Guilherme Marcelo Zanghelini

PONDERAÇÃO DE CATEGORIAS DE IMPACTO AMBIENTAL ATRAVÉS DE ANÁLISE DE DECISÃO MULTICRITÉRIO

Weighting Environmental Impact Categories through Multicriteria Decision Analysis

Tese submetida ao Programa de Pós-Graduação em Engenharia Ambiental da Universidade Federal de Santa Catarina para a obtenção do Grau de Doutor em Engenharia Ambiental.
Orientador: Prof. Dr. Sebastião Roberto Soares.

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Esta Tese foi julgada adequada para obtenção do Título de "Doutor", e aprovada em sua forma final pelo Programa de Pós-Graduação em Engenharia Ambiental

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"It is good to have an end to journey toward; but
is the journey that matters, in the end."
Ursula K. Le Guin

RESUMO

Na avaliação do ciclo de vida (ACV) o decisor frequentemente se depara com situações complexas de resolver: os resultados das diversas categorias de impacto nem sempre pendem para uma mesma alternativa, ou ainda, se modificam a medida que cenários são analisados, situação conhecida como *trade-off*. Para auxiliar na interpretação destes resutados, a ponderação é uma etapa que atribui significâncias para os impactos ambientais e permite converter todos os indicadores em uma *score final* através de uma agregação. Esta significância pode ser determinada pelo julgamento dos *stakeholders* e é influenciada por preferências individuais. Mesmo que diferentes grupos julguem de forma diferente a importância dos impactos, hoje, não existe um conjunto de pesos relacionados ao contexto brasileiro. Assim, esta proposta de tese tem como objetivo central desenvolver a ponderação de categorias de impacto ambiental em nível *midpoint*. A metodologia compreende dois painéis: (i) composto por especialistas da ACV para pesar critérios relacionados aos impactos ambientais, e (ii) formado por três grupos de *stakeholders* nacionais (Academia, Governo e Indústria) para indicar suas preferências com relação às categorias de impacto. A estruturação deste modelo foi embasada na hibridização de duas abordagens da Análise de Decisão Multicritério (MCDA), o *Analytical Hierarchy Process* (AHP) para ponderar os critérios e o *Preference Ranking Organization METHod for Enrichment of Evaluations* (PROMETHEE II) para comparar e agregar os valores para finalizar a ponderação das categorias de impacto. O conjunto de categorias de impacto e o delineamento do grupo de *stakeholders* considerou elementos da bibliometria da ACV nacional. Para avaliar a variação das respostas por atores para as categorias utilizou-se a ANOVA por meio do software Statistic®. Os 16 especialistas em ACV consideraram o critério de efeitos à saúde humana (0,27) como mais importante seguido pelo critério de efeitos ao ecossistema (0,18). Outros 6 critérios completaram à comparação pareada na escala de Saaty. Com relação aos impactos ambientais, o painel recebeu 76 respostas (taxa de retorno de 40%) que apontaram o Aquecimento Global como o mais significativo por todos os grupos de *stakeholders*, com média de 0,185. As outras categorias que preenchem o conjunto de pesos e suas significâncias são, respectivamente: Depleção da Cama de Ozônio, 0,155; Depleção Abiótica, 0,150; Toxicidade Humana, 0,129; Uso de terra, 0,106; Acidificação, 0,105; Formação de Ozônio Fotoquímico, 0,086; e Eutrofização, 0,083. A análise da dispersão das respostas dos *stakeholders* nacionais demonstrou uma convergência estatística do balanço de preferencias para 7 das 8 categorias de impacto. No entanto a ANOVA indicou que para Depleção Abiótica os grupos formados pela Academia e pela Indústria não responderam de forma idêntica. O conjunto de pesos encontrados facilita a interpretação de resultados de ACV, e possui similaridades e disparidades com conjuntos de pesos existentes na comunidade científica e aplicados pelas indútrias, o que demonstra a importância de um conjunto representativo para o Brasil. O modelo baseado em MCDA foi considerado de fácil assimilação pelos painelistas e é replicável para situações específicas (como uma indústria). Complementarmente, nenhum importante tomador de decisão (ou grupo de *stakeholders*) pode ser excluído do processo, uma vez que há variação no julgamento das partes.

Palavras-chave: Avaliação do ciclo de vida, Análise de decisão muti-critério, Ponderação, AHP, PROMETHEE II, Brasil.

ABSTRACT

In life cycle assessment (LCA), decision maker (DM) often faces complex results to interpret. It is common that values of different indicators are conflicting and varies amongst scenarios alternatives, situation that carry the trade-off condition between categories. To address this issue, weighting is a step that assigns significance to the environmental impacts and converts all the indicators into a final score. This significance can be determined by stakeholder's judgment and is influenced by each individual preferences. However, even with different groups judging differently the importance of impacts, currently there is no set of weights related to the Brazilian context (or by Brazilian stakeholders). Thus, the aim of this PhD thesis is to calculate a set of weights for LCA midpoint impact categories to assist the interpretation of LCAs in Brazil. The methodology comprises two panels: (i) composed by LCA experts for the criteria pairwise comparison, and (ii) formed by three national stakeholder groups (Academy, Government and Industry) to indicate their preferences for impact categories. We applieda hybrid Multicriteria Decision Analysis (MCDA) formed by the Analytical Hierarchy Process (AHP) for criteria panel and the Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE II) to compare and aggregate the values of the impact categories. The set of impact categories and the outline of the stakeholders groups considered elements of Brazilian LCA bibliometry. ANOVA was used to evaluate the variation of responses according to each group of DM. The 16 LCA experts considered the Damage to Human health (0.27) as the more important criterion followed by Damage to Ecosystem (0.18). Another six criteria completed the pairwise comparison in the Saaty scale. With respect to environmental impacts, 76 partitipants answered the questionnaire (return rate of 40%) and considered Global Warming as the most significant indicator with weighting factor of 0.185. Other categories that fill the set of weights and their significance are, respectively: Ozone Layer Depletion, 0.155; Abiotic Depletion, 0.150; Human Toxicity, 0.129; Land use, 0,106; Acidification, 0.105; Photochemical Ozone Formation, 0.086; and, Eutrophication, 0.083. The dispersion of answers from the stakeholders indicated a statistical convergence of the balance of preferences for seven in eight impact categories. However, ANOVA indicated that for Abiotic Depletion the groups formed by the Academy and Industry did not respond identically. The set of weights calculated facilitates the interpretation of LCA results, and has similarities and disparities with sets of weights in the scientific community and applied by industries, which demonstrates the importance of a representative set for Brazil. The model developed with support of MCDA approach was considered easy to implement and allow one to replicate it in any condition (e.g., for an industry). In addition, no DM should be excluded from the process, since there is variation in the judgment of the parties.

Keywords: Life cycle assessment, Multi-criteria decision analysis, Weighting, AHP, PROMETHEE II, Brazil.

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LISTA DE ABREVIATURAS E SIGLAS

ABNT	-	Associação Brasileira de Normas Técnicas
ACV	-	Avaliação do ciclo de vida
AECV	-	Avaliação Econômica do Ciclo de Vida
AHP	-	Analytic Hierarchy Process
AICV	-	Avaliação do impacto do ciclo de vida
ANOVA	-	Análise de variância
AoP	-	Áreas de proteção
ASCV	-	Avaliação Social do Ciclo de Vida
BEES	-	Building for Environmental and Economic Sustainability
CC	-	Climate change
CI	-	Índice de Inconsistência
CICLOG	-	Grupo de Pesquisa em Avaliação do Ciclo de Vida
CIn	-	Confidence intervals
CML		Center of Environmental Science of Leiden University
CR		Taxa de Consistência
CV	-	*Coeficient of variation*
DALY		*Disability adjusted life years*
DETR		*Department of the Environment, Transport and the Regions*
DpA		Distância para um Alvo
DpP		Disposição para Pagar
DtT		*Distance to Target*
EC		*European Commission*
EDIP		*Environmental Design of Industrial Products*
ELECTRE		*ELimination Et Choix Traduisant la REalité*
Embrapa	-	Empresa Brasileira de Pesquisa Agropecuária
EPS		*Environmental Priority Strategies*
EPD	-	*Environmental Product Declaration*
EPAGRI		Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina
eq.		Equivalente
FATMA		Fundação do Meio Ambiente
FLORAM		Fundação Municipal do Meio Ambiente de Florianópolis
GEE	-	Gases de efeito estufa
GHG	-	*Greenhouse gas*
GWP	-	*Global Warming Potential*
H		*Hierarchist*
IBGE	-	Instituto Brasileiro de Geografia e Estatística
IBICT		Instituto Brasileiro de Informação em Ciência e Tecnologia
ICV	-	Inventário de ciclo de vida
IES		*Institute for Environment and Sustainability*
ILCD	-	*International Reference Life Cycle Data System*
INMETRO		Instituto Nacional de Metrologia
IPCC	-	*Intergovernmental Panel on Climate Change*
ISO	-	*International Organization for Standardization*

JRC		*Joint Research Centre*
HSD	-	*Honest significant difference*
LCA	-	*Life cycle assessment*
LCI	-	*Life cycle inventory*
LCIA	-	*Life cycle impact assessment*
LIME		*Life cycle Impact assessment Method based on Endpoints*
MARSAN		*Méthode d'Analyse, de Recherche et de seleção d'Activités Nouvelles*
MATLAB		*MATrix LABoratory*
MAUT		*Multi Attribute Utility Theory*
MAVT		*Multi Attribute Value Theory*
MC		*Monte Carlo Analysis*
MCA		*Multicriteria Analysis*
MCDA		*Multicriteria Decision Analysis*
MMA		Ministério do Meio Ambiente
NBR		Norma Brasileira
NEEDs		*New Energy Externalities Development for Sustainability*
NOCEGA		*Netherlands Oil and Gas Exploration and Production Association*
OECD		*Organization for Economic Co-operation and Development*
ONG		Organização não Governamental
PAG		Potencial de Aquecimento Global
PCR	-	Regra de Categoria de Produto
PCS		Produção e Consumo Sustentáveis
PROMETHEE		*Preference Ranking Organization METHod for Enrichment of Evaluations*
ReCiPe		Método de AICV criado em parceria entre RIVM, CML, PRe Consultants e Radboud University.
RI		Índice de Consistência
RIVM		*National Institute for Public Health and the Environment*
SAB		*Science Advisory Board*
SEMA		Empresa francesa criadora do MARSAN
SETAC		*Society of Environmental Toxicology and Chemistry*
SS		*Single Score*
TR		*Technical Report*
TS		*Technical Specification*
UF	-	Unidade Funcional
UFSC		Universidade Federal de Santa Catarina
USEPA		*United States Environmental Protection Agency*
WtP		*Willingness-to-pay*

LISTA DE SÍMBOLOS E UNIDADES

%	Porcentagem
Cd	Cádmio
CFC	Clorofluórcarboneto
CFC-11	Triclorofluormetano
CH_4	Metano
CO_2	Dióxido de carbono
CO_2 eq.	Dióxido de carbono equivalente
DB eq.	Diclorobenzeno equivalente
DDT	Diclorodifeniltricloroetano
σ	Desvio Padrão
e.g.	*exempli gratia* / por exemplo
g	Gramas
i.e.	*id est* / isto é/ou seja
kg	Quilograma
km	Quilometro
kWh	Kilowatt hora
L	Litro
MJ	Megajoule
m^2a	Metro quadrado ano
μ	Média amostral
m^2	Metro quadrado
m^3	Metro cúbico
m	Metro
mg	Miligrama
N	Nitrogênio
N_2O	Óxido nitroso
NH_3	Amônia
NMVOC	Composto orgânico volátil não metânico
NO_3	Nitrato
NO_x	Óxidos de nitrogênio
Oil eq.	Óleo combustível equivalente
P	Fósforo
PO_4	Fosfato
PO_4 eq.	Fosfato equivalente
P_2O_5	Pentóxido de fósforo
SO_2	Dióxido de enxofre
SO_2 eq.	Dióxido de enxofre equivalente
tkm	Tonelada quilometro
V	Volume
VOCs	Compostos orgânicos voláteis
W/m^2	Forçamento Radioativo Infravermelho por metro quadrado

SUMÁRIO

Capítulo I. Contextualização, objetivos e revisão bibliográfica

I.1 INTRODUÇÃO DA TESE

Com as atenções voltadas para a sustentabilidade, diversas ferramentas e metodologias foram e estão sendo desenvolvidas, permitindo o gerenciamento dos passivos ambientais existentes, o acompanhamento das atividades por indicadores de desempenho socioambiental para a melhoria contínua, a escolha por alternativas mais eficientes, a antecipação de impactos gerados por determinadas atividades, entre diversas outras possibilidades.

A avaliação do ciclo de vida (ACV) é uma destas metodologias, aplicada para usos múltiplos em fornecimento de informações internas e externas e de apoio à decisão (BAITZ et al., 2013). Diversos usuários, na academia, indústria, ou consultoria em todo o mundo aplicam a ACV em processos científicos, industriais, agrícolas, sociais ou políticos para a avaliação de produtos, processos, cenários e alternativas. Muitos autores confirmam a sua importância e ampla aplicação para avaliações ambientais (BAITZ et al., 2013; BAUMANN; TILLMAN, 2004; GUINÉE et al., 2002).

Reflexo dessa consolidação é a crescente exigência por parte das políticas públicas externas e internas com relação a ACVs de produtos e serviços, desde programas de produção e consumos sustentáveis (UNIÃO EUROPEIA, 2008), barreiras alfandegárias na exigência de mercado representada por selos e rótulos ambientais tipo I e tipo III (UNIÃO EUROPEIA, 2009) e por aspectos legais como a Política Nacional de Resíduos Sólidos (LEI Nº 12.305, BRASIL, 2010), e *European Union Directive* 2002/96/EC (UNIÃO EUROPEIA, 2008). Esta realidade também pode ser identificada na evolução acadêmica da publicação de artigos pesquisada na base de dados SCOPUS, onde a ACV como palavra-chave apresentou um aumento de 64% nos últimos 5 anos no mundo e de 84% no Brasil durante o mesmo período (ZANGHELINI et al., 2014).

A ACV tem-se mostrado vital para o desenvolvimento sustentável de uma forma mais concreta, aplicado em nível de produto, em que os caminhos apontados são geralmente aqueles considerados com menores impactos ambientais (ver ALVARENGA; PRUDÊNCIO DA SILVA; SOARES, 2012) ou aqueles que sugerem mudanças para a redução dos impactos (ver CHERUBINI et al., 2015). Talvez a contribuição mais importante desta metodologia para o desenvolvimento sustentável e a Produção e Consumo Sustentáveis (PCS) seja a sua base conceitual chamada de “pensamento em ciclo de vida[1]”. O pensamento em ciclo de vida é uma evolução em termos de gestão e controle ambiental, ampliando a visão dos efeitos de determinado sistema para todo o seu ciclo de vida. Este embasamento fica evidente na definição de ACV estabelecida pela Associação Brasileira de Normas Técnicas (ABNT): “Compilação e avaliação das entradas, saídas e dos impactos ambientais potenciais de um sistema de produto ao longo do seu ciclo de vida” (ABNT ISO, 2009a).

A abordagem mais recorrente é a da ACV “ambiental”[2] ou tradicional, cuja metodologia é a única normatizada (ABNT ISO 2009a; 2009b). A base metodológica da ACV tradicional é converter aspectos ambientais de um produto ou serviço (fluxos compilados no inventário de ciclo de vida) em potenciais impactos ambientais por meio de modelos de caracterização consolidados, de forma que os resultados interpretados tomam formas numéricas (a caracterização ocorre na etapa de avaliação de impactos do ciclo de vida – AICV). Estes potenciais impactos ambientais são divididos nas chamadas categorias de impacto ambiental ou de danos, que são “classes que representam as questões ambientais relevantes às quais os resultados da análise do ciclo de vida podem ser associados” (ABNT ISO, 2009a).

Os valores podem ser representativos de dois níveis na cadeia causa-efeito ambiental: nível *midpoint* ou nível *endpoint*[3]. Em nível *midpoint*, os impactos são entendidos como "problemas ambientais", como as mudanças climáticas. Em nível *endpoint*, as categorias *midpoint* são agregadas em categorias de danos, como a saúde humana. A diferença entre as duas abordagens está no momento em que o estressor ambiental ocorre, sendo o *endpoint* o dano final que ocorre na cadeia (e o *midpoint* o impacto intermediário que gera o dano). Por exemplo, a ocorrência da

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[1] *Life Cycle Thinking*, termo original em ingles.

[2] Entende-se nesta tese por ACV ambiental, aquela definida pela Norma NBR ISO 14040 (ABNT ISO 2009a)

[3] Categoria de impacto é sinônimo de ‘a nível *midpoint’*, enquanto que categoria de dano, ‘em nível *endpoint’*.

diminuição de vida útil de um ser humano por conta do aumento de incidência de câncer de pele em virtude de um aumento da temperatura no globo. Boa parte dos estudos de ACV interpreta seus resultados a nível *midpoint*, porque são valores com menor incerteza, embora de difícil comunicação.

A quantificação para cada categoria de impacto ou dano representa um indicador de desempenho ambiental (relacionado àquele mecanismo específico da categoria). Por exemplo, para a categoria de impacto de mudanças climáticas, o indicador é a quantidade emitida de gases causadores do efeito estufa (GEE), caracterizados para um valor de massa de dióxido de carbono equivalente emitido (i.e., toneladas de CO_2 equivalente) (UDO DE HAES et al., 2002). Existem diversas outras categorias de impacto disponíveis na ACV, como a destruição da camada de ozônio, toxicidade humana ou a eutrofização. A forma mais representativa de resultado, para uma análise abrangente e equilibrada, e uma tomada de decisão baseada em considerável volume de informação, é quando se considera múltiplas categorias de impacto, bem como várias fases do ciclo de vida (LIPPIATT, 2007).

Em posse dos resultados de uma ACV, a tomada de decisão, com relação à variável ambiental tem sido realizada com relativo sucesso. Entretanto, o que acontece quando um sistema de produto representa um bom desempenho ambiental para a categoria de impacto de mudanças climáticas, mas apresenta valores muito elevados para outras categorias? E se, ao tomar a decisão por um determinado cenário que reduzirá a eutrofização, consequentemente aumentará a acidificação? Os tomadores de decisão muitas vezes consideram múltiplos objetivos que entram em conflito ou se compensam em um conjunto de opções (situação conhecida como *trade off*) (REAP et al., 2008).

Quando isso ocorre, a tomada de decisão carece de métodos de interpretação que auxiliem as escolhas após a AICV. Não é uma situação incomum o usuário chegar à análise dos resultados sem conseguir indicar com certeza qual caminho seguir. Por exemplo, se em uma comparação entre dois produtos (A) e (B), (A) tem uma pontuação mais elevada para uma determinada categoria de impacto (e.g., mudanças climáticas), e (B) apresenta uma pontuação mais alta para outra categoria (e.g., acidificação), torna-se difícil compará-los e justificar qualquer conclusão. Esta preocupação é explicitada pelos autores Gloria, Lippiatt e Cooper (2007) e Lipuščѐk et al. (2010) na afirmação de que dificilmente acontece na prática uma situação na qual todas as categorias de impacto pendem para um produto em comparação ao outro (i.e., Produto (A) possui maiores emissões tanto para a categoria de mudanças climáticas quanto de acidificação se comparado ao produto (B)).

Para tentar solucionar estes problemas, a própria ACV faz uso de algumas abordagens de auxílio à interpretação. Em especial, três são recorrentes: normalização, ponderação e agregação de resultados. Estas etapas são consideradas opcionais por norma pelo motivo do acréscimo de subjetividade ao resultado, mas no entanto, sua prática têm se tornado mais constante para apoiar a decisão final. Finnveden, Eldh e Johansson (2006), explicam que na normalização, os resultados da caracterização são relativizados a algum valor de referência, na qual a ideia é demonstrar a significância dos resultados com relação a esta referência. Enquanto que na ponderação, a partir dos valores obtidos na caracterização e normalização, os resultados são convertidos por fatores numéricos relacionados à importância de cada categoria de impacto. Ao final da ponderação, pode haver uma agregação das categorias de impacto (FINNVEDEN; ELDH; JOHANSSON, 2006), em que o resultado final é uma pontuação única, conhecida como *Single Score* (SS).

A normalização pode auxiliar na interpretação de resultados de uma ACV, pois converte as diversas categorias em uma unidade comum (dependendo da referência). No entanto, somente a ponderação, segundo Johnsen e Lokke (2012) pode revelar quais impactos ou danos ambientais são (considerados) mais significantes para o processo ou produto em questão. Ao final, quando agregado, o SS pode facilitar a interpretação em análises comparativas (GLORIA; LIPPIATT; COOPER, 2007; LIPPIATT, 2007; SOARES; TOFFOLETTO; DESCHÊNES, 2006).

No entanto, indicar qual impacto ambiental é mais importante não é uma tarefa fácil, e muito se tem discuto a respeito (BARE; GLORIA, 2006; CASTELLANI et al., 2016; CORTÉS-BORDA; GUILLÉN-GOSÁLBEZ; ESTELLER, 2013; GELDERMANN; RENTZ, 2005; KALBAR et al., 2016; PIZZOL et al., 2017; SOARES TOFFOLETTO; DESCHÊNES, 2006). A importância de impactos leva em conta muito mais do que relações das ciências exatas, incluindo (e devendo incluir) diversos critérios e setores para identificar estas significâncias. Afinal, quando se trata de impactos para o meio ambiente, o tomador de decisão é tanto o impactador, quanto o impactado.

Na ACV, três abordagens se destacam para encontrar estes pesos: a monetização das categorias de impacto, à distância (em termos de redução) para atingir determinadas metas (*distance-to-target*), e a consulta a grupo de especialistas (também conhecido como painel) nas quais os resultados são baseados em julgamentos (AHLROTH et al., 2011). Ideologicamente, talvez o painel seja a abordagem mais democrática, pois possibilita a consideração de todos os atores que conformam a sociedade, caso no qual uma resposta representa todos os interessados. Talvez por este motivo, Finnveden, (1999) e Souza (2010) a tenha considerado uma das abordagens mais promissoras; afirmação que está alinhada com Guinée et al. (2002), que sugerem que a ponderação deve ser embasada em um painel de especialistas, incluindo todas as partes relevantes ou que deve ser embasada em informações publicadas.

A ponderação por consulta a especialistas é baseada na escolha de valores, assim, pode apresentar variações conforme especificidades do próprio grupo de indivíduos. Esta situação é bem clara na constatação de que em última instância, a importância dos efeitos ambientais considerados baseia-se num julgamento (HUPPES; VAN OERS, 2011). Embora o julgamento leve em consideração o modo como cada indivíduo entende o problema, parte-se do pressuposto que especialistas e atores que conformam um grupo tendem a convergir em suas opiniões e convicções, se bem estruturadas.

