x, $PM_{2.5}$, N_2O, CH_4, and CO (biogenic) are estimated based on França et al. (2012).

APPENDIX 3 Equations and values applied to calculate Intake Fraction

This study adopted the recommended values and method by Humbert et al. (2011) to calculate Intake Fraction. Recommended emission-weighted average iF for Latin America is applied to calculate the iF with respect to primary and secondary $PM_{2.5}$ under the conditions of different emission heights and population densities. Values for iF of primary $PM_{2.5}$ for Latin America are as follows: Urban – 29 ppm; Rural – 0.75 ppm; Remote – 0.1 ppm; and Population-weighted average – 12 ppm (ppm stands for parts per million, representing mg PM inhaled per kg PM emitted). These recommended values of iF are for unknown stack height emissions. In order to differentiate emission heights, following equations are applied,

$$iF_{high\text{-}stack} = iF_{unknown\text{-}stack} / (f_{e,\ high\text{-}stack} + Y \times f_{e,\ low\text{-}stack} + X \times Y \times f_{e,\ ground\text{-}level})$$

$$iF_{low\text{-}stack} = Y \times iF_{unknown\text{-}stack} / (f_{e,\ high\text{-}stack} + Y \times f_{e,\ low\text{-}stack} + X \times Y \times f_{e,\ ground\text{-}level})$$

$$iF_{ground\text{-}level} = X \times Y \times iF_{unknown\text{-}stack} / (f_{e,\ high\text{-}stack} + Y \times f_{e,\ low\text{-}stack} + X \times Y \times f_{e,\ ground\text{-}level})$$

where $f_{e,\ high\text{-}stack}$, $f_{e,\ low\text{-}stack}$ and $f_{e,\ ground\text{-}level}$ are the fractions of total emissions from high-stack (>100m), low-stack (>25m) and ground-level respectively. Values applied in this study is in consistent with Humbert et al. (2011), which is based on American conditions, with $f_{e,\ high\text{-}stack}$= 41%, $f_{e,\ low\text{-}stack}$ = 17%, $f_{e,\ ground\text{-}level}$ = 42%. X and Y are the intake fraction ratios of ground-level to low-stack and low-stack to high-stack emissions respectively. In the Humbert method, X and Y values from RiskPoll were applied, in which X equals to 1.9 for rural and 2.9 for urban conditions, and Y equals to 1.2 for rural and 1.3 for urban conditions. To calculate population-weighted average iF, the population fractions for urban, rural and remote conditions are assumed to be 41%, 57% and 2%. In terms of secondary $PM_{2.5}$, the Humbert method adopted the regressions of Greco et al. (2007) and Van Zelm et al. (2008). For secondary $PM_{2.5}$, stack height has limited importance in affecting iF. Equations applied to calculate secondary $PM_{2.5}$ are shown in the table below.

Table: Equations applied to calculate secondary $PM_{2.5}$

	Urban	Rural	Remote
SO_2	Based on Greco et al. (2007) with adjusting breathing rate to 13 m^3 $person^{-1} day^{-1}$, the values are equal to ones in Humbert et al. (2011).		$= iF(SO_{2\ rural}) \times (iF(PM_{2.5\ remote}) / iF(PM_{2.5\ rural}))$
NO_x			$= iF(NO_{x\ rural}) \times (iF(PM_{2.5\ remote}) / iF(PM_{2.5\ rural}))$
NH_3	Based on Van Zelm et al. (2008), $iF_{urban} = iF_{rural}$		$= iF(NH_{3\ rural}) \times (iF(PM_{2.5\ remote}) / iF(PM_{2.5\ rural}))$

APPENDIX 4 Survey material for collecting experts′ opinions on weights of LCA and SLCA categories

Dear LCA and SLCA experts,

We are performing a life cycle study on environmental and social impacts of sugarcane production in Brazil using manual and mechanical harvesting. We are contacting you to collect your opinions on the weighting factors of environmental and social categories. This survey should only take 8 - 10 minutes to complete. Be assured that all answers you provide will be kept in confidentiality.

Thank you in advance for your cooperation!

<u>THE SURVEY STARTS HERE</u>

In this comparative LCA study, we assessed environmental impacts of sugarcane production using manual and mechanical harvesting in the Centre-South region of Brazil on 8 mid-point categories. The mid-point LCA results obtained are presented in Table 1.