Identificar quais impactos são mais importantes por meio da consulta a especialistas e critérios pré-estabelecidos ainda mantém duas questões importantes: (1) Como avaliar os impactos frente aos critérios, e; (2) Qual critério deve ter maior importância? Para responder a estas perguntas, Finnveden et al. (2009) indicam que métodos e dados utilizados nos métodos de ponderação podem e devem ser discutidos e avaliados, em termos de consistência, por métodos científicos. Diante desta problemática (que não é exclusividade da ACV), métodos de decisão multi-critério (MCDA[4]) foram desenvolvidos (REAP et al., 2008; ROWLEY et al., 2012), e são considerados por diversos autores como a abordagem mais adequada para a mensuração de preferências na ACV (CHEVALIER; ROUSSEAUX, 1999; MYLLYVIITA et al., 2012; SOARES; TOFFOLETTO; DESCHÊNES, 2006). Finnceden et al. (2009) ilustram esta condição afirmando que o desenvolvimento de métodos de ponderação/agregação para uso na ACV tem se beneficiado de evoluções de áreas como a economia ambiental e análise de decisão multi-critério. De fato, existe uma relação muito próxima entre a ACV e a MCDA, principalmente ligada ao fato de que a própria ACV é uma metodologia de auxílio à tomada de decisão, estruturada seguindo os preceitos desta ciência. Relações entre as duas metodologias são bem descritas por Geldermann e Rentz (2005).

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[4] MCDA, sigla de *Multicriteria Decision Analysis* em inglês.

Assim, para auxiliar na interpretação dos *trade offs* na AICV, precisa-se atribuir valores de significância para as categorias de impacto (ponderação). Estes valores são obtidos geralmente por consulta a especialistas, que podem variar em seus julgamentos conforme cada indivíduo entende o problema. Para auxiliar este julgamento, as MCDA podem ser aplicadas. Se a atribuição de pesos é baseada no modo como um indivíduo compreende um dado problema, é possível cogitar que diferentes realidades acabem por gerar diferentes julgamentos. A variação nos pesos para as categorias de impacto de métodos de AICV existentes hoje confirmam esta hipótese, pois apresentam valores que variam uns dos outros. Assim, a consideração de questões locais pode ser um influenciador na atribuição de significâncias para as categorias de impacto por parte de painelistas, de modo que um modelo de ponderação para o Brasil pode ser diferente de um Europeu.

I.1.1 PERGUNTA DE PESQUISA

Dado o contexto exposto na introdução, foram formuladas as seguintes perguntas de pesquisa:

(1) O conjunto de categorias de impacto ponderadas com base em consulta aos *stakeholders* brasileiros representará o julgamento dos tomadores de decisão?

(2) O grupo de *stakeholders* influenciará de maneira significativa no julgamento de pesos das categorias de impacto?

(3) Comparações baseadas no resultado da ponderação proposta, e agregados em um SS, simplificam a tomada de decisão?

I.1.2 HIPÓTESES

A partir da problemática associada à interpretação de *trade offs* na ACV, perguntas de pesquisa foram elaboradas e hipóteses foram estabelecidas:

(1) O conjunto de categorias de impacto ponderadas por um painel de especialistas representa a preferência para um grupo consultado.

(2) Cada grupo de *stakeholders* possui um julgamento que pode variar estatisticamente do outro grupo.

(3) A aplicação da ponderação/agregação proposta simplifica a interpretação.

I.1.3 OBJETIVOS

I.1.3.1 Objetivo geral

Desenvolver um modelo multicriterioso de ponderação e ponderar as categorias de impacto ambiental em nível *midpoint*.

I.1.3.2 Objetivos específicos

(1) Mapear os *stakeholders* nacionais do governo, indústria e da academia relacionados com o desenvolvimento da ACV;

(2) Elicitar pesos para os critérios de comparação relacionada aos impactos ambientais segundo especialistas em ACV;

(3) Calcular o balanço de preferências ponderadas dos *stakeholders* brasileiros para as categorias de impacto de acordo com cada critério estabelecido em no objetivo específico (2);

(4) Avaliar as diferenças estatísticas no julgamento dos diferentes grupos de tomadores de decisão.

I.1.4 JUSTIFICATIVA

Como mencionado na contextualização desta tese, os resultados de um ACV são de difícil interpretação. Mittier e Scholz (2008) ilustram esta situação quando afirmam que geralmente a ACV demanda a análise de uma lista de 3 a 12 indicadores; que potencializa a complexidade da decisão quando na ocorrência dos *trade offs* (situação presente em BOUFATEH et al., 2011; GELDERMANN; RENTZ, 2005; GLORIA; LIPPIATT; COOPER, 2007; HERMANN; KROEZE; JAWJIT, 2007; LAURIN et al., 2016; LE TENÓ; MARESCHAL, 1998; MYLLYVIITA; LESKINEN; SEPPÄLÄ, 2013; PRADO-LOPEZ et al., 2013; SUBRAMANIAN et al., 2015). Desta forma a ACV carece de métodos de interpretação que auxiliem as escolhas após a AICV.

Embora não seja uma etapa obrigatória pelas normas e exista até uma relutância em discutir modelos de ponderação no âmbito da normatização e harmonização dentro dos grupos de pesquisa (FINNVEDEN et al., 2009), o maior uso da ACV em nível decisional (e.g., políticas públicas) tem aumentado a necessidade da ponderação na ACV, tornando-se uma fase típica (MYLLYVIITA et al., 2012) como ferramenta de auxílio a interpretação (JOHNSEN; LOKKE, 2012; ROTH et al., 2009). É importante que os métodos de ponderação para ACV continuem a ser publicados na literatura científica para aumentar a credibilidade e verificação de dados e métodos da ACV (FINNVEDEN et al., 2009; PIZZOL et al., 2017).

Vários autores indicam a importância da ponderação, na possibilidade de revelar quais impactos são mais significativos para o processo ou produto em questão e de calcular o desempenho de um sistema em um valor final (BARE; GLORIA, 2006; HUPPES; VAN OERS, 2011; JOHNSEN; LOKKE, 2012; SOARES; TOFFOLETTO; DESCHÊNES, 2006). Geldermann e Rentz (2005), Kagi et al. (2016) e Pizzol et al. (2017) complementam afirmando que a ausência de uma ponderação não é uma solução real para o problema, porque neste caso, são atribuídos os mesmos pesos para as categorias de impacto, situação que agrega tanto incerteza quanto não reflete a visão do tomador de decisão pois não possui nenhuma base científica.

Ainda assim, Ahlroth et al. (2011) e Prado-Lopez et al. (2013) afirmam que a ACV enfrenta a falta de métodos robustos que auxiliem a interpretação, principalmente dos referidos *trade offs*. As etapas pós AICV têm recebido menos atenção se comparados ao desenvolvimento dos inventários e modelos de avaliação de impacto (PRADO-LOPEZ et al., 2013). Talvez por este motivo, não exista uma metodologia comumente aceita que pondere e atribua importâncias para os impactos avaliados na ACV (MYLLYVIITA et al., 2012). De forma que diversos autores apontam a necessidade da evolução destas áreas no âmbito da ACV (i.e., SEPPÄLÄ; HÄMÄLÄINEN, 2001) para guiar os tomadores de decisão de uma maneira transparente sem que as escolhas subjetivas sejam mascaradas por tendências indesejadas (PRADO-LOPEZ et al., 2013).

Recentemente Cinelli, Coles e Kirwan (2014) notaram os benefícios da relação da Análise de Decisão Multicritério (MCDA) para auxiliar à interpretação na ACV. Sinergismo estabelecido também por Soares, Toffoletto e Deschênes (2006) e outros (GELDERMANN; RENTZ, 2005; HERMANN; KROEZE; JAWJIT, 2007; JESWANI et al., 2010; MIETTINEN; HÄMÄLÄINEN, 1997; SEPPÄLÄ; BASSON; NORRIS, 2002) o que indica uma tendência e um interessante tema a ser investigado. No entanto, De Luca et al. (2015), Domingues et al. (2015) e Seppälä, Basson e Norris (2002) consideram que as possiblidades de uso do MCDA no âmbito da ACV são ainda pobremente abordadas, fazendo com que mais pesquisas sejam necessárias neste campo segundo Myllyviita et al. (2012).

No Brasil, a comunidade que desenvolve e aplica a ACV, ou toma a decisão em nível de resultados *midpoint* (de certo modo negligenciando os *trade offs*) ou fazem uso de métodos já estabelecidos (métodos de AICV que oferecem a possibilidade de ponderar e agregar os resultados em SS). Em ambos os casos, talvez os resultados não representem a melhor realidade, podendo comprometer a tomada de decisão. Por exemplo, Pizzol et al. (2017) de forma semelhante a Soares, Toffoletto e Deschênes (2006) e Ahlroth et al. (2011), questionam se os impactos seriam ponderados de forma semelhante em diferentes regiões ou países.

Neste sentido, até o momento não existe um modelo de ponderação aplicado para a realidade nacional, com base nas principais categorias de impacto utilizadas no Brasil e envolvendo importantes *stakeholders* na tomada de decisão ambiental nacional. Ademais, o conjunto de métodos de MCDA propostos para calcular as significâncias das categorias de impacto representa um ineditismo no campo da ACV para quantificar pesos por meio de consulta aos especialistas.

Para o Grupo de Pesquisa em Avaliação do ciclo de Vida (CICLOG), a etapa de interpretação dos resultados da ACV, com relação à tomada de decisão e às incertezas é uma área pouco explorada. Dos elementos não obrigatórios da ACV, apenas a Normalização já foi tema de pesquisa (ver SOUSA, 2008). Enquanto que a metodologia de um modo geral vem sendo tema recorrente nas pesquisas do Grupo em busca de melhor compreende-la e praticá-la (para alocação ver GALINDRO, 2012; LÉIS, 2013; RAMÍREZ, 2009; SOUZA JÚNIOR, 2015; para unidade funcional ver LÉIS, 2013; PRUDÊNCIO DA SILVA, 2011; para a definição de fronteiras do sistema ver ZANGHELINI, 2013; para métodos de AICV ver ALVARENGA, 2010; para incertezas, BENEDET JÚNIOR, 2007; CHERUBINI, 2015).

Neste sentido, a presente tese almeja complementar a análise de elementos de incerteza dentro de uma ACV, conforme evolução dos temas pesquisados no CICLOG (Tab. I-1), atuando na etapa de AICV e interpretação, mais especificamente na ponderação de categorias de impacto que permita a agregação em uma pontuação única.

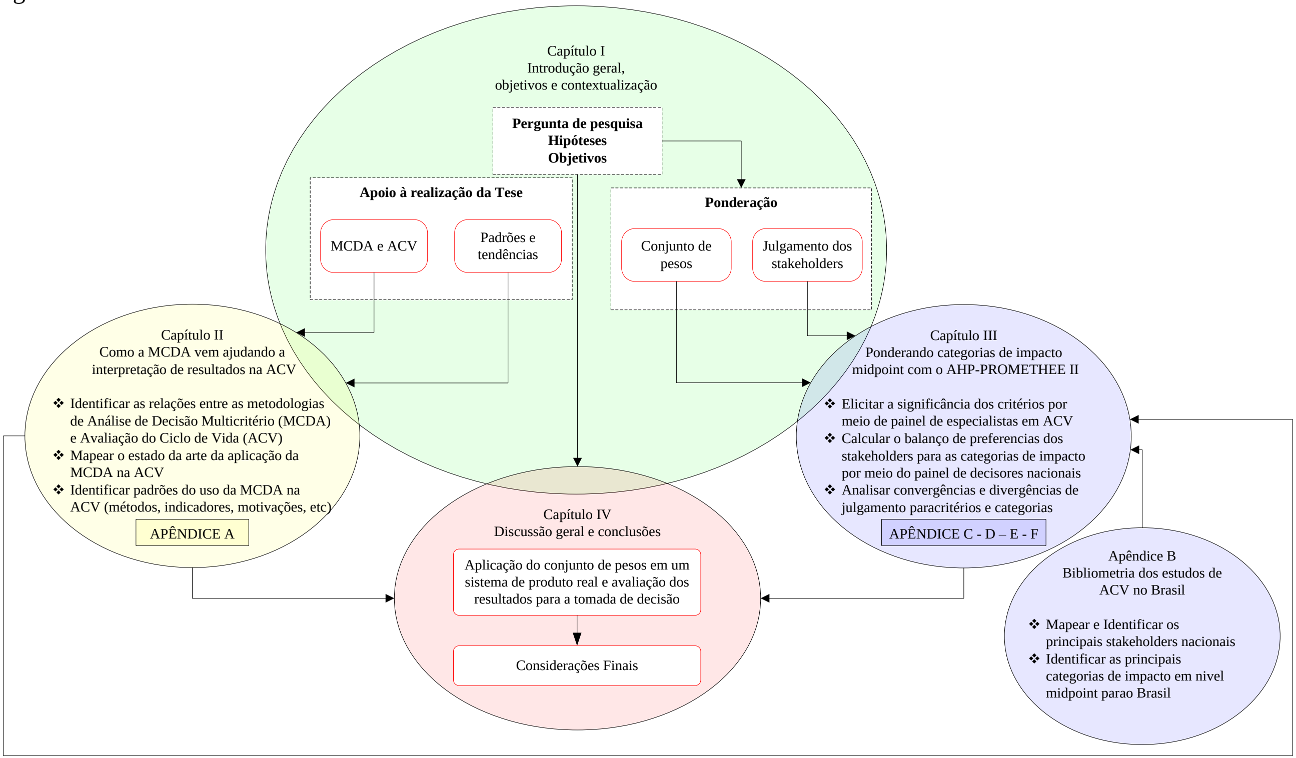
Tab. I-1. Sequência de pesquisa do CICLOG para análise de incertezas na ACV.

Autor	Tema	Incerteza
GALINDRO, 2012; LÉIS, 2013; PRUDÊNCIO DA SILVA, 2011; SOUZA JÚNIOR, 2015; ZANGHELINI, 2013;	Unidade Funcional, Alocação, Fronteiras do Sistema	Objetivo e escopo
BENEDET JÚNIOR, 2007	Incertezas na modelagem do inventário	Inventário
CHERUBINI, 2015	Incertezas na escolha metodológica	Alocação/AICV
ZANGHELINI, 2018	Ponderação e Agregação de Impactos	AICV/Interpretação

I.1.5 ESTRUTURA DA TESE

Para facilitar a leitura e levando em conta o formato definido para a elaboração desta tese – na forma de artigos – o documento está estruturado em quatro capítulos inter-relaciondos conforme Fig. I-1. Deste modo, os Capítulos II e III representam alguns dos artigos desenvolvidos no período de doutoramento. O primeiro já publicado (página 85) e o segundo a ser submetido (página 127). Ambos estão escritos em inglês, e são acompanhados de resumos expandidos em português, conforme determinado pelo Programa de Pós-Graduação em Engenharia Ambiental (PPGEA). Em termos de conteúdo, o documento procurará abordar primeiro o tema da Análise de Decisão Multicritério (MCDA) no Âmbito da Avaliação do Ciclo de Vida (ACV), para então ser abordado a aplicação do modelo de MCDA para a elicitação das significâncias das categorias de impacto segundo *stakeholders* brasileiros. O motivo para este posicionamento de ordem dos conteúdos está relacionado com os objetivos de cada artigo. O primeiro mapeia o estado da arte da MCDA na ACV, identificando a lacuna que justifica a realização do segundo. Uma breve descrição dos elementos contidos na Fig. I-1 é apresentada a seguir.

Fig. I-1. Estrutura da tese.



O Capítulo I apresenta inicialmente o contexto inicial, o enquadramento do tema de pesquisa e a problemática. Na sequência as perguntas de pesquisa são lançadas a luz da problemática, enquanto as hipóteses para estas perguntas são estabelecidas. Para confirmar ou refutar tais hipóteses o objetivo geral é traçado e estruturado pelos objetivos específicos, enquanto que a justificativa complementa a realização da pesquisa. Na sequência, o referencial teórico divide a base de suporte metodológico desta pesquisa entre a ACV (com foco especial na etapa de normalização/ponderação e suas abordagens) e a teoria de apoio a decisão onde o conceito da MCDA é descrito, bem como os modelos matemáticos de elicitação e agregação utilizados na tese são apresentados. O estado da arte do tema desta pesquisa é apresentado no capítulo II, sob o artigo intitulado “How Multi-Criteria Decision Analysis (MCDA) is aiding Life Cycle Assessment (LCA) in results interpretation”. Este capítulo complementa o capítulo I e justifica o capítulo III. O capítulo III traz o artigo central desta tese Intitulado de “Weighting Midpoint Impact Categories in Life Cycle Assessment with AHP-PROMETHEE II” apresenta a metodologia aplicada, os resultados e as discussões. O formato de artigo científico nem sempre nos permite se estender nas discussões. Desta forma, os resultados apresentados no capítulo III estão complementados e diversificados no capítulo IV. Este capítulo contém o fechamento da tese com conclusões, respostas as perguntas de pesquisa e atendimento aos objetivos propostos; Recomendações para estudos futuros e Análise Crítica.

Os apêndices são elementos que apoiam o desenvolvimento desta pesquisa. No entanto, a sua localização central é considerada como ‘não fundamental’ para a compreensão do teor contido em cada capítulo. Assim, e de forma a preservar a fluidez da leitura, os apêndices foram alocados ao final do capítulo IV.

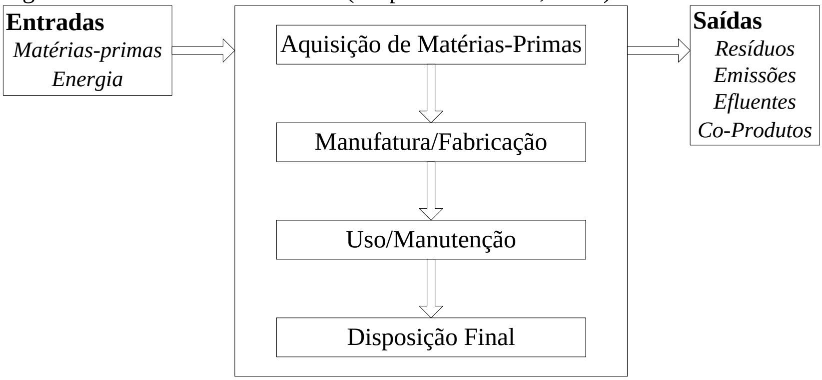
O Apêndice A é a tabela comparativa dos 109 artigos avaliados no Capítulo II. Ela contém aspectos de suma importância para o entendimento deste universo da aplicação MCDA/ACV, e reforçam escolhas metodológicas do capítulo III (e.g., os métodos de MCDA e as categorias de impacto). O Apêndice B contém um artigo publicado em 2015 e que apoia a estruturação da metodologia definida no capítulo III. Este suporte ocorre na identificação, e consequentemente definição, das categorias de impacto para a ponderação no modelo de MCDA (mais aplicadas no Brasil). Além disso, o estudo bibliometrico identificou as principais instituições de pesquisa e apoio ao desenvolvimento da ACV no Brasil, subsidiando o delineamento dos stakeholders para painel das categorias de impacto. Os apêndices C e D compõem os questionários enviados aos especialistas de ACV e stakeholders brasileiros, respectivamente. Estes são elementos fundamentais na construção do modelo MCDA e agregação de julgamentos para o cálculo dos pesos para as categorias de impacto. O primeiro deles elicita a significância dos critérios enquanto que o segundo extrai o balanço de preferencias pelas categorias de impacto. Por fim, os apêndices E e F subsidiam a escolha do método de MCDA aplicado nesta tese e a definição dos critérios para a avaliação dos impactos através de tabelas comparativas e discussão pautada em referências científicas.

I.2 AVALIAÇÃO DO CICLO DE VIDA (ACV)

A avaliação do ciclo de vida (ACV) é uma metodologia de gerenciamento ambiental, que identifica e quantifica aspectos e impactos ambientais potenciais ao longo do ciclo de vida de um produto ou serviço (ABNT ISO, 2009a; BAUMANN; TILLMAN, 2004; GUINÉE et al., 2002). “Geralmente as informações desenvolvidas em estudos de ACV e Inventário de Ciclo de Vida (ICV) podem ser usadas como parte de um processo decisório” (ABNT ISO, 2009a), de modo que a metodologia é considerada como de apoio à tomada de decisão.

A ACV é fundamentada no conceito de ciclo de vida, entendido como “estágios consecutivos e encadeados de um sistema de produto desde a aquisição da matéria-prima ou de sua geração a partir de recursos naturais até a sua disposição final” (ABNT ISO, 2009a); e no conceito de sistema de produto, que é o “conjunto de processos elementares, com fluxos elementares de produto, desempenhando uma ou mais funções definidas, e que modela o ciclo de vida de um produto” (ABNT ISO, 2009b). Um ciclo de vida tradicional envolve quatro etapas principais, conforme Fig. I-2, e inevitavelmente demanda consumos e resulta em gerações e emissões, e, portanto, causa impactos ao meio ambiente.

Fig. I-2. Ciclo de vida tradicional (adaptado de SAIC, 2006)



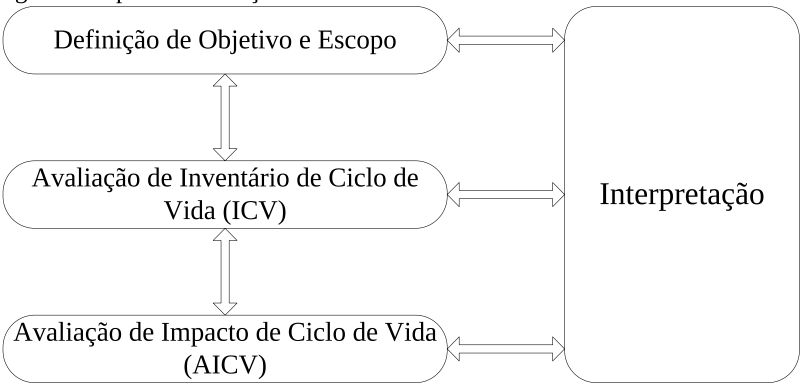
A ACV é normatizada dentro da série de normas da gestão ambiental, ISO 14000, mais especificamente no subcomitê cinco (Avaliação do Ciclo de Vida). A Tab. I-2 descreve a normatização existente no exterior e o equivalente para o território nacional, traduzido pela Associação Brasileira de Normas Técnicas (ABNT). Não existem ainda traduções para os relatórios técnicos.

Tab. I-2. Normatização da ACV no Brasil (SOUSA, 2008)

Documento	Descrição	Equivalente ABNT
ISO 14040	Define os princípios da metodologia, seus conceitos e estrutura (ISO, 2006a).	NBR ISO 14040 Princípios e Estrutura (ABNT ISO, 2009a)
ISO 14044	Aborda a estrutura metodológica, apresentando requisitos e diretrizes para a realização de um estudo (ISO, 2006b).	NBR ISO 14044 Requisitos e Orientações (ABNT ISO, 2009b).
ISO TR 14047	Apresenta exemplos de aplicação, especificamente sobre a etapa de avaliação do impacto (ISO, 2012a).	-
ISO TS 14048	Traz considerações quanto ao formato de apresentação dos dados (ISO, 2002).	-
ISO TR 14049	Fornece exemplos de aplicação (ISO, 2012b).	-

Para a realização (condução) de uma ACV, quatro fases principais, iterativas e interligadas são indicadas conforme a norma (ABNT ISO, 2009a) (Fig. I-3):

Fig. I-3. Etapas na condução de uma ACV.



Na primeira etapa, são decididos os caminhos metodológicos que servirão como um norte para a realização do restante da análise.

> "O objetivo é formulado em termos da exata questão a ser respondida, público alvo e aplicação pretendida. Enquanto que o escopo é definido em termos de cobertura temporal, geográfica e tecnológica, além do nível de sofisticação da metodologia com relação ao objetivo determinado" (GUINÉE et al., 2002).

Nesta fase são definidas questões importantes como a unidade funcional (UF), fluxos de referência, fronteiras do sistema e procedimentos para a coleta e o tratamento de dados, incluindo a interpretação dos resultados e outras análises de sustentação. Baumann e Tillman (2004), explicam que esta é uma fase crucial em um estudo de ACV, uma vez que diferentes propósitos requerem diferentes metodologias, ou ao contrário, diferentes metodologias fornecem respostas para diferentes questionamentos. Nesta etapa deve ser definido o possível uso dos elementos opcionais de uma ACV.

Na segunda fase, respeitando as definições de objetivo e escopo, todo o inventário é coletado. Em uma ACV, as emissões e os recursos consumidos associada a um produto específico são compilados e documentados em um inventário de ciclo de vida (ICV) (EC/JRC/IES, 2011). O resultado é uma completa lista de entradas e saídas para o meio ambiente, relacionadas à UF (GUINÉE et al., 2002). Muitas das definições da primeira etapa são refinadas durante o ICV, de modo que as flechas em ambas as direções entre a primeira e a segunda etapa da ACV representam está iteratividade característica da metodologia (Fig. I-3).

A AICV é a fase na qual os aspectos são traduzidos em impactos e representa a cadeia de "causa-efeito". Conforme a ABNT ISO (2009a), esta etapa visa ao entendimento e à avaliação da magnitude e significância dos impactos potenciais de um sistema de produto ao longo de seu ciclo de vida. Os resultados são possíveis em nível *'midpoint'* para categorias de impacto, e o *'endpoint'* para categorias de danos ambientais. Categorias de impacto incluem as mudanças climáticas, depleção da camada de ozônio, eutrofização, acidificação, toxicidade humana (carcinogênicas e não-carcinogênicas), efeitos respiratórios (inorgânicos), radiação ionizante, ecotoxicidade, formação de ozônio fotoquímico, uso de terra e esgotamento de recursos (EC/JRC/IES, 2011), enquanto que categorias de danos apresentam valores em termos de áreas de proteção, como a saúde humana e danos ao ecossistema (HUPPES; VAN OERS, 2011).

Esta tradução é realizada respeitando a modelos de caracterização de cada método de AICV, e refletem pressões por unidade de emissão ou recurso consumido no contexto de cada categoria de impacto. Um modelo de caracterização é apresentado na Tab. I-3, exemplificado pela categoria de aquecimento global (ou mudanças climáticas), modelo desenvolvido pelo *Intergovernmental Panel on Climate Change* (IPCC, 2014).

Tab. I-3. Linha de raciocínio para a AICV segundo a categoria de impacto aquecimento global (ABNT ISO, 2009b).

Termo	Exemplo
Categoria de Impacto	Aquecimento global
Resultado do ICV	Quantidade de gás do efeito estufa por unidade funcional (por exemplo: metano, óxido nitroso, dióxido de carbono)
Modelo de Caracterização	Modelo de linha de base para 100 anos do *Intergovernamental Panel on Climate Change* (IPCC).
Indicador de Categoria	Forçamento radioativo infravermelho (W/m²)
Fator de Caracterização	Potencial de aquecimento global (PAG) ou *global warming potencial* (GWP) para cada gás do efeito estufa em kg de CO_2 equivalente por kg de gás emitido.
Resultado do Indicador de Categoria	kg de CO_2 equivalente por unidade funcional
Relevância Ambiental	O forçamento radioativo infravermelho representa os efeitos potenciais sobre o clima, dependendo da adsorção cumulativa de calor pela atmosfera causada por emissões e da distribuição da adsorção de calor ao longo do tempo

As razões para a aplicação da caracterização são enumeradas por Udo De Haes et al. (2002) e Baumann e Tillman (2004) abaixo:

- Tornar o resultado ambientalmente mais relevante, compreensível e fácil de comunicar;
- Melhorar a leitura dos resultados;
- Tornar os resultados mais comparáveis;
- Identificar os processos de maior participação em termos de impacto;
- Possibilidade de atingir uma pontuação única;

De acordo com a norma ABNT ISO (2009a) a AICV consiste em duas etapas obrigatórias, classificação e caracterização, e três etapas opcionais, normalização, ponderação e agregação. A Fig. I-4 representa a relação das etapas obrigatórias e opcionais de uma AICV.

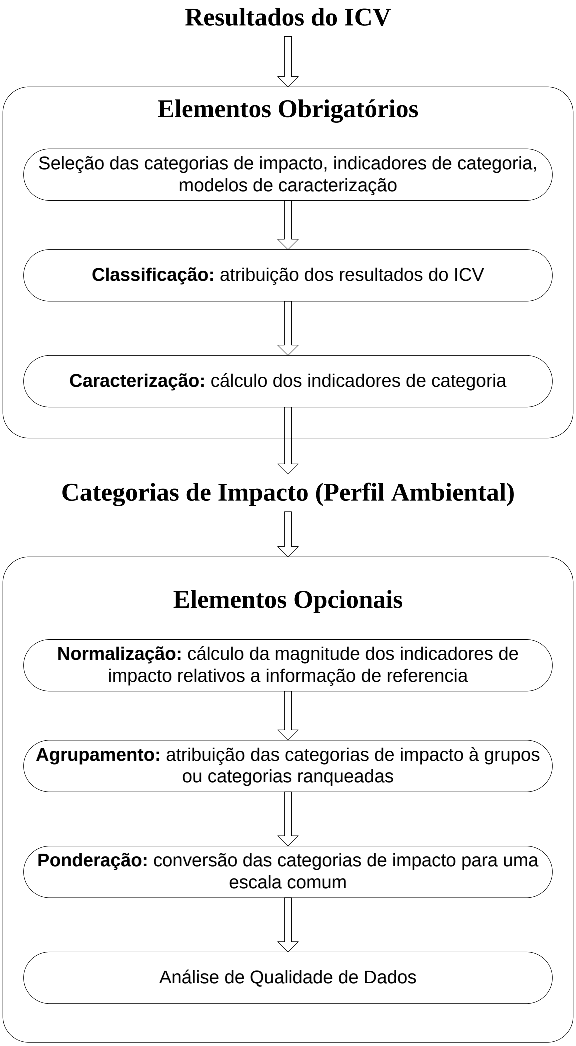
A classificação basicamente relaciona os aspectos ambientais coletados no inventário para cada categoria de impacto a qual o aspecto afeta de alguma forma, enquanto que a caracterização é a conversão dos valores inventariados e classificados para o indicador da categoria de impacto. A conversão é realizada por meio de fatores de caracterização contidos nos respectivos modelos (e.g. Tab. I-3 - conversão de gases emitidos e inventariados, classificados para a categoria de aquecimento global, convertidos para o indicador de massa de CO_2 eq. emitido por meio do modelo do IPCC, baseado no potencial de aquecimento global ou GWP – *global warming potential*).

A interpretação, última etapa da ACV, objetiva indicar gargalos do sistema de produto, explicitar impactos e indicadores de impacto, abre possibilidade para a variação de cenários e busca sempre auxiliar no processo de tomada de decisão.

A normalização é o procedimento de cálculo da magnitude dos indicadores de impacto com relação a uma determinada referência (BAUMANN; TILLMAN, 2004; UDO DE HAES et al., 2002; GUINÉE et al., 2002). Segundo a ABNT ISO (2009b), a normalização, embora opcional, pode ser útil para identificar inconsistências do estudo, bem como fornecer e comunicar informações sobre a significância relativa dos resultados dos indicadores além de preparar o caminho para os demais elementos opcionais de uma AICV.

O agrupamento é o procedimento de classificação e possivelmente ranqueamento dos indicadores de impacto (BAUMANN; TILLMAN, 2004; GUINÉE et al., 2002) em um processo qualitativo ou semi-qualitativo (UDO DE HAES et al., 2002). A norma NBR ISO 14044 (ABNT ISO, 2009b) aponta dois possíveis procedimentos de agrupamento: (a) agrupar as categorias de impacto em uma base nominal, por características como entradas e saídas ou escalas global, regional ou local; (b) classificar as categorias de impacto de acordo com uma hierarquia como alta, média ou baixa prioridade. Ainda, a norma alerta para o fato de que o agrupamento é baseado em uma escolha de valores, e que a mesma pode variar conforme o grupo de indivíduos, organizações e sociedades.

Fig. I-4. Elementos obrigatórios e opcionais durante a AICV (adaptado de ABNT ISO, 2009a; BAUMANN; TILLMAN, 2004; UDO DE HAES et al., 2002).



Por fim, a ponderação é o processo de conversão dos resultados de indicadores de diferentes categorias de impacto pela utilização de fatores numéricos baseado no julgamento de valores (ABNT ISO, 2009b), de forma que os pesos são a ligação entre os resultados quantitativos da ACV e os resultados baseados em valores pessoais e escolhas subjetivas dos tomadores de decisão (GLORIA; LIPPIATT; COOPER, 2007). A ponderação pode incluir a agregação dos resultados caracterizados das categorias de impacto (ABNT ISO, 2009b; BAUMANN; TILLMAN, 2004), situação que gera o single score (SS). A ponderação é baseada no julgamento de valores, motivo pelo qual apresenta variações conforme se varia também o grupo de indivíduos. Com relação a esta potencial variação, Guinée et al. (2002), sugerem que a ponderação deve ser embasada em um painel de especialistas, incluindo todas as partes relevantes ou que deve ser embasada em informações publicadas.

I.2.1 CADEIA ‘CAUSA-EFEITO’

A ACV objetiva medir a importância de determinados estressores ambientais tabulados em um inventário (ICV), agregar estes estressores a um pequeno número de categorias de impacto, ou ainda, em alguns casos, a um indicador final (UDO DE HAES et al., 2002). Esta interação que descreve os mecanismos ambientais é chamada de cadeia ‘causa-efeito’. Pode-se entender esta cadeia como o ‘caminho’ desempenhado pelo aspecto ambiental até ele se tornar um dano. Em outras palavras, é o quanto um inventário de ciclo de vida (ou um dado ou fluxo específico do inventário) vai impactar o meio ambiente ou danificar as grandes áreas de proteção. EC/JRC/IES (2011) e ISO (2006a) definem a cadeia causa-efeito como um sistema de processos biológicos, físicos e químicos para uma dada categoria de impacto, que liga o ciclo de vida do resultado da análise de inventário para a unidade comum do indicador da categoria por meio de um modelo de caracterização.

Portanto, neste caminho, encontram-se as categorias de impacto, ‘a nível *midpoint*’ e as categorias ‘a nível *endpoint*’ ou categorias de danos que dizem respeito às grandes áreas de proteção (BARE; GLORIA, 2006). Uma área de proteção, segundo Guinée et al. (2002), é representada por um conjunto de categoria *endpoints* de valor reconhecido para a sociedade, classificados para as áreas estabelecidas (i.e., saúde humana). Um exemplo de cadeia de ‘causa-efeito’ é apresentado na Fig. I-5, com base na estrutura do método de AICV do ReCiPe 2008 (GOEDKOOP et al., 2009), enquanto que um exemplo de procedimentos de cálculo envolvendo caracterização, normalização e ponderação para SS é apresentado na Fig. I-6 para as categorias *midpoint* de acidificação e mudanças climáticas.

Muitos estudos de ACV interpretam seus resultados a luz das categorias *midpoint* (BARE; GLORIA, 2006). Este nível implica em menos incertezas, já que o inventário é sujeito a modelos de caracterização mais precisos (MYLLYVIITA; LESKINEN; SEPPÄLÄ, 2013), o que faz com que exista a tendência por um maior consenso entre os autores quando comparado com os cálculos *endpoint* (BARE; GLORIA, 2006). No entanto, os resultados *midpoint* são mais difíceis de interpretar, comunicar e nem sempre auxiliam a tomada de decisão, pois são analisados separadamente (BARE et al., 2000). Esta relação dupla é bem ilustrada por Prado-Lopez et al. (2013), que afirmam que a subjetividade nas etapas de normalização e ponderação dos impactos ambientais frequentemente fazem com que os praticantes da ACV parem a sua avaliação na caracterização. Enquanto isso pode ser efetivo para a avaliação de um sistema de produto, na comparação, os dados caracterizados ofertam aos tomadores de decisão grandes volumes de informação para interpretar (BOUFATEH et al., 2011). As categorias de dano, *endpoint*, por outro lado são geralmente consideradas mais compreensíveis para os tomadores de decisão (BARE et al., 2000), mas elevam as incertezas dos resultados.

Fig. I-5. Cadeia causa-efeito (GOEDKOOP et al., 2009).

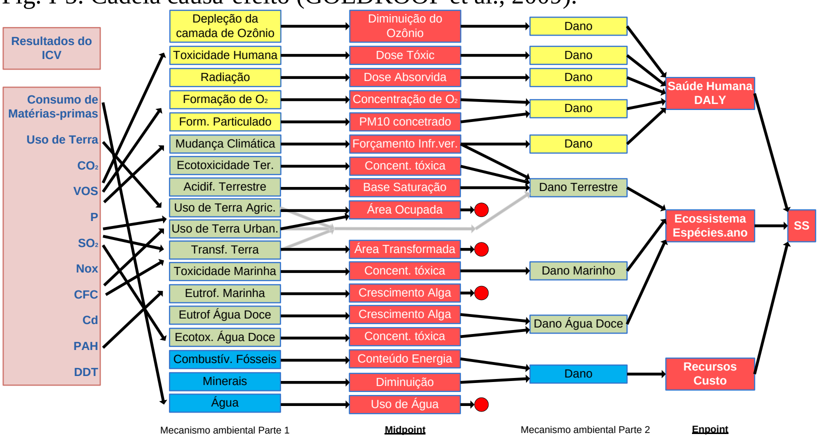
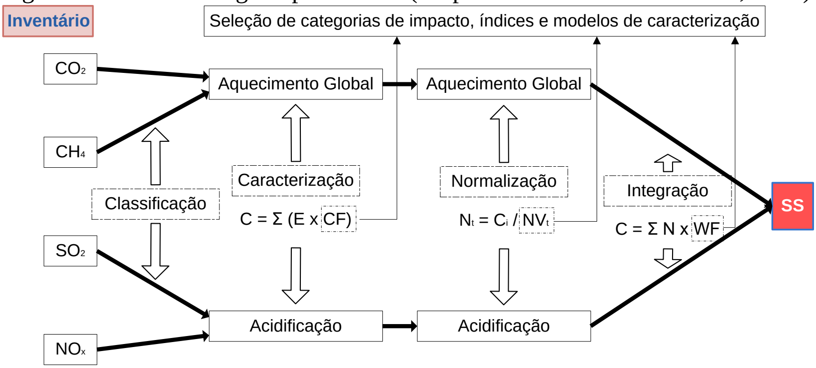


Fig. I-6. Procedimento geral para AICV (adaptado de ITSUBO e INABA, 2012).



I.2.2 A NORMALIZAÇÃO NA ACV

A ponderação é obrigatoriamente precedida da normalização, porque esta normaliza as unidades das categorias de impacto. Como apontado por Huppes eVan Oers (2011), existem duas razões principais para aplicar uma etapa de normalização: anteceder a ponderação e possibilitar a comparação entre sistemas. Na ponderação, diferentes tipos de efeitos ou impactos são somados a um indicador, de modo que tais efeitos devem estar em uma mesma unidade, como unidades monetárias, ou adimensionais. Os pesos estabelecidos podem ser aplicados apenas para os valores padronizados com unidades iguais (HUPPES; VAN OERS, 2011).

Geralmente as normalizações ocorrem em duas diferentes abordagens definidas por Norris (2001) em interna e externa. No contexto da ACV, a normalização geralmente refere-se à normalização externa (MYLLYVIITA; LESKINEN; SEPPÄLÄ, 2013), que é quando se divide por uma referência a uma área geográfica ou população (por exemplo, um país ou um habitante deste país). Um bom exemplo é dado por Baumann e Tillman (2004): a normalização relaciona os impactos do produto avaliado com os impactos gerados pelo total de poluentes de uma determinada região. Outros exemplos de referências para a normalização, geralmente utilizados nos estudos de ACV, são impactos de determinado país ou mesmo per capita deste país (i.e., um cidadão sueco “médio”). Na normalização interna, busca-se comparar o valor das alternativas de decisão com outras alternativas, isso pode ser feito com os máximos ou mínimos (MYLLYVIITA; LESKINEN; SEPPÄLÄ, 2013). Norris (2001) indica que entre as duas abordagens, a mais popular é a divisão por máxima. Enquanto a normalização interna almeja auxiliar na comparação de possibilidades, o objetivo da normalização externa é auxiliar o entendimento da significância dos resultados, colocando-os em um contexto (NORRIS, 2001). Na Tab. I-4 encontram-se alguns dos métodos de AICV mais utilizados em estudos de ACV, bem como seus valores-referência para o procedimento de normalização.

Tab. I-4. Principais métodos de AICV e suas referências para a normalização.

Método	Normalização	Referência
CML-IA	Mundo (1990), Europa (1995) e Holanda (1997)	(GUINÉE et al., 2002)
ReCiPe 2008	Mundo e Europa (2000).	(GOEDKOOP et al., 2009)
EDIP97	Mundo (1994).	(STRANDDORF; HOFFMAN; SCHMIDT, 2005)

Tomar a decisão com base nos resultados da normalização também não é o mais recomendado. Prado-Lopez et al. (2013) descrevem diversos problemas desta etapa em específico, incluindo a normalização interna, criticada porque no final das contas, o analista acaba por ponderar de forma igualitária os impactos ambientais (o que por si só já é uma escolha subjetiva, agravados por não possuir fundamento na significância dos impactos), e a normalização externa com seus defeitos de falta de dados recentes, e valores de referência por vezes exageradas. Norris (2001) e Heijungs et al. (2006), por exemplo, indicam que a normalização pode produzir resultados ilógicos ou distorcidos nos casos em que as pontuações de desempenho das alternativas avaliadas são antagônicas, ou seja, superiores para determinada categoria e inferiores para outras.

I.2.3 A PONDERAÇÃO E AGREGAÇÃO NA ACV

O objetivo da ponderação na ACV é facilitar a interpretação e posteriori comunicação dos resultados pela criação de um indicador agregado único de impacto ambiental (HUPPES; VAN OERS, 2011). Como a facilidade interpretativa reside na decisão em nível de SS, quase que exclusivamente a ponderação é seguida de uma agregação.

Embora este procedimento não substitua a análise mais detalhada das categorias de impacto (principalmente em nível *midpoint*), desempenha papel fundamental para diminuir a complexidade da decisão. Por exemplo, ao ponderar as categorias, o *trade off* entre as diferentes emissões é calculado por meio do processo. Questões como: quantas toneladas de emissões adicionais de CO_2 são permitidas para a redução de uma tonelada de SO_2 podem ser respondidas nesta etapa (HUPPES; VAN OERS, 2011). Com relação à cadeia de causa-efeito (Fig. I-5) a ponderação pode ser aplicada nos dois níveis (MYLLYVIITA; LESKINEN; SEPPÄLÄ, 2013), devendo ser precedida de uma normalização.

Na ACV, normalmente a ponderação/agregação é aplicada segundo a Eq. I-1 de Finnveden (1999) e Prado-Lopez et al. (2013) que realiza, em posse dos pesos (ponderação já efetuada) das categorias, o cálculo do SS por soma ponderada:

$$IA = \sum Vi.Si$$

Eq. I-1. Cálculo por soma ponderada.

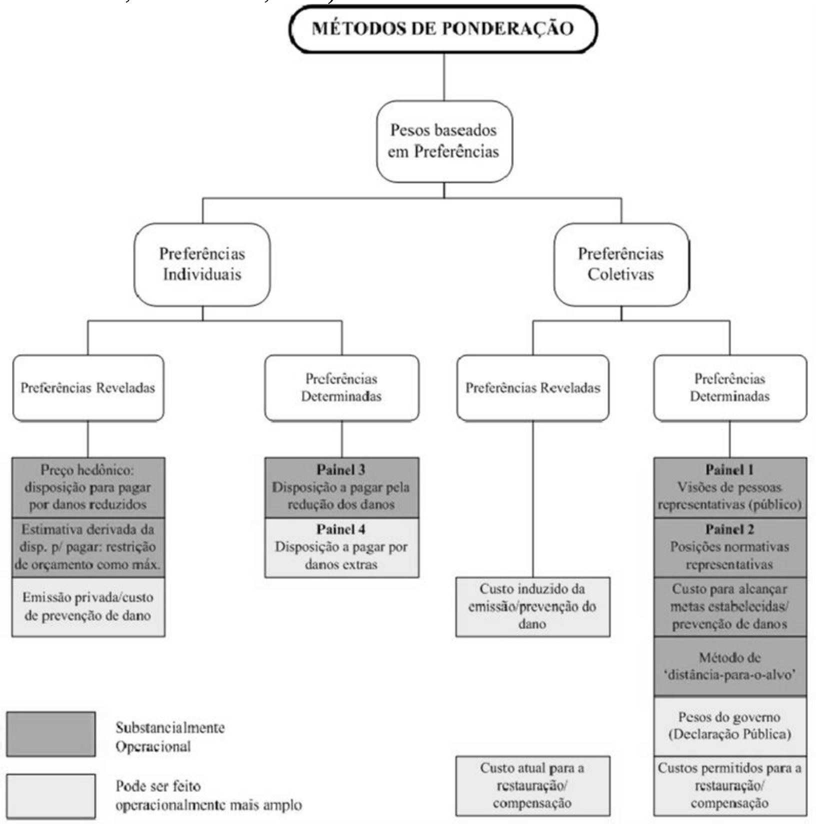
Onde:

IA : Impacto ambiental ponderado (single score ou pontuação única)
Vi: Pesos referentes a cada categoria i
Si: Resultado normalizado do sistema de produto para a categoria

Os métodos utilizados para quantificar a significância das categorias de impacto (i.e., o Vi da Eq. I-1) na ACV, podem ser classificados em três diferentes abordagens, conforme Guinée et al. (2002); Huppes e Van Oers (2011) e Myllyviita, Leskinen e Seppälä (2013): método de painel, método de monetização e método de distância em relação a um alvo ou objetivo. Outros autores ainda descrevem abordagem Proxy e Tecnológica como métodos de obtenção de pesos na ACV (UDO DE HAES et al., 2002; FINNVEDEN, 1999).

A taxonomia destas abordagens de ponderação é apresentada no fluxograma da Fig. I-7. É possível notar o maior desenvolvimento para pesos baseados em preferências, as quais podem representar preferências coletivas ou individuais. As três principais categorias indicadas anteriormente também são visualizadas nesta taxonomia, por exemplo, para ponderação por monetização (*willingness-to-pay*) no Painel 3, ponderação por painelistas nos painéis 1 e 2 e ainda, distância para o alvo (distance-to-target) no método baseado no atendimento a metas.

Fig. I-7. Taxonomia dos métodos de ponderação empregados na ACV (adaptado de HUPPES; VAN OERS, 2011).