Table 1 Mid-point results of sugarcane production with manual and mechanical harvesting (per t of sugarcane)

Impact category	Unit	Manual harvesting product system	Mechanical harvesting product system
Climate change	kg CO_2 eq	38	29
Fossil depletion	kg oil eq	6.7	8
Ozone depletion	kg CFC-11 eq	1.5E-6	1.8E-6
Terrestrial acidification	kg SO_2 eq	1.3	1.6
Freshwater eutrophication	kg P eq	0.0019	0.002
Human toxicity	kg 1,4-DB eq	4.2	4.4
Photochemical oxidant formation	kg NMVOC	0.7	0.08
Particulate matter formation	kg PM_{10} eq	0.6	0.2

Considering i) **the context of sugarcane production in Brazil**, and ii) **importance of changes on impacts from manual to mechanical harvesting** (e.g. on Climate Change, reducing emissions from 38 kgCO_2 eq/t of sugarcane to 29 kgCO_2 eq/t of sugarcane), please assign weights (0-100 points) to each of the selected mid-point categories below. All the weights assigned should be summed up to 100 points.

No.	Impact category	Score
1	Climate change	
2	Fossil depletion	
3	Ozone depletion	
4	Terrestrial acidification	
5	Freshwater eutrophication	
6	Human toxicity	
7	Photochemical oxidant formation	
8	Particulate matter formation	
	TOTAL	**100**

We also assessed environmental impacts of sugarcane production on 3 end-point categories. LCA results at the damage level are shown in Table 2.

Table 2 End-point results of sugarcane production with manual and mechanical harvesting (per t of sugarcane)

Damage category	Unit	Manual harvesting product system	Mechanical harvesting product system
Damage to human health	DALY	4.3E-04	9.7E-05
Damage to ecosystem diversity	species.yr	3E-07	2.4E-07
Damage to resource availability	$	1.1	1.3

Considering i) **the context of sugarcane production in Brazil**, and ii) **importance of changes on damages from manual to mechanical harvesting** (e.g. on Damage to ecosystem diversity, reducing impacts from 3E-07 species.yr /t of sugarcane to 2.4E-07 species.yr /t of sugarcane), please assign weights (0-100 points) to each of the end-point categories below. All the weights assigned should be summed up to 100 points.

No.	Damage category	Score
1	Damage to human health	
2	Damage to ecosystem diversity	
3	Damage to resource availability	
	TOTAL	**100**

Sugarcane sector in Brazil has increasingly adopted mechanical harvesting in the past decade. Mechanization has profoundly changed the landscape of sugarcane sector regarding employment, working conditions and influences on local communities. Comparison of social impacts of manual and mechanical sugarcane harvesting based on our systematic analysis of relevant literature is presented in Table 3.

Table 3 Comparison of social impacts of manual and mechanical sugarcane harvesting

Subcategory	Manual harvesting system	Mechanical harvesting system
Health and safety	Sugarcane workers are likely to be exposed to high health risks due to agrochemicals use. Cutting cane is a repetitive task, and workers often work under high temperature. Exhaustion, fatigue, spinal diseases, and high psychological stress have been reported.	High psychological stress due to long working hours has been reported.
Local employment	Manual sugarcane harvesting creates a large number of jobs per year.	Mechanization of sugarcane harvesting is reported to cause job loss. One harvester is estimated to replace 80-100 sugarcane cutters.
Fair salary	Sugarcane cutters are paid by productivity.	Mechanical sugarcane workers are paid by a fixed wage.
Access to material resources	No risks identified	Large producers occupied 75% of sugarcane croplands. Number of smallholder farmers has been declining.
Delocalization and migration	Majority of sugarcane cutters in the centre-south region are from North-Northeast of Brazil. Lack of job opportunities has been reported in the home states of migrant workers.	No risks identified
Public commitment to sustainability issues	The state government of São Paulo and the Brazilian sugarcane industry union (UNICA) signed the voluntary document Green Protocol, aiming at eliminating pre-harvest field burning.	No risks identified
Safe and healthy living conditions	Sugarcane pre-harvest burning has been associated with increasing health risk on respiratory diseases of communities near sugarcane plantations.	No risks identified
Equal opportunity and discrimination	Very few females work as sugarcane cutters. Cases have been reported that women were required to be sterilized to obtain a job.	Workers with low schooling are the most vulnerable population to lose jobs in face of mechanization; meanwhile, demand for skilled labour will increase. Number of female workers is expected to increase too.

Considering **i) the context of sugarcane production in Brazil**, and **ii) importance of changes on social performances on each social issue from manual to mechanical harvesting** (based on the information from Table 3 and your knowledge), please assign weights (0-100 points) to each social issue below. All the weights assigned should be summed up to 100 points.

No.	Social issues	Score
1	Health and safety	
2	Local employment	
3	Fair salary	
4	Access to material resources	
5	Delocalization and migration	
6	Public commitment of sustainability issues	
7	Safe and healthy living conditions	
8	Equal opportunity and discrimination	
	TOTAL	**100**

Thank you for completing our survey!