I.2.3.1 Consulta aos Especialistas (Painel)

Método indicado por Guinée et al. (2002), cuja abordagem é baseada em um grupo de peritos (especialistas), representantes das diferentes partes interessadas (também chamados de *stakeholders*), que são convidados a fornecer os fatores de ponderação ou julgamentos mediante outras abordagens (HUPPES; VAN OERS, 2011) como questionários, entrevistas ou mesmo grupo de discussões. Os valores são definidos pelo processo de elicitação (UDO DE HAES et al., 2002; MYLLYVIITA; LESKINEN; SEPPÄLÄ, 2013), que é um mecanismo para extrair informações de um indivíduo (ou indivíduos).

Os painéis se diferenciam entre si por conta de alguns fatores indicados por Udo De Haes et al. (2002):

- Tamanho do painel e tipo de painelistas (grupo de painelistas);
- Procedimento de elicitação (questionários, entrevistas, Delphi...);
- Formato da questão;
- Apresentação e informação de apoio;
- Modo de resposta (ranqueamento, comparação de pares...);
- Modo de agregação (consenso, métodos matemáticos...);

Por essas razões, muito tem sido discutido sobre a subjetividade e a representatividade da abordagem do painel (ver, por exemplo, FINNVEDEN, 1999; HOFSTETTER, 1998; HUPPES e VAN OERS 2011, METTIER e SCHOLZ, 2008, PIZZOL et al., 2017). Dentre estes aspectos o processo de elicitação é peça chave na consulta à especialistas. Udo De Haes et al. (2002) apontam dois motivos principais para este fato: (1) não existe procedimento definido para a condução de um painel, e (2) existem diversos métodos de elicitação. De maneira geral, a elicitação é realizada por meio de métodos de análise de decisão muti-critério, principalmente porque apresentam um apoio elicitatório muito interessante quando o objeto a ser julgado ou escolhido representa uma situação complexas.

Entre as principais abordagens de ponderação, o painel ganhou popularidade e foi reconhecido como sendo uma das maneiras mais promissoras para obter os fatores de ponderação da categoria requerida (FINNVEDEN et al., 2002; KOFFLER; SCHEBEK; KRINKE, 2008). Por exemplo, Ecoindicator 99, TRACI e ReCiPe são métodos de AICV que consideraram procedimentos de ponderação baseados em painéis (BENGTSSON e STEEN, 2004; LIPPIATT, 2007; HUPPES et al., 2007; HUPPES e VAN OERS, 2011). Os painéis são baseados nas opiniões das partes interessadas e representam preferências coletivas por aqueles cujo interesse deve ser consultado, o que o transforma em um processo mais direto (HUPPES e VAN OERS, 2011). Soares, Toffoletto e Deschênes (2006) estão alinhados com essa percepção quando afirmam que a abordagem oferece a possibilidade de uma ponderação mais qualitativa devido à natureza qualitativa da percepção humana da gravidade dos impactos ambientais.

I.2.3.2 Monetização

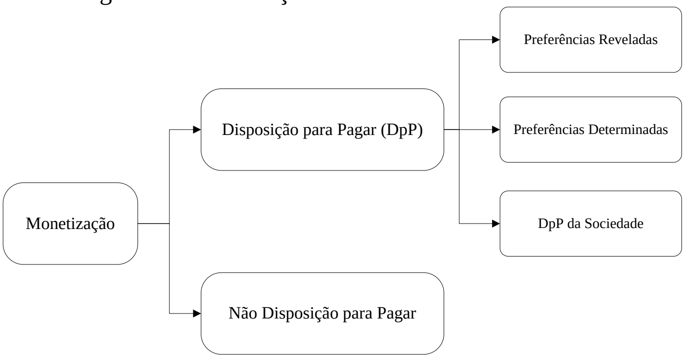
Abordagem na qual a ponderação é estruturada com base em custos relacionados às consequências ambientais (AHLROTH et al., 2011). Existem vários métodos de monetização de impactos ambientais (UDO DE HAES et al., 2002). Finnveden (1999) os classifica em dois grandes grupos: (a) oriundos da "disposição para pagar (DpP)" (*willingness-to-pay* – WtP) que ainda apresenta três variações de abordagem, ou (b) Não baseados na "disposição para pagar" (e.g., custo para recuperar certo dano ambiental), conforme Fig. I-8.

A DpP é normalmente relacionada com a prevenção de algo. Assim, para Finnveden (1999), alguém está disposto a pagar certa quantia de dinheiro, a fim de evitar alguma coisa. Esse algo pode ser adiantado ou atrasado dentro do mecanismo ambiental de aspecto-impacto, ou seja, se mais tarde na cadeia causa-efeito, a DpP atua para evitar um dano. Caso for cedo, a DpP é para prevenir uma ameaça. Se cada impacto tem um custo, e estes custos variam conforme DpP, cada categoria de impacto possuirá um peso, sendo que quanto maior o custo maior a significância da categoria.

Dentro das abordagens DpP, os métodos baseados nas preferências reveladas dos indivíduos partem do princípio de que o indivíduo revela sua preferência por meio do comportamento no mercado (UDO DE HAES et al., 2002). Este método é normalmente relacionado ao uso direto. Algumas abordagens para a revelação das preferências são: método da valoração hedônica e método do custo de viagem (FINNVEDEN, 1999). A determinação destes custos (Preferências Determinadas) é uma abordagem semelhante ao painel de especialistas, pois parte da consulta explícita a indivíduos, como por exemplo, a abordagem de avaliação de contingente (FINNVEDEN, 1999).

Por fim, a DpP da sociedade pode variar de decisões políticas e governamentais (UDO DE HAES et al., 2002). Uma maneira de se realizar esta quantificação é mensurar os esforços da sociedade por evitar certo impacto, como reduzir emissões até um limite estipulado (UDO DE HAES et al., 2002). Outro modo é por meio de taxas ambientais em determinadas emissões. O preço por certa emissão pode ser encarado como DpP da sociedade para aquela substância em específico. As abordagens que se baseiam em outros preceitos, que não a DpP, são utilizadas quando não se tem certeza de quem vai pagar pelo dano. Udo De Haes et al., (2002) apontam que um exemplo bem claro para esta abordagem é quando se estima o preço para se alcançar uma meta futura de emissão. Estes valores podem ser adquiridos de fontes governamentais, uma vez que o governo, teoricamente representa a sociedade.

Fig. I-8. Abordagens de Monetização.



Existem alguns modelos de ponderação disponíveis no âmbito da ACV baseados na monetização, como o *Environmental Priority Strategies* (EPS). Estes métodos apresentam uma variação em seu conteúdo, nas formas de quantificar os valores dos impactos. Segundo Udo De Haes et al. (2002), esta variação ocorre porque os métodos utilizam uma mistura de técnicas de avaliação econômicas como: valoração ambiental (contingente), método de preços hedônicos, custos de abatimento e valores de mercado.

I.2.3.3 Distância para um Alvo (DpA)

Abordagem que se baseia em uma distância em relação a um alvo ou objetivo. Os fatores de ponderação são calculados com base em função de algum tipo de valor-alvo, que são muitas vezes baseadas em decisões políticas (UDO DE HAES et al., 2002), normalmente da situação atual para uma situação futura (SEPPÄLÄ; HÄMÄLÄINEN, 2001), ou seja, nesta abordagem o fator de ponderação é definido para cada categoria de impacto ambiental como a razão entre o impacto real e o impacto alvo (HUPPES; VAN OERS, 2011). Quanto maior for a diferença entre o impacto real e o impacto alvo, maior o fator de ponderação. Existem várias opções diferentes para determinar o impacto alvo como sugerido por Huppes e Van Oers (2011): capacidade de carga e sustentabilidade, objetivos políticos e espaço ambiental politicamente determinado. Os fatores de ponderação na abordagem (DpA) seguem resumidamente a Eq. I-2 apresentada por Udo De Haes et al. (2002):

$$Vi = \frac{1}{Ti}$$

Eq. I-2. Cálculo da ponderação por DpA.

Onde:
Vi: Peso atribuído ao impacto i
Ti: Alvo a ser alcançado.

Em termos, esta ponderação se assemelha à normalização externa, aquela em que a referência é realizada para um valor relacionado a uma localização ou população.

I.2.3.4 Pesos e Ponderações existentes

A Tab. I-5 apresenta uma compilação para os conjuntos de pesos ou ponderação existentes (com base nos métodos de AICV disponíveis e em publicações específicas no tema) em relação a sua taxonomia e nível das categorias (i.e., de impacto ou de danos/*midpoint* ou *endpoint*) (HUPPES; VAN OERS, 2011).

Uma série de métodos utilizados para AICV convertem as emissões de substâncias perigosas e extrações de recursos naturais em indicadores de categoria de impacto em nível midpoint, enquanto outros empregam como indicadores de impacto, categorias a nível endpoint (GOEDKOOP et al., 2009). A partir da Tab. I-5, percebe-se que a maior parte dos métodos disponíveis para a AICV aplica a ponderação ao nível endpoint por meio da abordagem de DpP em conjunto com consulta à painelistas (métodos ReCiPe, EPS, LIME e NEEDS). Em seguida, o Painel 1 que se refere à consulta a um grupo de especialistas é a segunda abordagem mais aplicada, em ambos níveis, *midpoint* (BEES e ReCiPE NOGEPA) e *endpoint* (ReCiPe PRé, Ecoindicator 99), sendo o preferível quando a ponderação ocorre a nível *midpoint*. Outros estudos desenvolveram abordagens de ponderação *midpoint*, mas não se encontram associados a nenhum método de AICV, como por exemplo Soares, Toffoletto e Deschênes (2006) e Bengtsson et al. (2010).

Tab. I-5. Modelos de ponderação existentes na ACV, seu nível de categoria e metodologia de embasamento (HUPPES; VAN OERS, 2011).

Nível	Painel 1	DpA	Custo Prevenção de Danos	Painel 3
Mid.	BEES / SAB	EDIP	-	-
	ReCiPe-Nogepa	-	-	-
	Soares, Toffoletto e Deschênes (2006)	-	-	-
	Hermann, Kroeze e Jawjit (2007)	-	-	-
	Bengtsson, Howard e Kneppers (2010)	-	-	-
End.	ReCiPe PRè	-	ReCiPe - CE	ReCiPe
	Ecoindicator 99	-	-	EPS
	-	-	-	LIME
	-	-	-	NEEDS

A seguir estão descritos os modelos de ponderação de impactos em nível *midpoint*, obtidos por painel de especialistas, com base na Tabela 5.

- BEES E SAB (LIPPIATT, 2007)

O BEES (*Building for Environmental and Economic Sustainability*) (LIPPIATT, 2007) é um método de AICV baseado no TRACI (método criado pelo departamento de pesquisa e desenvolvimento do USEPA, chamado de *Tool for the Reduction and Assessment of Chemical and other environmental Impacts*) com o acréscimo de um modelo de ponderação desenvolvido por meio da consulta a painelistas do setor de construção civil americano (LIPPIATT, 2007). O modelo aplicado a um software, possui mais um conjunto de ponderação que têm por base um estudo da agência ambiental americana (EPA *Science Advisory Board* - SAB).

O BEES analisa 12 categorias de impacto, partindo de dez das onze categorias do TRACI 1.0: aquecimento global, acidificação, eutrofização, depleção de recursos fósseis, alteração de habitat (uso de terra), poluição do ar, saúde humana, smog, depleção da camada de ozônio e ecotoxicidade. Além destas, o consumo de água e a qualidade do ar (interna) são avaliados diretamente de valores do ICV. A segunda opção, baseada no painel de especialistas do BEES, envolveu os tomadores de decisão “interessados” na ponderação das categorias de impacto. Foram ao todo 19 indivíduos incluindo consumidores, fornecedores e experts em ACV. Assim como no SAB, o painel de especialistas do BEES aplicou o método AHP para a análise pareada de critérios. O resultado deste conjunto de pesos é apresentado na Tab. I-6.

Tab. I-6. Ponderações BEES e SAB (LIPPIAT, 2007).

Categoria de Impacto	BEES	SAB
Aquecimento Global	29	16
Acidificação	3	5
Eutrofização	6	5
Depleção de Recursos Fósseis	10	5
Smog	4	6
Ecotoxicidade	7	11
Substâncias tóxicas		
Uso de terra (alteração de habitat)	6	16
Depleção da Camada de Ozônio	2	5
Saúde humana		11
Efeitos carcinogênicos	8	
Efeitos não carcinogênicos	5	
Poluição do ar	9	6
Consumo de água	8	3
Qualidade interna do ar	3	11

O SAB qualificou dez categorias de impacto do BEES em: (1) Risco mais Alto: aquecimento global e uso de terra (alteração de habitat); (2) Risco Alto: qualidade interna do ar, ecotoxicidade e saúde humana; (3) Risco Médio: depleção da camada de ozônio, smog, acidificação, eutrofização e poluição atmosférica. Como no SAB a depleção fóssil e a demanda hídrica não foram incluídas, o autor do BEES os considerou como de médio e de baixo risco respectivamente. Tal ranking de importâncias foi convertido em números pelo método de decisão multicritério *analytic hierarchy process* (AHP) que sugere uma escala numérica de comparação de 1 a 9. Ambos os conjuntos de pesos calculados e agregados são apresentados na Tab. I-6.

- RECIPE NOGEPA (HUPPES et al., 2007)

Método de Ecoeficiência quantitativo desenvolvido por Huppes et al. (2007) para priorizar investimentos pela Associação Holandesa de Exploração e Produção de Óleo e Gás (*Netherlands Oil and Gas Exploration and Production Association* - NOGEPA). O grande objetivo foi desenvolver um único indicador ambiental (SS) baseado nas preferencias coletivas reveladas (i.e., painel de *stakeholders*). Esta decisão foi embasada na comparação entre métodos de ponderação existentes. Por exemplo, Huppes et al. (2007) afirmam que os métodos de danos ambientais baseados em preferências privadas com base em WtP (DpP) e preços hedônicos, têm amplos intervalos de resultados, aplicabilidade limitada em termos de cobertura de impactos ambientais e aceitabilidade limitada entre críticos, economistas e não economistas.

Segundo os autores, métodos de DtT (DpA) deram apenas resultados espúrios, por causa da dependência de conjunto de dados específicos e da disponibilidade limitada de metas políticas relevantes.

Para resultados representativos a composição do painel é essencial (HUPPES et al., 2007). Nesta experiência, os autores consideraram um painel misto, contando como participantes representantes de um Pacto firmado pela NOGEPA em conjunto com o governo Holandês para a diminuição de impactos ao meio ambiente, empresas regulamentadas e especialistas de institutos científicos (vistos como representando a parte bem informada da sociedade em geral).

Tab. I-7. Ponderação NOGEPA.

Categoria de Impacto	Huppes et al. (2007)
Aquecimento Global	32
Acidificação	6
Eutrofização	13
Smog	8
Toxicidade	
Marinha	8
Terrestre	5
De água doce	6
Depleção da Camada de Ozônio	5
Saúde humana	16

Os resultados desta experiência indicam uma preferência estrita pela categoria de Aquecimento Global (um terço da significância aproximadamente), acompanhado pela Saúde Humana e pela Eutrofização, com pesos de 16 e 13, respectivamente. As demais categorias de impacto complementam o modelo de ponderação (Tab. I-7).

- SOARES, TOFFOLETTO E DESCHÊNES (2006)

Soares, Toffoletto e Deschênes (2006) desenvolveram uma ponderação com base na consulta a especialistas canadenses para 10 categorias de impacto *midpoint* (aquecimento global, depleção da camada de ozônio, depleção abiótica, uso de terra, acidificação, smog fotoquímico, ecotoxicidade, substâncias tóxicas, eutrofização aquática e eutrofização terrestre) usando um método de MCDA como auxílio à elicitação do julgamento dos especialistas. Na proposta dos autores, sete critérios foram avaliados, sendo três deles em nível de consequência ambiental: saúde humana, saúde do ecossistema, consumo de recursos; e quatro deles em nível de probabilidade desta ocorrência ambiental: escala, duração, reversibilidade e distância para o alvo (DtT).

Os pesos dos critérios foram avaliados de acordo com as respostas de 14 especialistas embasadas em uma adaptação da metodologia de "Resistência à Mudança", nas quais dois limites são estabelecidos para cada critério e comparados em uma matriz. Os limites definem um nível desejado e um indesejado para determinada ocorrência, enquanto que cada painelista deveria indicar quando um limite poderia migrar para o indesejável em detrimento a manter o outro desejável. As categorias de impacto foram analisadas pelo mesmo painel, na qual o especialista foi incumbido de julgar cada categoria em uma escala de 0-100 para seis intervalos pré-definidos com relação a 'não existência' até a 'muito elevada repercussão' destas categorias de impacto (SOARES, TOFFOLETTO; DESCHÊNES, 2006). Por exemplo, para o critério de "Escala", os intervalos definidos foram desde "pontual" em um nível mais baixo, até "Global" no último nível, em que numericamente o primeiro representa a variação de 0-1 e a última de 80-100. Assim, caso um painelista julgasse o aquecimento global como "Global" para o critério Escala, o valor atribuído a esta avaliação deve estar entre 80 e 100. As incertezas deste julgamento foram incluídas e computadas por meio de pergunta direta ao especialista. Os autores calcularam os pesos para as categorias analisadas realizando uma agregação dos critérios por soma ponderada, mas, não aplicam a agregação dos valores para um SS, pois não utilizam o modelo a um sistema de produto (estudo de caso).

Os resultados deste painel são apresentados na Tab. I-8, onde é possível identificar a categoria de mudanças climáticas como a mais significativa dentre aquelas avaliadas, com 0,182 de peso em um total de 1. Outras categorias que se destacam pela importância segundo Soares, Toffoletto e Deschênes (2006) são a Depleção da Camada de Ozônio e a Depleção de Recursos Fósseis.

Tab. I-8. Conjunto de pesos calculados por Soares, Toffoletto e Deschênes (2006)

Categoria de Impacto	Soares, Toffoletto e Deschênes (2006)
Aquecimento Global	18,2
Acidificação	9,2
Eutrofização	
Aquática	7,9
Terrestre	6,1
Depleção de Recursos Fósseis	12,9
Smog	6,8
Ecotoxicidade	8,5
Substâncias tóxicas	6,6
Uso de terra	10,6
Depleção da Camada de Ozônio	13,1

- HERMANN, KROEZE E JAWJIT (2007)

A proposta publicada por Hermann, Kroeze e Jawjit (2007) aplica o AHP para agregar a significância das categorias de impacto. Embora ela não tenha sido aplicada a um painel de especialistas (os pesos foram atribuídos pelos próprios autores), este estudo possui uma singularidade que é a consideração da escala geográfica para a atribuição de significâncias. Os autores partem da premissa que, dependendo da escala geográfica da ocorrência dos impactos (Global, Regional, Local) as categorias devem possuir diferentes pesos. Isso significa que, por exemplo, em uma perspectiva global, uma maior importância é atribuída ao Aquecimento Global (que ocorre em escala global), enquanto que impactos locais como Saúde humana e eutrofização dominam na perspectiva local. Por esta condição, Hermann, Kroeze e Jawjit (2007) atestam que diferenças geográficas em termos de consequências ambientais também influenciam no modo como atribuímos significância aos impactos. Os resultados desta proposta estão apresentados na Tab. I-10 de acordo com as 3 perspectivas de escala.

Tab. I-9. Conjunto de pesos do COMPLIMENT.

Categoria de Impacto	**Hermann, Kroeze e Jawjit (2007)**		
Perspectiva	**Global**	**Regional**	**Local**
Aquecimento Global	42	6	6
Acidificação	26	34	10
Eutrofização	16	34	16
Toxicidade humana	6	13	42
Smog	9	13	26

- BENGTSSON, HOWARD E KNEPPERS (2010)

O objetivo deste estudo foi determinar um conjunto de pesos médios para as categorias de impactos ambientais segundo a realidade Australiana. Após um workshop que contou com praticantes e desenvolvedores de ACV para discussão de possibilidades metodológicas, o método aplicado pelos autores foi a consulta a especialistas por meio de um painel. Segundo Bengtsson, Howard E Kneppers (2010), o painel é o mais transparente e simples dentre os métodos de se obter a significâncias para as categorias. Mesmo assim, os autores consideram que o modo como as questões são perguntadas imprime certo grau de complexidade, incluindo: até que ponto o grupo de participantes é estatisticamente representativo; de que forma garantir que os respondentes tenham suficiente conhecimento sobre os impactos para responder ao painel; de que forma evitar resultados tendenciosos refletidos no modo como a informação de base é expressa e no modo como os resultados são expressos.

Neste questionário, os participantes foram incumbidos de posicionar cada categoria de impacto em uma escala de 0-100 de acordo com suas convicções e escolha de valores. Diversos *stakeholders* participaram deste painel que ocorreu em 11 *workshops*, incluindo representantes da sociedade e do governo divididos pelas regiões da Austrália. Aparentemente o questionário não foi estruturado sob uma MCDA, e apesar desta condição, os autores indicam que o método alcançou resultados consistentes entre os grupos de *stakeholders* e entre outros conjuntos de pesos que forma comparados posteriormente.

Os resultados médios deste painel de especialistas são apresentados na Tab. I-10. Segundo os painelistas australianos, a categoria de impacto com maior significância é o Uso de terra (20) acompanhado de Mudanças Climáticas com 19 pontos. As demais categorias somadas completam 100. Para Bengtsson, Howard e Kneppers (2010), estes valores podem ser consistentemente utilizados para informar uma larga faixa de decisões, incluindo *scoring* para programas de rotulagem ambiental, para realizar análise adequada de *trade-offs* em ACVs, informar de que forma créditos são atribuídos em construções sustentáveis, para priorizar estratégias ambientais em empresas ou indicar políticas públicas ambientais.

Tab. I-10. Conjunto de pesos calculados por Bengtsson, Howard e Kneppers (2010)

Categoria de Impacto	Bengtsson, Howard e Kneppers (2010)
Aquecimento Global	19
Acidificação	3
Eutrofização	3
Depleção de Recursos Fósseis	8
Smog	3
Ecotoxicidade	
Marinha	10
Terrestre	6
De água doce	10
Toxicidade humana	3
Uso de terra	20
Depleção da Camada de Ozônio	4
Consumo de água	6
Efeitos respiratórios	3
Radiação ionizante	2

I.3 O PROCESSO DE TOMADA DE DECISÃO

A tomada de decisão faz parte do cotidiano das pessoas, mesmo que muitas vezes inconscientemente. O procedimento de julgamento e escolha está inserido na rotina de uma forma natural, automática. Decisões ocorrem em todos os níveis, dos mais fáceis: Onde almoçar? O que vestir? Até as questões mais difíceis: Onde morar? Que carro comprar? Que carreira seguir? Onde investir? Alcançando decisões organizacionais muito complexas como: Onde implantar uma nova fábrica? Que estratégia adotar? Qual impacto ambiental devo reduzir? Ensslin, Montibeller Neto e Noronha (2001) enumeram as principais dificuldades de uma tomada de decisão:

- Incertezas sobre que caminho seguir, sobre quais objetivos a serem alcançados, sobre quais as diferentes alternativas de solução, sobre o grupo de pessoas envolvidas e/ou atingidas pela decisão;
- Conflito de valores e objetivos entre os múltiplos decisores;
- Diferentes relações de poder entre os grupos de interesse envolvidos no processo decisório;
- Deve-se levar em conta múltiplos critérios na avaliação das alternativas que, em princípio não são claro;
- Grande quantidade de informações (quantitativas e qualitativas) que devem ser levadas em conta no processo decisório;
- As informações disponíveis são usualmente incompletas;

Assim, a decisão geralmente é produto de diversas interações entre as preferências de cada indivíduo e grupos de influência, também conhecido como atores ou *stakeholders* (ENSSLIN; MONTIBELLER NETO; NORONHA, 2001), de forma que cada tomador de decisão percebe e interpreta de forma diferente o contexto decisório. Logo, percebe-se que (quase) sempre a decisão é influenciada pelo julgamento e valores pessoais.

Para auxiliar o entendimento do processo, a teoria de decisão fornece fundamentos para abordagens lógicas e racionais para a tomada de decisão. Desta maneira, os métodos são centrados na escolha de alternativas e em encontrar uma solução ótima, diminuindo a subjetividade inerente ao processo, possibilitando ao tomador de decisão a realização da melhor escolha (ENSSLIN; MONTIBELLER NETO; NORONHA, 2001; SEPPÄLÄ; BASSON; NORRIS, 2002). Por estes motivos, um processo de tomada de decisão de qualidade deve envolver as pessoas apropriadas, identificar boas alternativas, coletar a quantidade certa de informações, ser lógico, usar os recursos de forma eficiente e produzir escolhas que são consistentes com as preferências dos tomadores de decisão responsáveis (MERKHOFER; MAXWELL, 1999).

Até ser identificado o caminho mais indicado, recomenda-se a desestruturação do problema em vários passos. No início as diferentes opções devem ser identificadas e um grupo de parâmetros deve ser criado para a comparação destas alternativas. Todos os cenários devem ser avaliados segundo este critério pré-definido para a identificação das soluções possíveis, conforme Fig. I-9.

Linkov e Moberg (2012), descrevem os cinco passos (visualmente apresentados por RECCHIA et al., 2011) da tomada de decisão desta forma:

1) Identificação do Problema: etapa na qual o problema é definido em termos de tomadores de decisão relevantes e estrutura geral, mas ainda de forma qualitativa;

2) Estruturação do Problema: o problema é aprofundado com a definição de alternativas e de critérios, em que: (a) Alternativas são as potenciais opções gerenciáveis, e (b) Critérios é o conjunto de propriedades que descreve o desempenho das alternativas. Por exemplo, um conjunto de alternativas para o fornecimento de energia elétrica para determinada planta fabril (hidrelétrica, termelétrica, eólica...) é avaliada pelos critérios de geração de impacto ambiental e custo de modo a auxiliar à tomada de decisão.

3) Modelo de Avaliação e Construção: etapa nas quais são atribuídos valores numéricos às alternativas e critérios. As alternativas são contrapostas aos critérios, criando um ranking ou pontuação. Os tomadores de decisão podem ponderar determinados critérios de acordo com a importância atribuída a cada um. Os resultados nos informam o posicionamento de cada alternativa em comparação às demais, além de posicionar os critérios de acordo com seus pesos dentro do processo decisório;

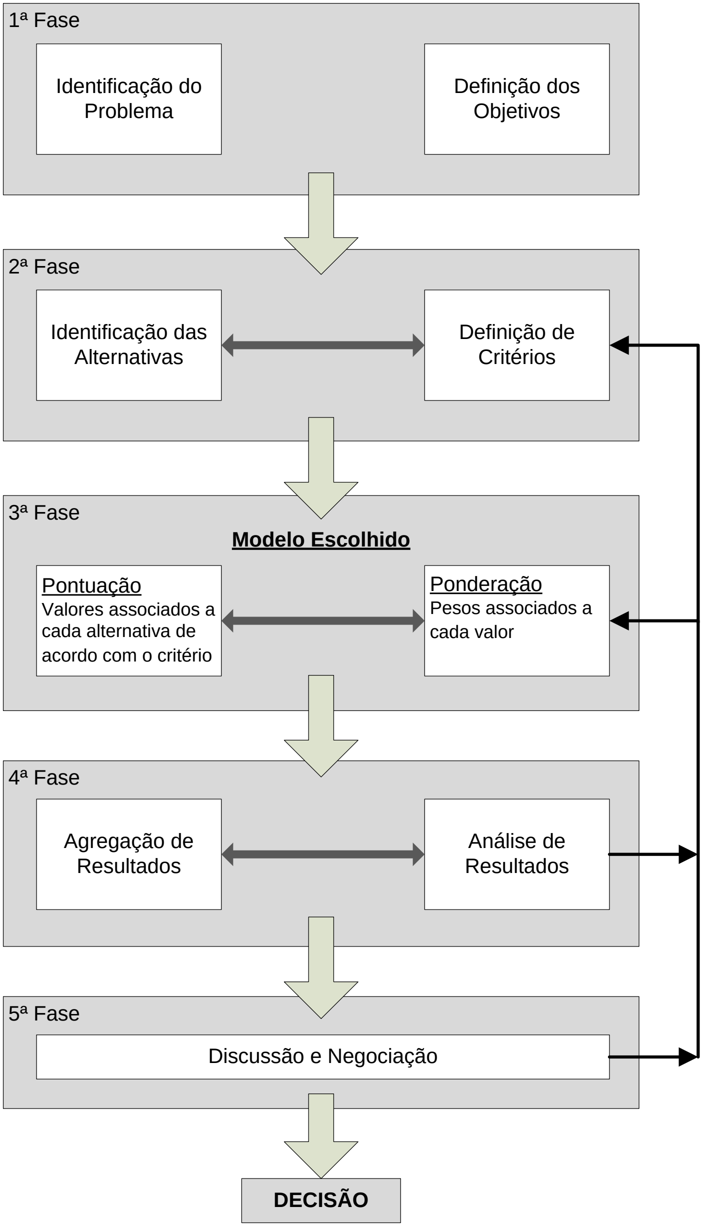
4) Aplicação do Modelo: os critérios, pesos e pontuações das alternativas são aplicados a modelos para viabilizar a melhor decisão. Existem vários modelos, mas essencialmente eles combinam informações de preferência e pontuação. O resultado normalmente é um ranking de alternativas, ou mesmo um conjunto de probabilidades em que uma alternativa será aceita ou não;

5) Planejamento e Extensão: com o modelo funcionando, as decisões e planejamentos podem ser realizados.

Destas cinco etapas, “talvez a tarefa mais criativa na tomada de decisão, seja a escolha dos fatores para a tomada da própria decisão” (SAATY, 1990), contida no segundo passo da metodologia e avaliada no passo três, normalmente mediante alguma abordagem de suporte para a escolha. Esta abordagem de suporte, normalmente é um modelo de análise do grupo de Análise de Decisão Multi-critério (MCDA) (SEPPÄLÄ; BASSON; NORRIS, 2002).

A análise de decisão multicritério (MCDA) é uma área de estudo que tem sido desenvolvida nos últimos 30 anos com o objetivo de abarcar, nesta avaliação, diversas consequências de soluções propostas para resolver uma gama de tipologias de problemas (RECCHIA et al., 2011). Considerada uma das ferramentas para apoio à tomada de decisão, busca identificar um caminho para a solução correta quando ele não é claro, com base na organização de toda a informação disponível e na avaliação de prós e contras associados com cada alternativa. Além de auxiliar o tomador de decisão a lidar com complexas quantidades de informação, a MCDA pode ser usada para identificar uma única opção preferível, para classificar as opções, para limitar um conjunto de opções para posterior avaliação (facilitada), ou simplesmente para distinguir o aceitável do inaceitável (DETR, 2001).

Fig. I-9. Fluxograma do processo de tomada de decisão (RECCHIA et al., 2011).



Por este motivo, seu emprego oferece uma flexibilidade de aplicação que permite atuar em foco gerencial ou político, em nível micro, meso ou macro, e ainda, ser empregada nas dimensões, social, ambiental e econômica (levantamento apresentado por JESWANI et al., 2010). Complementarmente, a integração do meio ambiente na estratégia da tomada de decisão é um pré-requisito essencial para a evolução do desenvolvimento sustentável (POPE; ANNANDALE; MORRISON-SAUNDERS, 2004). Estas características explicam, de certa forma, porque esta metodologia tem sido utilizada de forma crescente na tomada de decisão na área ambiental (DE MONTIS et al., 2000; HUANG; KEISLER; LINKOV, 2011; LINKOV; MOBERG, 2012). Para Kucukvar et al. (2014) a integração de técnicas de MCDA com ferramentas de gestão ambiental, em especial a ACV, pode fornecer um importante guia para os tomadores de decisão e contribuir significativamente para o desenvolvimento de estratégias sustentáveis.

A relação da ACV com a MCDA se torna ainda mais evidente na afirmação de que "a tomada de decisão é notadamente um processo que envolve complexidade, e a ACV é complexa porque quase sempre envolve consequências incertas relacionadas a múltiplos critérios" (SEPPÄLÄ; BASSON; NORRIS, 2002). Por isso, algumas etapas da ACV são comuns à própria MCDA (GELDERMANN; RENTZ, 2005; SEPPÄLÄ; BASSON; NORRIS, 2002), como a estruturação do problema (definição de objetivo e escopo), ponderação, agregação, normalização (etapas opcionais da ACV) e análise de sensibilidade (uma das análises para identificar a incerteza na ACV).

Mais especificamente para a sua aplicação, Guinée et al. (2002) afirmaram que existe um crescente interesse no uso de métodos de análise multicritério, enquanto que Udo De Haes et al. (2002) corroboram indicando que os resultados, conclusões e experiências da MCDA podem ser aplicados à ACV, possibilitando a criação de base teórica para elementos da AICV e ajudando a discernir 'boas' e 'más' abordagens. Diversos outros autores notaram que a MCDA pode ser aplicada no contexto da ACV para auxiliar a interpretação e a tomada de decisão (AHLROTH et al., 2011; BARE; GLORIA, 2006; BENOIT; ROUSSEAUX, 2003; UDO DE HAES et al., 2002; MYLLYVIITA; LESKINEN; SEPPÄLÄ, 2013; PRADO-LOPEZ et al., 2013; ROWLEY et al., 2012; SEPPÄLÄ, 2003; SOARES; TOFFOLETTO; DESCHÊNES, 2006; PIZZOL et al., 2017).

Como existem diversos tipos de decisão para várias problemáticas, nas quais podem variar o tempo necessário para a tomada de decisão, a quantidade de dados disponível, a habilidade analítica do tomador de decisão, bem como suas convicções (DETR, 2001), a metodologia possibilita uma extensa cobertura de aplicações, de forma que existem vários modelos desenvolvidos na literatura. Diante deste cenário, existem vários modelos de apoio à decisão (HUANG; KEISLER; LINKOV, 2011; JESWANI et al., 2010).

Guitouni e Martel (1998) dividem a MCDA em três grupos: (1) abordagens monocritério; (2) abordagens *outranking*, e ainda; (3) abordagens baseadas em julgamentos interativos com iterações de tentativa e erro. Benoit e Rousseaux (2003), complementam afirmando que o terceiro grupo não pode ser aplicado à ACV, porque, enquanto os primeiros dois são embasados em modelos matemáticos estruturalmente claros, este não possui nenhum procedimento formalizado ou automatizado. Segundo os autores, seus julgamentos incorporam somente consequências locais, o que não é valido para a ACV. Exemplos de modelos do primeiro grupo são os métodos *Multi-Attribute Utility Theory* (MAUT/MAVT) e *Analytic Hierarchy Process* (AHP), enquanto que exemplos do segundo incluem a família PROMETHEE e ELECTRE.

A estrutura metodológica destes modelos possui algumas semelhanças. Todos partem da definição das alternativas e dos critérios para a comparação (destas mesmas alternativas), estes critérios devem ser mensuráveis e indicativos para o alcance do objetivo (SEPPÄLÄ; BASSON; NORRIS, 2002). A mensurabilidade significa geralmente a aplicação de uma escala que permite ordenar as alternativas de acordo com o objetivo. Seppälä, Basson e Norris (2002), explicam que as alternativas são analisadas sob a ótica de cada critério e conformam uma matriz base (Fig. I-10Fig. I-10), em que Xi(aj) significa uma pontuação da alternativa aj com relação ao critério Xi.

Fig. I-10. Matriz base dos modelos de MCDA (adaptado de SEPPÄLÄ; BASSON; NORRIS, 2002)

		Atributos / Critérios				
		X_1	**X_2**	**X_3**	**. . .**	**X_m**
	a_1	**$x_1(a_1)$**	**$x_2(a_1)$**	**$x_3(a_1)$**	**. . .**	**$x_4(a_1)$**
	a_2	**$x_1(a_2)$**	**$x_2(a_2)$**	**$x_3(a_2)$**	**. . .**	**$x_4(a_2)$**
Alternativas	**:**	**:**	**:**	**:**	**: : :**	**:**
	a_n	**$x_1(a_n)$**	**$x_2(a_n)$**	**$x_3(a_n)$**	**. . .**	**$x_m(a_n)$**

A diferença entre os modelos é referente aos dados de entrada e aos procedimentos de elicitação de preferências e de agregação (DE MONTIS et al., 2000). Assim, são diferentes no modo como o tomador de decisão interpreta Xi(aj), os ‘mede’ e em como os resultados são compilados (esta compilação pode incluir pesos que refletem os *tradeoffs* que o tomador de decisão está disposto a fazer entre as performances das alternativas para alcançar o objetivo) (SEPPÄLÄ; BASSON; NORRIS, 2002).

O modo como o tomador de decisão quantifica a sua preferência é uma importante propriedade dentro da análise multicritério. Na maioria delas, este procedimento é realizado conforme relações binárias básicas apresentadas abaixo, que precisam atender a algumas características como transitividade e comparabilidade (SEPPÄLÄ; BASSON; NORRIS, 2002).

$a > b \leftrightarrow aPb$ (alternativa ‘a’ é preferencial à ‘b’)
$a = b \leftrightarrow aIb$ (alternativa ‘a’ é indiferente à ‘b’)
$a \geq b \leftrightarrow aQb$ (alternativa ‘a’ é ao menos tão preferível quanto ‘b’)

Independente das variações de cada modelo, Cinelli, Coles e Kirwan (2014), demonstraram que todos os MCDA são passíveis de serem utilizados no âmbito da ACV, embora cada qual tenha seus pontos positivos e negativos (AL-SHEMMERI; AL-KLOUB; PEARMAN, 1997).

Dentre as abordagens mais aplicadas na interface ACV/MCDA pode-se identificar os métodos baseados em critério único de síntese, onde o método AHP é um dos representantes, e aqueles da família outranking (HUANG; KEISLER; LINKOV, 2011) (onde o ELECTRE e o PROMETHEE, são exemplos), constatação reforçada no Capítulo II. How Multi-Criteria Decision Analysis (MCDA) is aiding Life Cycle Assessment (LCA) in results interpretation.

I.3.1 ANALYTICAL HIERARCHY PROCESS (AHP)

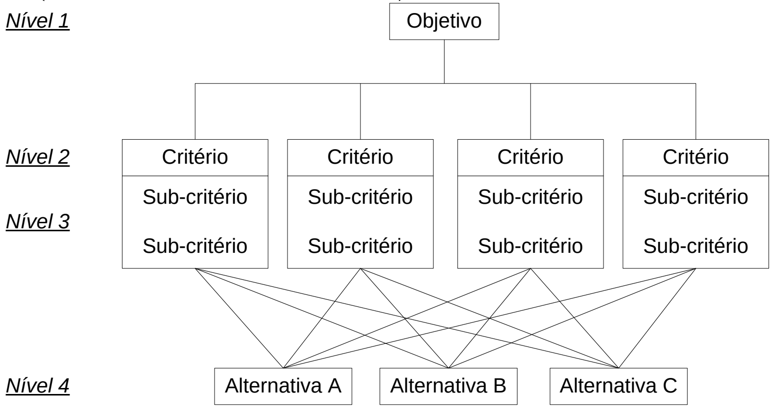
O AHP, método criado na década de 80 por Thomas Saaty é um dos mais populares MCDA (GELDERMANN; RENTZ, 2005; SEPPÄLÄ, 2003; SEPPÄLÄ; BASSON; NORRIS, 2002; VAIDYA; KUMAR, 2006). Esta abordagem diferencia-se dos demais por ser baseado em análise comparativa de pares (LINKOV; MOBERG, 2012). Ao invés de ponderações diretas ou funções de valor, os critérios são diretamente confrontados em pares e o tomador de decisão realiza um julgamento relativo, como por exemplo, o critério econômico é muito mais importante que o critério ambiental. Na sequência este “muito mais importante” recebe um valor dentro de uma escala. Esta escala normalmente varia de 1 a 9 (LINKOV; MOBERG, 2012; MYLLYVIITA; LESKINEN; SEPPÄLÄ, 2013).

No AHP a organização dos fatores envolvidos na decisão é estruturada hierarquicamente de forma descendente de uma meta geral, para subcritérios e alternativas em níveis sucessivos (SAATY, 1990) conforme Fig. I-11. A abordagem realiza então uma comparação de critérios, de forma sistemática, obtendo como produto uma matriz nas quais as alternativas são confrontadas, para então ser aplicada uma regressão linear para definir a melhor decisão. Ao reduzir as decisões complexas a uma série de comparações de pares, seguida da síntese dos resultados, a AHP ajuda a capturar ambos aspectos subjetivos e objetivos de uma decisão (DOUMPOS; ZOPOUNIDIS, 2004).

A estruturação do problema é parte fundamental do AHP. Uma regra geral para hierarquizar a problemática, segundo Saaty (1987), é que a hierarquia deve ser complexa o suficiente para captar a situação, mas pequena e ágil para ser sensível a mudanças. Com a hierarquização (passo 1), o AHP possui geralmente mais três etapas segundo Doumpos e Zopounidis (2004), (2) Inserção dos dados, (3) Estimativa dos pesos relativos do critério avaliado, (4) Combinação dos valores relativos para criar uma avaliação geral das alternativas (Agregação de critérios).

A avaliação das alternativas no AHP é realizada segundo a comparação de pares para indicar o melhor cenário de acordo com o objetivo. Esta comparação é realizada de acordo com uma escala de 9-pontos, conforme Tab. I-11 de Saaty (1987), de forma a defrontar as alternativas em análise no esquema representado pela Fig. I-12.

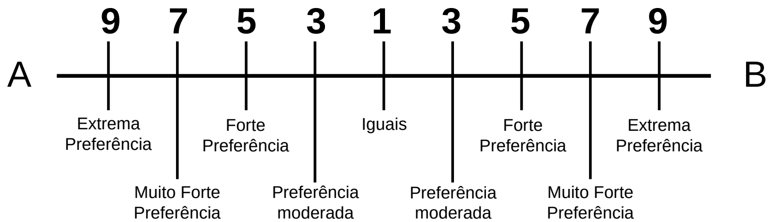
Fig. I-11. Estrutura hierárquica do processo de tomada de decisão por meio do AHP (DOUMPOS; ZOPOUNIDIS, 2004).



Tab. I-11. Escala de 9-pontos para a comparação de a frente ao b na hierarquia AHP (DOUMPOS; ZOPOUNIDIS, 2004).

Escala	Interpretação
1	*a* e *b* são ambos de igual importância (indiferente)
3	Preferência moderada de *a* frente ao *b*
5	Forte preferência de *a* frente ao *b*
7	Muito forte preferência de *a* frente ao *b*
9	Extrema preferência de *a* frente ao *b*
2, 4, 6, 8	Valores intermediários

Fig. I-12. Relação de escala de preferências em uma comparação hipotética da alternativa A versus alternativa B.



Os resultados destas comparações são lançados em uma matriz (n x n) para cada critério em uma comparação das opções onde n denota o número de elementos ao nível A (conforme Fig. I-13). Nesta matriz, a linha diagonal será sempre 1 pois apresenta a preferência de uma alternativa frente a esta mesma alternativa. O triângulo superior a esta diagonal geralmente é o completado com os valores da comparação de pares, sendo o triângulo inferior uma representação recíproca (e inversa) do triângulo superior. Assim, por conta desta reciprocidade e da diagonal representar elementos iguais, a partir de um número de julgamentos de ordem n que conformam uma matriz, o número de elementos comparados é n(n-1)/2 (SAATY, 1987). O resultado contido nesta matriz, A, são os pesos de cada elemento. Assumindo que todas as comparações são consistentes, os pesos são estimados por meio de um sistema linear calculando o autovalor (*eigenvalue*) da referida matriz, conforme Eq. I-3 (DETR, 2001; DOUMPOS; ZOPOUNIDIS, 2004; SAATY, 1990).

Fig. I-13. Matriz AHP. Adaptado de Doumpos e Zopounidis (2004).

$$A = (a_{ij}) = \begin{bmatrix} 1 & w_1/w_2 & \cdots & w_1/w_n \\ w_1/w_2 & 1 & \cdots & w_2/w_n \\ . & . & \cdots & . \\ . & . & \cdots & . \\ w_n/w_1 & w_n/w_2 & \cdots & 1 \end{bmatrix}$$

$$\widehat{W}k \times \widehat{w}k = \lambda_{max} \times \widehat{w}k$$

Eq. I-3. Cálculo do autovalor do AHP.

Onde:

$\widehat{W}k$ é a matriz normalizada resultante da comparação pareada;
$\widehat{w}k$ é o vetor normalizado que estima os pesos, e;
λ_{max} é o maior auto-valor de $\widehat{W}k$;

O cálculo pode ser realizado por softwares específicos como o MATLAB ou por uma simplificação matemática considerando médias, valores normalizados de forma a alcançar os pesos das alternativas comparadas considerando os diversos critérios analisados sob a ótica da comparação de pares e a escala de preferência. A solução simplificada da Equação (5) pode ser obtida por meio de uma aproximação normalizando as médias geométricas das linhas. Este resultado coincide com o autovetor para n < 3. Uma segunda maneira para obter uma aproximação é normalizando os elementos em cada coluna da matriz de julgamento e depois calculando a média sobre cada linha.

Embora o AHP seja bastante aplicado para a tomada de decisão em variadas esferas, Linkov e Moberg (2012) apontam certa inconsistência do método. A inconsistência ocorre quando as preferências não são logicamente compatíveis. Por exemplo, em um caso que o respondente indica que A >B e B > C, logo A > C. No entanto, o mecanismo de resposta para preenchimento da matriz permite que o especialista aponte que C = A. Doumpos e Zopounidis (2004) indicam que resultados com alta inconsistência podem ser indicativos de uma falha na estruturação do problema. Uma matriz recíproca consistente, segundo Saaty (1990), é quando o autovalor máximo é igual ao número de comparações (e.g. $\lambda_{max} = n$). Mesmo assim, é aceitável um nível de inconsistência no modelo, chamado índice de consistência (*CI*), calculado por meio da fórmula Eq. I-4.

$$CI = \frac{(\lambda_{max} - n)}{n - 1}$$

Eq. I-4. Cálculo do índice de consistência do AHP.

Onde:
CI = Índice de Inconsistência;
λ_{max} = auto-valor;
n = número de elementos da matriz;

O CI é então comparado a um índice de referência adequada, chamado índice de consistência (RI, demonstrado na Tab. I-12) conforme Eq. I-5 para identificar a taxa de consistência (CR). O RI são valores 'ideais' identificados por Saaty para matrizes desde 1x1 até 10x10, de modo que, a menor inconsistência aceitável para uma matriz 5x5, por exemplo, é quando seu índice de inconsistência for 0,112.

$$CR = \frac{CI}{RI}$$

Eq. I-5. Cálculo da taxa de consistência do AHP.

Onde:
RI = índice de consistência;
CR = Taxa de consistência;

Tab. I-12. Valores de correção para cálculo da taxa de consistência.

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0,58	0,9'	1,12	1,24	1,34	1,41	1,45	1,49

O CR deve ser inferior a 0,1 para ser aceitável a tomada de decisão (LINKOV; MOBERG, 2012; MACHARIS et al., 2004; SAATY, 1987). Quando a taxa se apresentar acima deste valor, Saaty (1987) indica a necessidade de um reexame dos julgamentos.

I.3.2 OUTRANKING - PROMETHEE

Outranking[5] significa literalmente 'ser superior à'. Neste tipo de MCDA, a decisão é baseada na agregação das preferências do *stakeholder*, estabelecidas quando comparadas diferentes alternativas sob a ótica de cada conjunto de critérios (BENOIT; ROUSSEAUX, 2003; SEPPÄLÄ; BASSON; NORRIS, 2002), partindo-se do pressuposto que o tomador de decisão consiga expressar preferência, pouca preferência ou indiferença, quando comparadas as alternativas sob os critérios (SEPPÄLÄ; BASSON; NORRIS, 2002). A ideia é que uma alternativa 'a' é superior a uma alternativa 'b' se existir argumentos suficientemente fortes a favor de que 'a' é ao menos tão bom quanto 'b' (do ponto de vista do tomador de decisão) (GELDERMANN; RENTZ, 2005; GUITOUNI; MARTEL, 1998). A partir desta relação é possível conduzir comparações pareadas para cada par de alternativas sob a ótica de cada critério para afirmar ou refutar que a alternativa é realmente superior a outra (SEPPÄLÄ; BASSON; NORRIS, 2002).

Geralmente os modelos *outranking* resultam em faixas de preferência, e, portanto, segundo Ensslin, Montibeller Neto e Noronha (2001), obtêm resultados menos ricos que as abordagens AHP e MAUT. Na literatura científica, a aplicação dos métodos *outranking* é dominada por dois modelos: o *ELimination Et Choix Traduisant la REalité* (ELECTRE) e o *Preference Ranking Organization METHod for Enrichment of Evaluations* (PROMETHEE) (BENOIT; ROUSSEAUX, 2003; DOUMPOS; ZOPOUNIDIS, 2004; FIGUEIRA; GRECO; EHROGOTT, 2005) desenvolvidos na década 60 por Roy e de 80 pelos pesquisadores Brans e Mareschal, respectivamente. Behzadian et al. (2010), complementam atestando a importância da abordagem *outranking* na Gestão Ambiental, que segundo os autores, é o principal campo de aplicação do PROMETHEE.

Independente do modelo, os *outranking* usam regras de cálculo que indicam que até um determinado nível, uma má performance de um critério não pode ser compensada por uma boa performance de outro (SEPPÄLÄ; BASSON; NORRIS, 2002), e por isso esta categoria de MCDA é considerada parcialmente compensatória (SEPPÄLÄ; BASSON; NORRIS, 2002), ou mesmo não compensatória. Cinelli, Coles e Kirwan (2014) explicam que os métodos ELECTRE e PROMETHEE explicitamente contabilizam as incertezas dos critérios de entrada por

[5] A abordagem *outranking* é traduzida como "de subordinação" por Ensslin et al. (2001).

conta da adoção do modelo de pseudo-critério que introduz limiares de indiferença e de preferência. Boufateh et al. (2011), complementam caracterizando os outranking com um bom nível de pragmatismo no contexto da tomada de decisão. Corroborando com a posição de Ensslin, Montibeller Neto e Noronha (2001), Geldermann, Spengler e Rentz (2000) relacionam o ELECTRE e o PROMETHEE. Outros autores indicam a preferência pelas abordagens outranking dentro do MCDA. Para Figueira, Greco e Ehrogott (2005), os métodos outranking constituem uma das abordagens mais frutíferas em MCDA. Behzadian et al. (2010), afirmam com base em uma revisão sobre aplicação do PROMETHEE, que o seu sucesso é basicamente devido as suas propriedades matemáticas e a sua particular facilidade de aplicação.

As abordagens ELECTRE são uma forma popular de tornar o conceito outranking operacional, mas este método tem uma desvantagem através de sua complexidade, decorrentes das nuances nas comparações: por conta dos pressupostos subjacentes ao algoritmo, o método é bastante difícil de explicar aos tomadores de decisão na indústria ou na política, especialmente porque os limiares introduzidos não têm um significado realista. Para superar estes obstáculos, o método outranking PROMETHEE foi desenvolvido, reunindo flexibilidade e simplicidade para o utilizador (GELDERMANN; SPENGLER; RENTZ, 2000).

Boufateh et al. (2011) diferenciam o PROMETHEE I e o PROMETHEE II em virtude de seus resultados. Segundo os autores, embora ambos tenham sido desenvolvidos pelos mesmos pesquisadores na década de 80, o primeiro método permite um ranqueamento parcial, enquanto que o segundo permite um ranqueamento completo. Além disso, Behzadian et al. (2010) concluíram em sua análise que o PROMETHEE é mais estável que o ELECTRE.

São três passos principais no método PROMETHEE: (1) Especificar uma função de preferência para cada critério (geralmente classificados nas possibilidades apresentadas na Fig. I-14); (2) Definir um vetor contendo a importância (peso) de cada critério; e (3) Definir para todas as alternativas, uma relação de subordinação (ou relação *outranking*) (GELDERMANN; RENTZ, 2005).

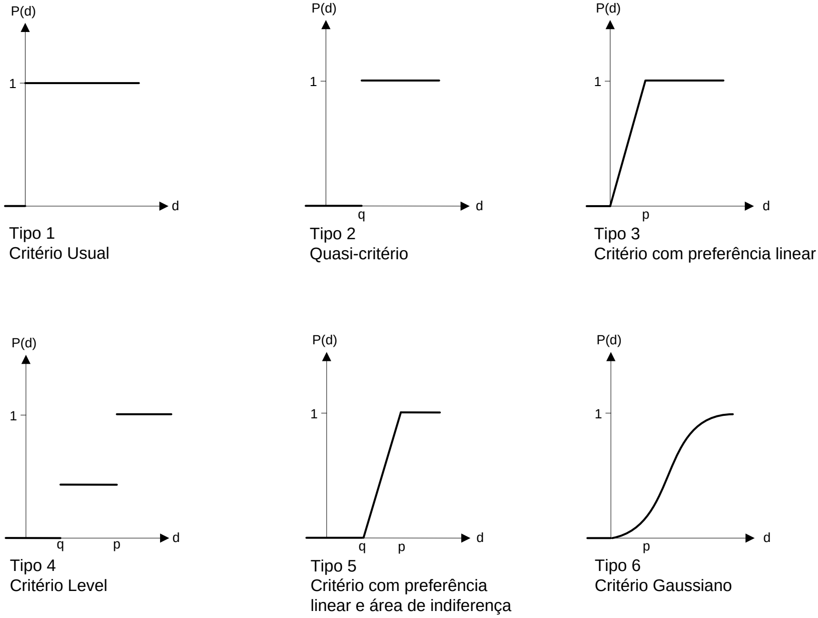
A função de preferência é estruturada em cima de limiares, que permitem que o especialista exponha seu julgamento na razão de uma determinada faixa de respostas. As respostas são convertidas em uma relação básica e binária, (S), de subordinação (ENSSLIN; MONTIBELLER NETO; NORONHA, 2001) cujo significado, como já mencionado, é "pelo menos tão bom quanto" quando comparadas duas alternativas, aSb (DOUMPOS; ZOPOUNIDIS, 2004; FIGUEIRA; GRECO; EHROGOTT, 2005). Estes limiares são os de preferência (P), indiferença (I) ou incomparabilidade (Q) (BOUFATEH et al., 2011; DOUMPOS; ZOPOUNIDIS, 2004). Assim, quatro situações podem ocorrer (FIGUEIRA; GRECO; EHROGOTT, 2005):

- aSb e não bSa, por exemplo aPb sendo ‘a’ estritamente preferível à ‘b’;
- bSa e não aSb, por exemplo bPa sendo ‘b’ estritamente preferível à ‘a’;
- aSb e bSa, por exemplo aIb sendo ‘a’ indiferente à ‘b’;
- não aSb e não bSa, por exemplo aRb sendo ‘a’ incomparável à ‘b’;

Assim como o AHP e o MAUT/MAVT, a abordagem *outranking* se utiliza do questionamento ao tomador de decisão. Este, atribui um valor em uma escala determinada para cada critério, e depois são convertidos em relações entre 0 a 1 de acordo com as condições para validar a proposta de que ‘a’ é superior a ‘b’ (BEHZADIAN et al., 2010; BOUFATEH et al., 2011). Esta relação, em partes, é muito semelhante com a abordagem desenvolvida a partir da ‘resistência à mudança’, apresentada por Soares, Toffoletto e Deschênes (2006).

A função de preferência de uma alternativa frente à outra geralmente segue seis padrões diferentes conforme Fig. I-14. Estes comportamentos, naturalmente, não são exaustivos, mas segundo Brans, Vincke e Mareschal (1986), eles são suficientes na maioria dos casos práticos. Assim, cada critério pode ter um comportamento e uma função de cálculo para a conversão nos valores do PROMETHEE.

Fig. I-14. Padrões de preferência para os limiares na abordagem PROMETHEE para classificação dos critérios (BRANS; VINCKE; MARESCHAL, 1986)



O Algoritmo do PROMETHEE representa estas preferências, conforme Eq. I-6, onde o grau de preferência de uma alternativa (a_t) em comparação com a outra ($a_{t'}$) pode variar de p_k (d) = 0, o que significa indiferença ao longo de uma zona de preferência fraca até p_k (d) = 1 que descreve uma preferência estrita. Esta variação ocorre conforme os seis tipos de critérios gerais (Fig. I-14).

$$p_k(f_k(a_t) - f_k(a_{t'})) = p_k(d) \in [0;\ 1]$$

Eq. I-6. Cálculo de preferências no PROMETHEE.

Onde:

p_k (d) = grau de preferência de a_t sobre $a_{t'}$ para o critério f_k

$f_k(a_t)$ é a avaliação da alternativa a_t com relação ao critério f_k

$f_k(a_{t'})$ é a avaliação da alternativa $a_{t'}$ com relação ao critério f_k

Um índice de preferência é então estimado pela Eq. I-7, representado por uma relação de subordinação π (a_t , $a_{t'}$), que significa a medida para a intensidade de preferência do decisor de uma alternativa

a_t , em comparação com uma alternativa $a_{t\prime}$ para uma análise simultânea de todos os critérios. Segundo Geldermann, Spengler e Rentz (2000), esta é basicamente uma média ponderada das funções de preferência p_k (d), cuja relação gráfica é apresentada pela Fig. I-15.

$$\pi: \begin{cases} \mathrm{A \times A} \rightarrow [0;\ 1] \\ \pi\,(a_t, a_{t'}) = \sum_{k=1}^{k} \mathrm{w_k}\ .\ p_k(f_k(a_t)\ -\ f_k(a_{t\prime})) \end{cases}$$

Eq. I-7. Cálculo do índice de preferências do PROMETHEE.

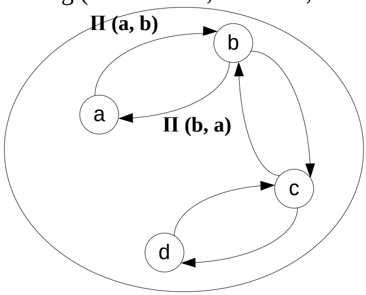
Onde:

π (a_t , $a_{t\prime}$) é a relação de subordinação de a_t sobre $a_{t'}$

$\mathrm{w_k}$ representa o peso de cada critério k previamente definido

Nesta equação, fica claro que se $\pi\,(a_t, a_{t'})$ é próximo a zero, indica uma preferência global fraca de a_t sobre $a_{t'}$, ao passo que se $\pi\,(a_t, a_{t'})$ é próximo de um, indica uma forte preferência de a_t sobre $a_{t'}$.

Fig. I-15. Gráfico-outranking (FIGUEIRA; GRECO; EHROGOTT, 2005).



Os pesos para os critérios, segundo vários autores deve ser mensurado a parte do procedimento usual do PROMETHEE, ou parte-se do princípio que o tomador de decisão saiba a significância de cada critério (BEHZADIAN et al., 2010). Por isso, é possível ponderar os critérios por meio de outros métodos, fazendo uma integração mista com o PROMETHEE. Utilizar os métodos PROMETHEE em conjunto com outros métodos de MCDA do ponto de vista de aplicações práticas torna uma decisão mais realista e promissora do que o PROMETHEE individualmente (BEHZADIAN et al., 2010). A combinação do PROMETHEE com o AHP já é perceptível em alguns estudos. Nestes casos, a classificação final das alternativas é realizada por meio do

PROMETHEE e a importância dos critérios, determinada pelo AHP (BEHZADIAN et al., 2010).

O passo seguinte no procedimento do PROMETHEE, segundo Boufateh et al. (2011), é o ranqueamento parcial das alternativas que é entendido como o 'fluxo de saída' (ϕ^{+}), como uma medida de força da alternativa a_t ϵ A (Eq. I-8). Geldermann, Spengler e Rentz (2000) salientam que o valor alcançado é a soma dos valores dos arcos que saem do nó a_t, e, por conseguinte, proporcionam uma medida do caráter *outranking* de a_t. Da mesma forma ϕ^{-} representa o fluxo de fraqueza de a_t ϵ A, onde o valor significa um 'fluxo de entrada' e, automaticamente um caráter *outraked* (vide Eq. I-8).

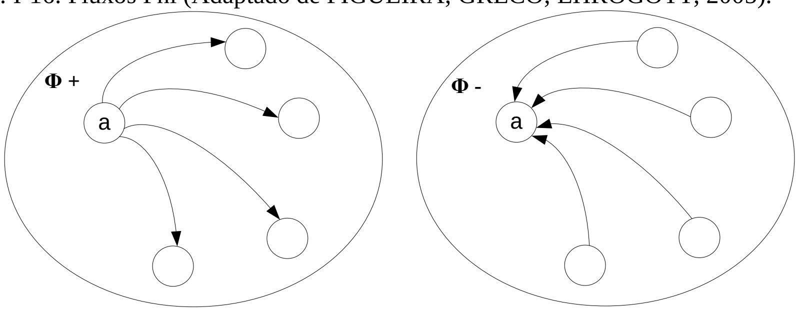
$$\phi^{+}(\mathrm{a}) = \frac{1}{\mathrm{n}-1} = \sum_{\mathrm{x}\,\epsilon\,\mathrm{A}} \pi\,(a, x) \qquad \phi^{-}(\mathrm{a}) = \frac{1}{\mathrm{n}-1} = \sum_{\mathrm{x}\,\epsilon\,\mathrm{A}} \pi\,(x, a)$$

Eq. I-8. Cálculo dos fluxos de saída e de entrada.

Onde:
$\phi^{+}(\mathrm{a})$ é o fluxo outranking da alternativa *a* sobre as demais
$\phi^{-}(\mathrm{a})$ é o fluxo outraked da alternativa *a* sobre as demais
n: é o número de alternativas avaliadas.

Graficamente, os elementos ϕ^{+} e ϕ^{-} são apresentados na Fig. I-16 para fluxos de entrada e de saída. O resultado de ϕ^{+} representa o quanto determinada alternativa é subordinante das demais, sendo que quanto maior o valor, mais significativa, enquanto que o ϕ^{-} representa o quanto uma alternativa é subordinada a outra. Estes resultados fornecem o ranqueamento parcial, típico resultado do PROMETHEE I.

Fig. I-16. Fluxos Phi (Adaptado de FIGUEIRA; GRECO; EHROGOTT, 2005).



Para o ranqueamento total (PROMETHEE II), uma relação entre Phis deve ser calculada. O valor resultante é denominado fluxo de rede (*net-flow*), apresentado na Eq. I-9.

$$\phi^{net}(a) = \phi^{+}(a) - \phi^{-}(a)$$

Eq. I-9. Cálculo do fluxo de rede

Onde:
$\phi^{net}(a)$ é o balanço de fluxos
$\phi^{+}(a)$ é o fluxo outranking da alternativa *a* sobre as demais
$\phi^{-}(a)$ é o fluxo outraked da alternativa *a* sobre as demais

O conjunto de resultados ϕ^{net}, ou o ϕ^{net} de cada alternativa representa a significância da mesma segundo o balanço de preferências dos *stakeholders*.

I.3.2.1 O modelo (híbrido) AHP-PROMETHEE

O AHP é considerado um modelo monocritério (critério único de síntese) segundo Ensslin, Montibeller e Neto (2001) e Guitouni e Martel (1998) e é bastante criticado por uma condição inerente e indesejável aos seus procedimentos de agregação de valores, que é a compensação conforme indicado por Benoit e Rousseaux (2003). Os autores argumentam que, de um ponto de vista mais intuitivo, isso significa que uma boa avaliação de um critério compensa uma avaliação ruim de outro. Modelos que acusam a compensação devem ser evitados no âmbito ambiental sempre que possível, porque um impacto muito sério a um ecossistema não pode ser compensado por outro, insignificante. Por este motivo o AHP só pode fornecer uma fraca perspectiva de sustentabilidade com relação aos critérios de *trade offs*, enquanto que o PROMETHEE representa uma forte perspectiva por limitar ou abolir a compensação entre/dentro das esferas de sustentabilidade (CINELLI; COLES; KIRWAN, 2014).

Todos os modelos de MCDA são, ou compensatórios, ou parcialmente compensatórios. Exceção feita aos modelos *outranking*, que Benoit e Rousseaux (2003) definem como “muito menos” compensatórios, porque esta abordagem promove ações médias em detrimento a alternativas que são muito boas para um critério e muito ruim para outros. Esta constatação é compartilhada por diversos outros autores (CINELLI; COLES; KIRWAN, 2014; ROY; SŁOWIŃSKI, 2013; GELDERMANN; RENTZ, 2005; PRADO-LOPEZ, 2013; POLATIDIS et al., 2006; TURCKSIN et al., 2011). O que faz com que os modelos baseados na abordagem *outranking* sejam muito interessantes quando uma decisão ambiental deve ser tomada (MUNDA, 2005; PRADO-LOPEZ, 2013) e em especial para a aplicação na ACV (BENOIT; ROUSSEAUX, 2003).

No entanto, como explicado por Behzadian et al. (2010), Turcksin et al. (2011) e Macharis et al. (2004), PROMETHEE assume que o tomador de decisão é capaz de pesar adequadamente os critérios, de modo que é necessário informar sobre a importância relativa dos critérios (pesos). Por causa desta condição e sendo que o AHP é uma maneira de determinar pesos a serem usados em abordagens de MCDA (PASTARE et al., 2014), a combinação de AHP e PROMETHEE é complementar. Uma comparação mais ampla e substancial entre os métodos MCDA aplicáveis à ponderação da ACV é apresentado sob diversos aspectos no APÊNDICE E – MCDA Methods.

I.4 A MCDA NA ACV

A Aplicação da MCDA na ACV é bastante diversificada e possui uma relação muito próxima para cada etapa da ACV. No entanto, a grande maioria ocorre para auxiliar a tomada de decisão em situações em que é necessária a comparação de cenários, alternativas ou opções concorrentes em função, dentro do ciclo de vida em questão (i.e., aplicado na comparação dos resultados de uma ACV). Estas questões, assim como outras conexões estão abordados no Capítulo II How Multi-Criteria Decision Analysis (MCDA) is aiding Life Cycle Assessment (LCA) in results interpretation. Este capítulo contém o artigo publicado em 2017 no *Journal of Cleaner Production* e realiza um mapeamento de como a MCDA tem auxiliado na interpretação de resultados conflitantes na ACV, incluindo o desenvolvimento de pesos ou significância para as categorias de impacto.

Complementar ao Capítulo II e para o entendimento do estado da arte da aplicação da interface MCDA/LCA, o APÊNDICE A - References considered in the publishing “How Multi-Criteria Decision Analysis (MCDA) is aiding Life Cycle Assessment (LCA) in results interpretation” compila todas as 109 referencias analisadas no artigo e elenca outros aspectos comparativos como métodos de AICV e de MCDA utilizados.

I.5 CONSIDERAÇÕES FINAIS

A partir da revisão bibliográfica, alguns tópicos podem ser destacados. A ponderação é uma etapa opcional dentre aquelas existentes em uma ACV. Esta condição existe por conta da subjetividade inerente à ponderação, fazendo com que ela não seja unanimidade entre os praticantes de ACV e refletindo na larga faixa de abordagens existentes para atribuir significâncias às categorias de impacto. Por outro lado, os resultados de uma ACV são quase sempre complexos de se interpretar, carregados de *trade off* entre cenários e possibilidades, o que mina a certeza da tomada de decisão. Neste sentido a ponderação tem muito a acrescentar ao tomador de decisão, seja como complemento a uma análise em nível *midpoint*, seja para a utilização como indicador final (SS) quando em conjunto com um procedimento de agregação. De uma forma mais generalista, uma ACV em indicador único seria útil e de fácil comunicação para a decisão em nível de políticas públicas, em nível macro organizacional e para atingir uma maior gama de consumidores em um possível programa de rotulagem ambiental. Por este motivo, já existem conjuntos de pesos (ou exercícios de ponderação) publicados na literatura, e como o modo de julgar ou atribuir valor é reflexo do grupo de stakeholders (ou das condições locais para métodos DtT e WtP) estas ponderações forma desenvolvidas para diversos países e regiões (e.g., Austrália, Japão, Estados Unidos, Europa).

Para auxiliar o tomador de decisão a ter mais certeza (ou menos incerteza) nesta tarefa, a área da Análise de Decisão Multicritério foi estabelecida. Hoje, a relação próxima entre a ACV e a área da MCDA tem acrescentado robustez à tomada de decisão. Por exemplo, Finnveden et al. (2009) afirmam que o desenvolvimento de ponderações para uso na ACV está sendo beneficiado pelo desenvolvimento em conjunto com ciência econômicas e da análise multicriteriosa de decisão (como em SOARES; TOFFOLETTO; DESCHÊNES, 2006 e AGARSKI et al., 2016). A abordagem de MCDA imprime uma metodologia científica e replicável à uma tarefa de julgamento pessoal (que é a ponderação). Esta relação é de mutualismo, com benefícios aos dois campos. Adicionalmente, a MCDA permite o envolvimento de *multistakeholders* na tomada de decisão, situação ideal para muitos especialistas, fazendo com que um painel de especialistas estruturado na MCDA como um caminho bastante interessante para evoluir na problemática. Dentre os métodos de MCDA, aqueles considerados não compensatórios são preferíveis para ponderar categorias de impacto porque não compensam uma alta significância de determinado impacto com um valor baixo para outra categoria de impacto em seu modelo de agregação matemática.

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Capítulo II. How Multi-Criteria Decision Analysis (MCDA) is aiding Life Cycle Assessment (LCA) in results interpretation

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Abstract: Life Cycle Assessment (LCA) is a robust methodology that assesses the environmental impacts of product systems. However, assessing its outcomes is not always easy. When decision-making must be carried out in such complex situations, Multi-Criteria Decision Analysis (MCDA) may be applied. In this paper, the way in which MCDA techniques are being applied within the LCA context to aid results interpretation was assessed. The aim is to investigate the current framework of this integration and to map the application of MCDA and LCA according to the LCA steps, references and criteria. Thus, a research was made in SCOPUS and Web of Science databases through a specific set of key-words. As a result, 109 papers were identified. The survey demonstrate that MCDA is applied at three different times in LCA steps: at Life Cycle Impact Assessment (LCIA) to analyze trade-offs between impact categories, damage categories, or the LCA score with other dimensions; at the Life Cycle Inventory (LCI) step, to interpret aspects from inventory (such as waste generation); and at the Goal and Scope definition step to identify impact categories and aspects of LCI. MCDA is also used for LCIA development, to attribute significance to impact categories. In general, the Triple Bottom Line (TBL) dimension was more recurrent, followed by Environmental and Eco-efficiency (environmental-economical) dimensions. The most common criteria were global warming, acidification and eutrophication in environmental prisms, costs and profits in economic aspects and job creation and labor security in social aspects. Results have shown mutual benefits and a clear and growing interest from the scientific community in relation to MCDA/LCA. Specific subjects to be further studied are: MCDA supporting other methodological choices, such as the allocation

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approach; MCDA to elicit meanings for impact categories in a way to compel stakeholders and verify geographical conditions for decision-making, and; Economic and social criteria used may contribute to Life Cycle Costing and Social LCA development.

Key-words: Multi-Criteria Decision Analysis; MCDA; Life Cycle Assessment; LCA; Interpretation; Decision-Making.

RESUMO EXPANDIDO EM PORTUGUÊS

Introdução. O objetivo deste capítulo é identificar as principais relações da aplicação da abordagem de Análise Decisão Multi-critério na Avaliação do Ciclo de Vida, averiguar a possiblidade de aplicação na ponderação e verificar se existe uma lacuna a ser preenchida no caso da aplicação de MCDA para identificar pesos para categorias de impacto. Um mapeamento do estado da arte desta interação nas publicações internacionais foi elaborado, conforme a etapa do ciclo de vida onde foi aplicada a metodologia da MCDA concomitantemente às dimensões da tomada de decisão (ambiental, econômico, social e técnico). Adicionalmente os principais critérios ambientais foram identificados e um quadro comparativo entre as publicações sob diversos aspectos foi construído.

Material e métodos. As publicações consideradas nesta análise foram delimitadas conforme palavras-chave específicas, aplicadas nos campos de busca de dois dos principais bancos de trabalhos científicos: SCOPUS and Web of Science (WoS). Ambos possuem alta incidência de acessos nos campos científico e acadêmico sendo a escolha de diversos outros autores para estudos bibliográficos desta mesma natureza (HOU et al., 2015; MYLLYVIITA; ANTIKAINEN; LESKINEN, 2016; QIAN, 2014; SOUZA; BARBASTEFANO, 2011; SUBRAMANIAN et al., 2015; XU; BOEING, 2013; ZANGHELINI et al., 2016).

As palavras-chave, definidas com o objetivo de delinear as publicações relacionadas a ACV e MCDA, foram “life cycle assessment” ou “life cycle analysis” ou “LCA” e “multi-criteria decision analysis” ou “multi-criteria analysis” ou “MCDA” ou “MCA”, em todas as possíveis combinações entre as mesmas. No SCOPUS, as palavras foram inseridas nos campos de busca (article title), (abstract) e (keyword), publicados em todos os anos até 2016, para todos os tipos de documentos. No Web of Science, elas foram lançadas como (title), (abstract) e (keywords), publicados em todos os anos até 2016, classificados como ‘journals’. Na sequência, o grupo de publicações foi refinado através da leitura do título, resumo e palavras-chave, onde artigos repetidos ou que não aplicaram ACV e MCDA foram descartados da análise aprofundada. Balizada por uma tabela comparativa sob vários aspectos qualitativos, a análise aprofundada foi dividida em análise do campo de pesquisa (embasada na Bibliometria, HOU et al., 2015) e análise de conteúdo dos artigos (interpretação aprofundada).

Resultados e discussões. A pesquisa sem qualquer filtro identificou inicialmente 427 documentos no SCOPUS e 265 referências no WoS. Depois de refinar, 109 documentos foram considerados para a análise.

Resultados demonstram que a MCDA é aplicada em três momentos diferentes nas etapas da ACV: na Avaliação do Impacto do Ciclo de Vida (AICV) para analisar os *trade-offs* entre categorias de impacto (*midpoint*), categorias de danos (*endpoint*) ou um *score* da ACV com outras dimensões (econômica, social e técnica); na fase de Inventário do Ciclo de Vida (ICV), para interpretar aspectos do inventário (onde as demandas de energia e água em conjunto com a geração de resíduos foram os principais critérios); e na etapa de definição de Objetivo e Escopo para identificar categorias de impacto e aspectos de ICV. O MCDA também é usado para o desenvolvimento da AICV, para atribuir significado às categorias de impacto. O mapeamento destas referências evidencia a lacuna existente na aplicação de abordagens multicriteriosas na definição de objetivo e escopo, onde outros problemas clássicos da ACV poderiam ser melhor definidos, e na elicitação de significâncias de categorias.

Com relação aos métodos, em nível de AICV a abordagem MCDA mais recorrente é a WSA e AHP. No entanto, o recente aumento da aplicação dos métodos da família *outranking* é uma tendência. Tendência confirmada na decisão em nível de ICV, onde a família dos métodos *outranking* é mais comum. Como critério utilizado nestes métodos, em geral, a dimensão Triple Bottom Line (TBL) foi mais recorrente, seguindo-se as dimensões Ambiental e Eco-eficiência (econômico-econômico). Os critérios mais comuns foram o aquecimento global, a acidificação e a eutrofização em prismas ambientais, custos e lucros em aspectos econômicos e criação de emprego e segurança do trabalho em aspectos sociais.

Conclusões. Os resultados mostraram benefícios mútuos e um interesse claro e crescente da comunidade científica em relação ao MCDA/LCA, principalmente por conta da necessidade de se ter melhores decisões e a necessidade de considerar várias dimensões.

No grupo de artigos foi possível identificar a aplicação da MCDA em todas as etapas da ACV, além da sua aplicação para o desenvolvimento de métodos de AICV. No entando, poucos trabalhos foram publicados para o auxílio às definições de objetivo e escopo e para o desenvolvimento de pesos/significâncias para as categorias de impacto, demonstrando uma lacuna a ser preenchida com pesquisas mais diversificadas. Neste caminho, e evidenciado pelos trabalhos recentes, a família *outranking* vem ganhando preferência sobre as abordagens mais antigas principalmente pela sua condição de parcial/não compensatoriedade.

A ampla variação em termos de escolhas, pressupostos e resultados diversos em uma ACV indica que a interpretação dos resultados ainda é muito complexa e não há um caminho metodológico preferencial para resolver a questão final da decisão, ainda mais quando os diferentes *stakeholders* devem participar. Essa é a razão pela qual são necessários métodos auxiliares, como o MCDA. Neste interim, há um interesse claro e crescente na tomada de decisões no nível TBL (sustentabilidade). Condição que reflete na necessidade de desenvolvimento de novos métodos ou melhorias de abordagens existentes, como LCC e SLCA.

Assuntos específicos a serem estudados são: MCDA como apoio a escolhas metodológicas (ex. alocação); MCDA para obter significados para categorias de impacto envolvendo stakeholders e verificar a influência geográfica na tomada de decisões.

II.1 INTRODUCTION

Decision-making is an inherent process that is involved in everyday life, from the simplest daily things as in which clothes to wear to more complex decisions that may have long-term effects, such as buying a house. At the environmental level, where the goal is to promote sustainability, decision-making is never simple. One of the reasons why the path towards sustainable development is unclear, according to Hermann, Kroeze and Jawjit (2007), is because most business contributes to a variety of interrelated environmental problems. Many authors define this interrelated-dynamic behavior, i.e. the trade-off between environmental burdens, as the core of decision-making complexity when any kind of impact assessment is held (BOUFATEH et al., 2011; GELDERMANN; RENTZ, 2005; HERMANN; KROEZE; JAWJIT, 2007; LAURIN et al., 2016; LE TENÓ; MARESCHAL, 1998; Seppälä et al., 2002; SUBRAMANIAN et al., 2015). At the sustainability level, this task is even more difficult. Besides the environmental aspects, sustainability must consider other dimensions. According to Drejeris and Kavolynas (2014), it is quite clear that the goal of sustainable development is to reconcile economic growth, social progress and sustainable use of natural resources, maintaining the ecological balance and ensure favorable living conditions now and in the future. Therefore, the ideal environmental decision-making must consider the triple bottom line (TBL) concept, which brings the trade-off situation to a higher level of complexity.

Other complex factors of decision-making towards sustainability are: uncertainty (DURBACH; STEWART, 2012) because knowledge on these subjects is still scarce and highly subject to change in the future (LE TENÓ; MARESCHAL, 1998); subjectivity, because personal judgment vary on which topics are most important (LE TENÓ; MARESCHAL, 1998); and, the multi-stakeholders' involvement that must be considered in ideal decision-making. Linkov et al. (2006) already emphasized this necessity when they affirmed that "no matter the context, stakeholder involvement is increasingly recognized as being an essential element of successful environmental decision making". Thus, it is no coincidence that a real and substantial application of sustainability through the measurement and comparability of results, in a way that satisfies the principles of sustainability of all the stakeholders is the biggest challenge for most organizations (PETRILLO et al., 2016).

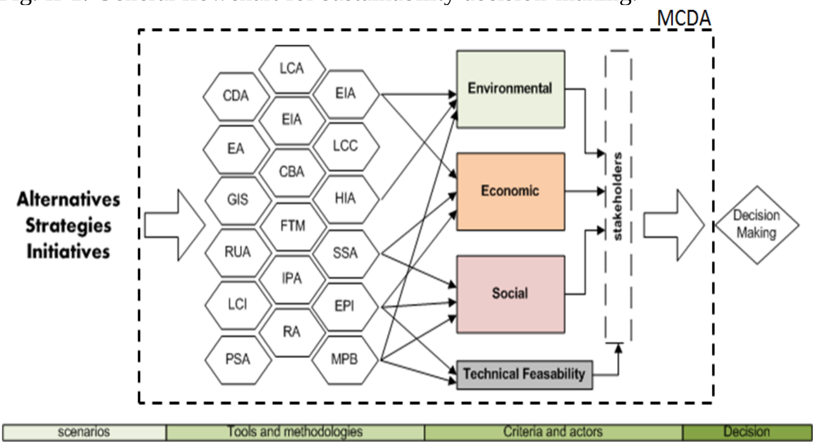
Related to the uncertainty due to a lack of knowledge, many tools were developed in order to bring more clarity on how sustainability aspects can be measured in the past few years. However, Duic, Urbaniec and Huisinghc (2015) indicates that there is still “a need for improvements and new developments in the conceptual, legal and methodological frameworks to facilitate the penetration of sustainability thinking into various system scales”. Authors emphasize that this task should essentially include the development of scientific foundations for the correct setting of boundaries of sustainability systems, enabling effective implementation of advanced models for system analysis and decision support. This kind of support, to aid decision makers to perform better choices in such complex situations can be reached by methods of decision analysis (BASSON; PETRIE, 2007; DE MONTIS et al., 2000; HUANG; KEISLER; LINKOV, 2011; NESS et al., 2007; SEPPÄLÄ et al., 2002).

Regarding tools that aid this process, perhaps the most important and popular are those that form the Multi-Criteria Decision Analysis (MCDA) group (SINCLAIR, 2011). MCDA is defined by Linkov and Moberg (2012) and Doumpos and Zapounidis (2004), as a set of tools and approaches that provides mathematical methodology that incorporates the values of decision makers and stakeholders, as well as technical information, to select the best solution or provide a classification of alternatives for a specific problem. The reason that they facilitate decision-making as a whole (SHIELDS; BLENGINI; SOLAR, 2011) lies on the ability to analyze these different alternatives with conflicting criteria (i.e. the aforementioned trade-offs) affected by various stakeholders (MANZARDO et al., 2014; MYLLYVIITA et al., 2012) in a transparent manner (JESWANI et al., 2010; HUANG; KEISLER; LINKOV, 2011; LINKOV; MOBERG, 2012; ROTH et al., 2009). For those aspects, MCDA is strongly indicated for environmental decision-making and it is especially useful when different social, economic, and environmental indicators are compared (DIAS; DOMINGUES, 2014; MOTUZIENE et al., 2016; MYLLYVIITA et al. 2014).

Myllyviita, Antikainen and Leskinen (2016) indicate that MCDA has the greatest potential to be successfully applied to support sustainability assessment, but solely applying MCDA is not suggested, since it needs input from other tools and methods in order to have reliable assessments. Accordingly, Ramanujan et al. (2014) affirms that a MCDA framework should be based on quantitative measurements of a product’s performance so as to instill a proactive approach. Illustratively, a general framework on how decision-making is being made is presented in Fig.

II-1, considering all important facets of sustainability plus technical criteria (for feasibility assessment). Generally, different scenarios or alternatives are compared for those criteria, and different methodologies/tools may be applied for a more robust quantification of scenario performance under such criteria. Some examples are presented in the flowchart, as Risk Analysis (RA), Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Cost-Benefit Analysis (CBA), Health Impact Assessment (HIA) and Environmental Impact Assessment (EIA). The final step is the decision made by stakeholders, where the different scenarios are compared according to different criteria performances, a task facilitated by the MCDA approach.

Fig. II-1. General flowchart for sustainability decision-making.



It is clear that MCDA is benefited by consolidated quantitative-based methodologies. Regarding all tools and methodologies to measure a products performance shown in Fig. II-1, LCA is one of the most preeminent. It is considered a robust method to assess systems and products (GUINÉE et al., 2002; VON DODERER; KLEYNHANS, 2014) recurrently used to evaluate decision alternatives (e.g. products, sites, projects) on the basis of various environmental indicators (BOUFATEH et al., 2011; ROWLEY et al., 2012). In effect, the integration of MCDA with LCA could be a practical solution (DE SOUZA et al., 2016) to facilitate interpretation of results and to aid decision-making. LCA is a methodology, grounded in the Life Cycle Thinking (LCT) concept, which allows one to assess environmental impacts of a product or a service from cradle to grave and analyze the situation from a multidimensional perspective (CASTELLINI et al., 2012; MYLLYVIITA et al., 2012). The relation between MCDA and LCA may be made in two ways as discussed in the following sections of this paper.

II.2 MCDA AND LCA

The first aspect to be highlighted to understand the relation between these two methodologies is the core essence of both, i.e., they are both decision-making aiding tools. For instance, impact indicators and criteria cover the same notion respectively from the LCA and the MCDA point of view (LE TENÓ; MARESCHAL, 1998). The difference is that LCA quantifies its impact indicators whereas MCDA often needs to be feed by criteria (interpretation-oriented only). This statement is clear regarding its applicability. The former is directed to products and services and it is based on the compilation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle (ISO, 2006a; 2006b). The latter is based on different protocols for eliciting inputs, structures, algorithms and processes to interpret and use formal results in actual advising or decision-making contexts (HUANG; KEISLER; LINKOV, 2011). Thus, generally, the combination of MCA and LCA can occur in a two-ways path: LCA can be applied to add an environmental indicator to the MCDA process and MCDA can be used to interpret LCA outcomes. This relation is sometimes so near that some authors such as Benoit and Rousseaux (2003) also considered LCA as a specific method among the MCDA methods. There are many reasons for combining these tools, but according to Hermann, Kroeze and Jawjit (2007), the main one lies in their complementary characteristics. LCA is objective, reproducible and standardized, whereas MCDA evaluation methods take into account subjective elements (such as the opinions of stakeholders and decision-makers) in the evaluation of the different criteria. On the other hand, the authors indicate that these combinations also have weaknesses. Operationally, they imply a large amount of information that needs to be collected and analyzed, which may block their implementation. Additionally, by including MCDA in this combination means that value-laden choices are made, influencing the results and introducing uncertainty through the loss of information when aggregating data (HERMANN; KROEZE; JAWJIT, 2007).

II.2.1 THE NEED OF LCA IN MCDA

There are several types of MCDA techniques (LINKOV; SEAGER, 2011; SHIELDS; BLENGINI; SOLAR, 2011), each involving its own framework. They can vary from simple approaches requiring very little information to sophisticated methods based on mathematical programming techniques that require extensive information on each attribute and the preferences of the decision-makers (GREENING; BERNOW, 2004). What all multi-criteria methods have in common, according to Durbach and Stewart (2012), is the view that most decisions and decision-making can be improved by decomposing the overall evaluation of alternatives into evaluations on a number of usually conflicting criteria relevant to the problem, in a systematic way (EKENER; HANSSON; GUSTAVSSON, 2016). MCDA can be used to identify a single most preferred option, rank scenarios, grouping or simply distinguish acceptable from unacceptable possibilities (BELTON; STEWART, 2002). However, and as already stated, when it comes to sustainability, the MCDA approach individually is unable to identify efficient levels of pollution production or resource use (ZAGONARI, 2016). Myllyviita, Antikainen and Leskinen, (2016) confirms this situation in "solely using MCDA to support sustainability assessments is not suggested, since MCDA, in many cases, needs input from other tools and methods, such as LCA". Therefore, the use of LCA to assess scenarios in order to feed MCDA methods with environmental content have become perhaps the most usual combination between both methodologies (for instance, see BOGACKA, 2015; BURCHART-KOROL; KOROL; FUGIEL, 2014; VON DODERER; KLEYNHANS, 2014).

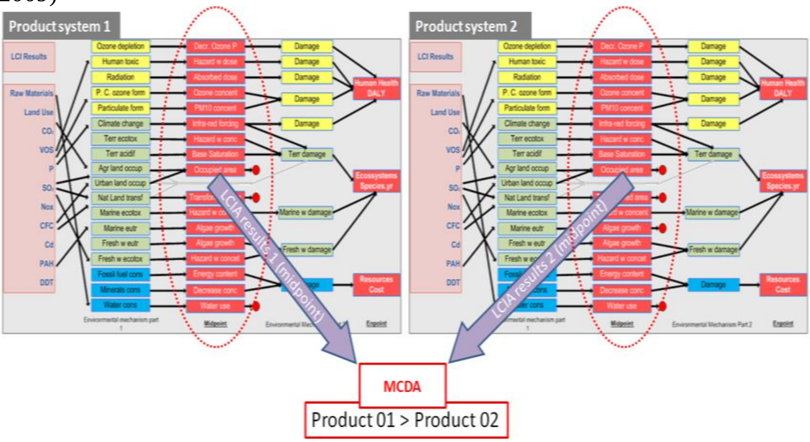
II.2.2 THE NEED OF MCDA IN LCA

Tsang et al. (2014) explains that, even though LCA is a broad-scope environmental management tool, it leaves decision-makers with the challenge of appropriately integrating this information into their decisions. This is primarily due to the fact that LCA has been developed without an explicit link to a specific decision analysis framework (RAMANUJAN et al., 2014). Essentially, LCA results in a list of environmental impacts (or damages) that may be understood as performance indicators of the product system under analyses. However, decisions and conclusions based on those outcomes are still dependent on a vital step after the inventory being characterized into those indicators, the interpretation. Unfortunately, this task is not always straightforward, especially in case of comparison between different alternative scenarios fulfilling the same function (BENETTO; DUJET; ROUSSEAUX, 2008). According to Le Tenó (1999), difficulty lies in the quantity of data, the multiple unit types, the various media to which substances outflow, judgmental values to be applied and the uncertainty of background and foreground data. This situation is aggravated when LCA outcomes show trade-offs between different scenarios. For instance, the mid-point category scores may not point to a single definitive choice as the 'best', i.e., the least environmentally damaging system. One alternative may be better with respect to global warming potential, while another is better with respect to ecotoxicity (SHIELDS; BLENGINI; SOLAR, 2011). Additionally, Laurin et al. (2016) states that the current visualization techniques used in LCA, as bar graphs of characterization results, can be misleading and do nothing to aid in assessing potential trade-offs. In effect, these results may be difficult to interpret by stakeholders and decision-makers.

Therefore, a remaining methodological challenge for environmental managers is how to construct a comprehensive judgment of environmental performance from the many indicators assessed in LCA (BENGTSSON, 2000; CURRAN, 2008; HERTWICH; HAMMITT, 2001). This challenge can be approached using MCDA methods (BENOIT; RESSOUX, 2003). Several authors noted that MCDA methodology can be applied to aid LCA with positive results (CINELLI; COLES; KIRWAN, 2014; GELDERMANN; RENTZ, 2005; HERMANN; KROEZE; JAWJIT, 2007; JESWANI et al., 2010; MIETTINEN; HÄMÄLÄINEN, 1997; SEPPÄLÄ et al., 2002; SOARES; TOFFOLETTO; DESCHÊNES, 2006) especially for preference measurement (MYLLYVIITA et al., 2012). Laurin et al. (2016) explains that MCDA can enrich LCA outcomes by providing studied methods to assess trade-offs mainly because it allows a broader view of different aspects (MANZARDO et al., 2014). Accordingly, Kucukvar et al. (2014) explains that this integration can provide a guidance for decision-makers, which can contribute to the development of sustainable strategies significantly.

Conceptually, MCDA is introduced in the LCA framework and standards as the 'weighting' step. This kind of combined application basically relies on using MCDA concept to aid in LCA trade-off interpretation. In this combination, the MCDA evaluation method is generally used to weight and sum LCA results into a single index (after classification, characterization and optionally normalization) (AGARSKI et al., 2016; HERMANN; KROEZE; JAWJIT, 2007). Fig. II-2 shows the complex framework behind the environmental assessment in LCA and the multiple indicators that provide information for decision-making. Therefore, to aggregate the results at the midpoint or even the endpoint level into a single index/information (e.g. Product 01 > Product 02, Fig. II-2) is desirable to make this an easier process. Coupling MCDA with LCA increases the usability of LCA in assessing product sustainability (SCOTT et al., 2016), is robust and, at the same time, easy to implement (RECCHIA; CINI; CORSI, 2011). Reflex of this beneficial association is present in recent LCA studies as in Boufateh et al. (2011), Kumar et al. (2016) and Scott et al. (2016).

Fig. II-2. LCA cause-effect chain and a schematic framework of a LCA comparison using MCDA for decision-making (based on GOEDKOOP et al., 2009)



However, despite those experiences, the possibilities of MCDA methods are still poorly elaborated in the field of LCA (DE LUCA et al., 2015; DOMINGUES et al., 2015; SEPPÄLÄ et al., 2002). Since incorporating MCDA into LCA includes several sources of uncertainties and methodological disagreements, more research in this field is needed (MYLLYVIITA et al., 2012). Consequently, some authors indicate that MCDA application that analyses objects in terms of the LCA is not common (as MOTUZIENE et al., 2016). As there is a wide variation in terms of simple MCDA/LCA application, different approaches, criteria assessed, results and new MCDA methods for decision-making, one way to contribute to this field is to trace the actual framework on how MCDA is being used regarding LCA specifically.

Overviews regarding MCDA and Environmental Management are not novelties and have already been the theme of several papers in scientific journals. For instance, Herva and Roca (2013) reviewed combined environmental evaluation approaches (including LCA) and multi-criteria analysis for specific industrial sectors such as energy and wastewater treatment, whereas Benoit and Rousseaux (2003) and Geldermann and Rentz (2005) have worked the relations between MCA and LCA methodology phases. However, to date, none have been directed to the way MCDA is applied in a LCA context. Therefore, how this mutual application is being held is assessed in this article, more specifically to aid results interpretation. For that, the aim is twofold: (1) To investigate the current framework of this integration categorizing the field under aspects such as research type, applied MCDA method, considered criteria, influence and motivations for MCDA application in LCA; and (2) To map references in this field regarding the position in LCA steps and level of decision-making in terms of criteria. The expectation is that this paper will indicate some important fields for further research and facilitate the path of those seeking to decrease uncertainty in life cycle thinking, supporting the research community concerned with improving the decision-making procedure.

II.3 MATERIAL AND METHODS

The papers were gathered from SCOPUS and Web of Science (WoS) databases through a specific set of key-words. According to Zanghelini et al. (2016) both have high incidence of access in academic and scientific fields. Consequently, several reviews and bibliometric studies, especially for LCA or MCDA also considered those databases (HOU et al., 2015; MYLLYVIITA; ANTIKAINEN; LESKINEN, 2016; QIAN, 2014; SOUZA; BARBASTEFANO, 2011; SUBRAMANIAN et al., 2015; XU; BOEING, 2013; ZANGHELINI et al., 2016).

The keywords applied to the databases were: “life cycle assessment” or “life cycle analysis” or “LCA” and “multi-criteria decision analysis” or “multi-criteria analysis” or “MCDA” or “MCA” in all possible combinations among them. In SCOPUS, those key-words were inserted in the search fields of (article title), (abstract) and (keyword), published in all years until 2016, for all types of documents. For Web of Science, they were settled as (title), (abstract) and (keywords) search fields, for all years until 2016 and journals as a publishing vehicle.

These sets of keywords were chosen to look for comprehensive publications regarding LCA and MCDA as well as enable one to have a proper yet manageable set of papers. The findings were refined through a previous content review of title and abstract whereas repeated publications were discarded. Since the scope of analysis is the MCDA and LCA integration, only documents that applied (in any matter) MCDA and LCA were considered. In this case, for instance, papers that applied only MCDA and considered LCA for discussion purposes were not considered (and vice versa). The selected papers that complied with these research boundaries were analyzed in detail to extract the information required by a comparative table. Tab. IV-3 (APÊNDICE A) was developed based on several aspects of the final gro up of published works, including direct information, such as reference, date of publication, authors, MCDA method, LCA method and others that were not always clear, for instance, position of MCDA in LCA steps, motivations, criteria applied to perform decision-making, and so forth. The outputs from Tab. IV-3 were divided into two main analyses: (1.) General analyses of this particular field of research, and (2.) Content analyses. For the former, a performance analysis on the basis of bibliometric analysis was conducted (HOU et al., 2015) which aims to evaluate the characteristics of the publications such as journals, evolution through time, dominant publishing type, main publishing vehicles and main economic sector (e.g. livestock, waste management). The second represents a more in-depth interpretation, seeking for patterns and trends in how LCA and MCDA are being applied and what kind of results and conclusions were made by the researchers.

II.4 RESULTS AND DISCUSSION

The survey without any filter identified 427 documents from SOPUS and 265 references from WoS. After refining this group with the proposed outlining strategy, 109 papers were accessed (listed in Tab. IV-3 in APÊNDICE A).

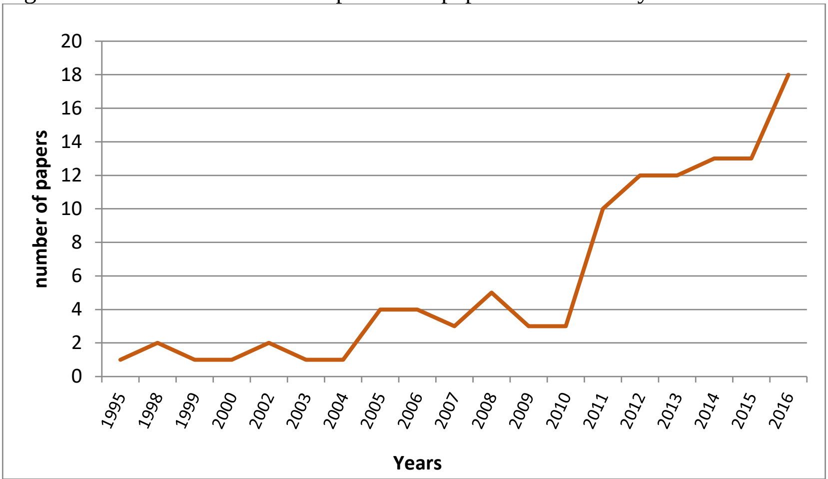
II.4.3 GENERAL ANALYSIS

By assessing this group of papers over time, it is possible to note that the first paper dates from 1995. Bloemhof-Ruwaard, Koudijs and Vis (1995) published a paper titled “Environmental Impacts of Fat Blends: A Methodological Study Combining Life Cycle Analysis, Multiple Criteria

Decision Making and Linear Programming", where LCA was used to obtain an environmental measure for refined oils, to rank scenarios and identify the best choice among different blends of fats and oils for the fuel sector. After 1995, until the early 2000s, the subject of MCDA and LCA was present but in a limited way. Only during the last 10 years it is possible to visualize an increasing behavior, with a more escalated period from 2010 to date (Fig. II-3). Making a parallel with what happened in terms of LCA maturity in the same period of time, during the 90s, LCA standards (ISO, 1997; 1998; 2000a and 2000b) and initial guidelines were published (for instance, SETAC, 1993). These were key factors for the initial use and publication of the LCA by industry and governments, since, due to the standards, the tool recovered its reliability and robustness. However, only with major developments in terms of LCA methodology, growth of databases, software availability and other fields of application of LCA results (e.g. labeling) is that interest in LCA increased and its application was spread to many other economic sectors. This behavior reflects in the increasing number of papers that are noted in Fig. II-3 in the last decade integrating LCA with MCDA. Several other authors, delimiting different kinds of LCA publishing groups, have shown this same tendency as Chen et al. (2014), Hou et al. (2015), Qian (2014), Xu and Boeing (2013) and Zanghelini et al. (2016).

Tab. II-1 presents some general information summarized from Tab. IV-3. Regarding scientific journals, the main vehicle is the Journal of Cleaner Production, with 12 papers followed by the International Journal of Life Cycle Assessment with 7 publications. These journals are dedicated to sustainability promotion and LCA, respectively and not surprisingly, the main vehicles in this matter. Nevertheless, what draws attention in this analysis is the wide variation of different journals, where 76 different vehicles complete the list from the most diverse fields (e.g. energy, waste management, building, fuels, among others). Classifying papers into types of research, 43 papers were labeled as "Application", i.e. when authors simply applied some existing MCDA/LCA methodology to assess its own scenarios. Examples of this kind of paper are Atilgan and Azapagic (2016) and Myllyviita et al. (2012). Both papers applied LCA to insert environmental indicators in decision-making. The former used the Multi-Attribute Value Theory (MAVT) with LCA to evaluate different scenarios for electricity production in Turkey using the CML2001 method as the input/feed for the environmental criteria along with social and economic criteria. Similarly, Myllyviita et al. (2012) used the characterized results from ReCiPe method (at midpoint level) for pulp and paper production scenarios to assess the different impact categories with Simple Multi-Attribute Rating Technique (SMART) to find the best scenario. The dominance of "Application" papers was an expected condition since the ultimate (and most usual) interest of stakeholders is the final decision, which is sustained by results from simple application. Besides, such tools have a multidisciplinary condition, enabling its use to any subject, which may also explain the wide variation in journals. Accordingly, Herva and Roca (2013) affirmed that among the topics covered in their review, applications were found for all the MCDA methods previously discussed by the literature (except one done for MACBETH at that time).

Fig. II-3. Evolution over time of published papers in this survey.



In the sample, 22 other references were categorized as "Review". These papers generally aggregate broader information into a specific subject. French and Geldermann (2005) for example, discussed which tools and techniques may be more appropriate for stakeholder involvement and how they might be deployed within the wider decision-making process. Others brought specific state of the art analysis, such as Strantzali and Aravossis (2016) for renewable energy or Subramanian et al. (2015) for the nanotechnology sector. It is also possible to find a few papers conditioned as "Review and case study", where the subject is reviewed and still applied to some example for illustrative demonstration.

This significant release of review works in the group of papers (24%) may indicate that the field of decision-making and life cycle thinking is still being developed in terms of methodology, a condition that reflects the necessity of discussion and compilation publishing. This effect is illustrated by motivations that led authors to this kind of publication (see Tab. IV-3), often based on a lack of information and literature in the field (FRENCH; GELDERMANN, 2005; MYLLYVIITA; ANTIKAINEN; LESKINEN, 2016; SEPPÄLÄ et al., 2002) or because new tools, methods and trends were created (LIU; LEAT; SMITH, 2011; MOOTANAH, 2005; O'RIORDAN; PHEAR, 2012).

Tab. II-1. General information.

Publishing Vehicle	N
Journal	93
Conference	14
Report	2
Journal	**N**
Journal of Cleaner Production	12
International Journal of LCA	7
Clean Technologies Environmental Policy	4
Sustainability	4
Risk Analysis	3
Environmental Science and Technology	3
Energy Policy	3
Waste Management	3
Others	70
General Subject	**N**
Application	43
Review	22
Creation and case study	21
Proposition and case study	11
Review and case study	4
Creation	4
General proposition	4

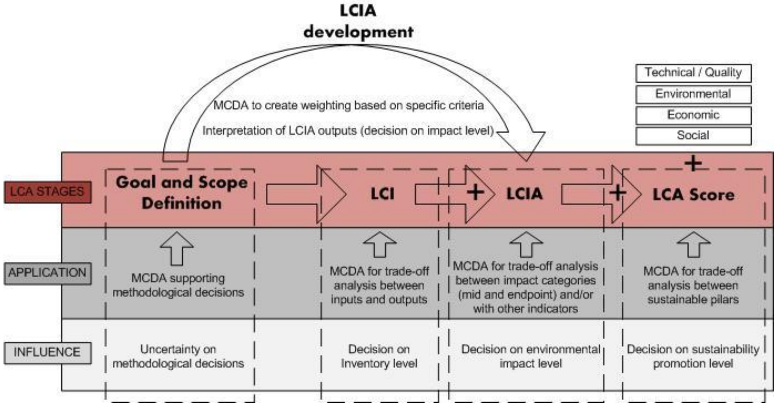
In sequence, 21 and 11 references were classified as "Creation and case study" and "Proposition and case study", respectively. The first group includes studies that proposed new methodologies/approaches, whereas the second group integrated different (but already existing) methods or different insights for existing approaches. To some extent, both group of papers applied its propositions to a real situation as in a case study. Two representative papers of this group in the survey are Le Tenó and Mareschal (1998) and Motuziene et al. (2016). Le Tenó and Mareschal proposed a new approach (PROMETHEE I) able to handle interval performances based on PROMETHEE. In a different way, Motuziene et al. created a general algorithm mixing different approaches including LCA (IMPACT method), LCC, COPRAS and AHP for the envelope selection of the energy efficient single-family house. Completing Tab. II-1, papers were also classified as “Creation”, when a methodology is created but not applied; and “General proposition”, when authors discuss methodology (beyond a review) to guide practitioners. The creation of methods and proposition of approaches is a condition aligned with the previous statement that the LCA/MCDA field is a growing research subject as well as the unsolved problems in sustainable decision-making.

II.4.4 MCDA IN LCA

By tracing a relation between MCDA and LCA, it is possible to identify two spots where MCDA is frequently used to aid LCA interpretation: at the LCI level and the LCIA/LCA Score level. In addition, although uncommon, MCDA has already been used for methodological alternatives, such as the definition of impact categories, and also in a parallel way for the LCA steps: when MCDA is used to create weight to impact categories. This last case is classified as LCIA development within LCA methodology. This condition illustrates a statement from Seppälä (2003), who indicated that MCDA within an LCA study can be used in all LCA phases. Fig. II-4 presents a schematic framework of this relation regarding its main applications and the kind of influence that generates into decision-making.

In the mapping research from Fig. II-5, the criteria (environmental, economic, social and technical) assessed was related in each study that effectively applied or proposed an integration of LCA and MCDA regarding the position of MCDA in LCA (phases). For example, references positioned in “Methodological Choices” applied MCDA to aid impact categories selection or to identify significant aspects in LCI. Publications located in LCI on the ‘LCA Localization’ axis assessed indicators at the inventory level, such as consumptions (water, energy) and generations (waste, CO2). Meanwhile, references positioned in LCIA assessed outcomes from LCIA methods such as midpoint impact categories (Global warming, Eutrophication and Acidification) and endpoint damage categories (Human Health, Ecosystem and Resources). Finally, references positioned in the LCIA development “umbrella” are those that extract significance of impact categories and create a set of weights for the weighting step in LCA. These possibilities are addressed in detail in the next sections.

Fig. II-4. Levels where MCDA may be integrated to aid interpretation on LCA approach.



II.4.4.1 MCDA in LCA methodological decisions

For the purpose of a better understanding, methodological decisions were positioned in the Goal and Scope Definition phase, although it can be argued that a LCA practitioner made decisions in all phases of a LCA. Therefore, in this phase, the intent is to set MCDA when it is applied to support a major methodological decision. Even though it is the first phase in the LCA framework (ISO, 2006a), this integration is uncommon as demonstrated in Fig. II-5. Only Myllyviita et al. (2012) is classified in this column as a panel-based MCDA that was used to add environmental impacts, not previously considered as being included in LCA. According to the authors, results show that the panelists recognized deficiencies in the impact categories of the ReCiPe methodology. Papers located in the middle of two columns, such as Liu et al. (2012), considered elements of two different locations in LCA phases. In the work of Liu et al., LCA was used to identify the cause-effect chain (aspects of the life cycle) and then apply MCDA combined with Risk Analysis to aid decision-making on waste management plants. The identification of the cause-effect chain is somehow a path that a LCA practitioner has to perform when outlining scope definitions (as product system boundaries) and beginning to gather data where aspects must be identified. That is the reason Liu et al. (2012) is positioned between Methodological Choices and LCI on Fig. II-5.

Myllyviita et al. (2012) explains that in situations where relevant impact categories may not be obvious, selecting impact categories with the assistance of MCDA in a process would deepen the standard LCA. This rationale can be expanded to other methodological options. For instance, MCDA could also be used to define the allocation approach, considered one of the most controversial definitions in LCA (REBITZER et al., 2004; ZAMAGNI et al., 2009) or even to aid in the definition of Inventory Methods (often not even considered by LCA practitioners when performing a LCA). This kind of application can already be found in scientific literature. In a recent Master thesis published by Souza Júnior (2015), MCDA was applied to a group of specialists to indicate a better allocation approach in an open-loop LCA case. According to the author, “for the process of choosing the allocation method, the proposal to use a multi-criteria analysis method for decision-making has shown good efficiency”. In this sense, MCDA at the Goal and Scope Definition may influence an uncertainty reduction in decision-making related to the LCA methodological options.

II.4.4.1 MCDA in LCI decisions

At the LCI level, decisions are made at the level of flows in a life cycle of a product system (Fig. II-4). The influence of such positions of MCDA application in LCA phases is a decision on the inventory level, where reduction of flows (either inputs or outputs) indicates the best option. El Hanandeh and El-Zein (2010), for instance, applied MCDA where indicators were only environmental aspects (including acidification gases, smog precursors, heavy metals, dioxins, greenhouse gas (GHG) reduction, green energy recovery and landfilled waste) to select a management strategy for the bio-degradable fraction in the municipal solid waste of Sydney (AUS). Some authors also considered other facets of sustainability at this level of LCA decision-making (e.g. environmental and economic aspects as in GELDERMANN; RENTZ, 2005; environmental, social and economic as in ZAGONARI, 2016 and PALME et al., 2005) or considered LCI altogether with LCIA indicators in the decision-making process (e.g., BAO; ARAMAKI; HANAKI, 2012; DE FELICE; CAMPAGIORNI; PETRILLO, 2013) as represented by Fig. II-5. This situation can be found in Bauer et al. (2008), whose research included midpoint impact categories from Ecoindicator 99 and flows as radioactive and non-radioactive waste as criteria in the MCDA approach for the decision-making procedure to rank energy sources in Switzerland.

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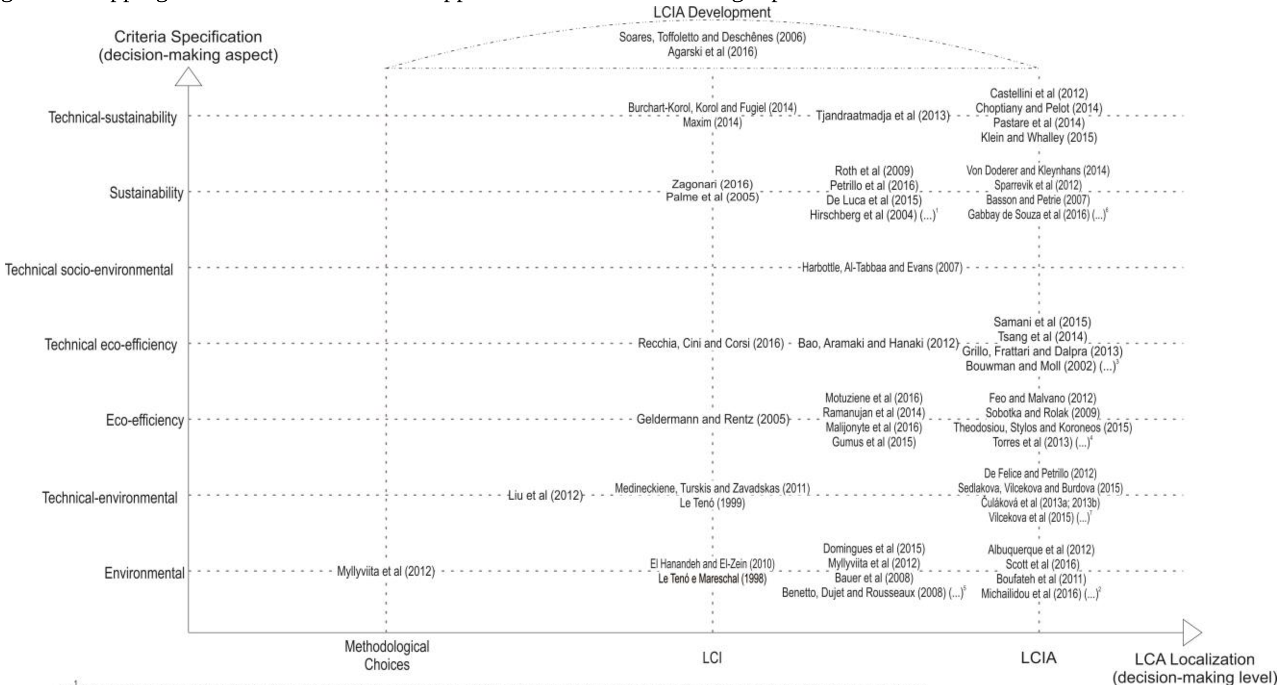
Fig. II-5. Mapping of references in the LCA approach and decision-making aspect



(...)[1] Elghali et al (2006), Weiss et al (2012), Basson and Petrie (2007), Bogacka (2015), Lolli et al (2016), De Felice, Campagiorni and Petrillo (2013), Hirschberg, Danes and Gantner (2000)

(...)[2] Hermann, Kroeze and Jawjit (2007), Bloemhof-Ruwaard, Koudijs and Vis (1995), Kumar et al (2016)

(...)[3] Allacker and De Troyer (2012), Ahmed et al (2012)

(...)[4] Allacker et al (2008), Neto et al (1998), Lee et al (2014), Kucukvar, Egilmez and Tatari (2016)

(...)[5] Moretti, Di Mascio and D'Andrea (2013), Azapagic et al (2013), Myllyviita, Leskinen and Seppala (2014)

(...)[6] Santoyo-Castelazo and Azapagic (2014), Atilgan and Azapagic (2016), Al-Nassar et al (2016), De Luca et al (2015), Loh, Dawood and Dean (2009), Pettit et al (2011), Sardinha et al (2010), Linkov et al (2006), Linkov and Seager (2011)

(...)[7] Sedlakova et al (2014)

II.4.4.2 MCDA in LCI decisions

At the LCI level, decisions are made at the level of flows in a life cycle of a product system (Fig. II-4). The influence of such positions of MCDA application in LCA phases is a decision on the inventory level, where reduction of flows (either inputs or outputs) indicates the best option. El Hanandeh and El-Zein (2010), for instance, applied MCDA where indicators were only environmental aspects (including acidification gases, smog precursors, heavy metals, dioxins, greenhouse gas (GHG) reduction, green energy recovery and landfilled waste) to select a management strategy for the bio-degradable fraction in the municipal solid waste of Sydney (AUS). Some authors also considered other facets of sustainability at this level of LCA decision-making (e.g. environmental and economic aspects as in GELDERMANN; RENTZ, 2005; environmental, social and economic as in ZAGONARI, 2016 and PALME et al., 2005) or considered LCI altogether with LCIA indicators in the decision-making process (e.g., BAO; ARAMAKI; HANAKI, 2012; DE FELICE; CAMPAGIORNI; PETRILLO, 2013) as represented by Fig. II-5. This situation can be found in Bauer et al. (2008), whose research included midpoint impact categories from Ecoindicator 99 and flows as radioactive and non-radioactive waste as criteria in the MCDA approach for the decision-making procedure to rank energy sources in Switzerland.

The main motivation of MCDA applied to the LCI level is to find the best option in terms of sustainability of different scenarios/options (DE FELICE; CAMPAGIORNI; PETRILLO, 2013; MEDINECKIENE; TURSKIS; ZAVADSKAS, 2011; PALME et al., 2005; ZAGONARI, 2016). However, even though reduction in LCI aspects frequently represents less environmental impacts, this cannot be considered a rule of thumb (as trade-offs between impacts categories may occur after characterization). Perhaps due to this fact, there are fewer papers located in this phase if compared to LCIA (Fig. II-5), also inventories generally have a higher number of flows, increasing the likelihood of having trade-offs among the set of criteria. Others also indicate the necessity of trade-off consideration among different environmental aspects in the decision (BAO; ARAMAKI; HANAKI, 2012), a very common motivation of MCDA sustainability studies. The most present trade-off, when analyzing all 35 papers linked to the LCI step, is the environmental/economic/social dimensions (13 references), which demonstrate the interest of decision-makers in considered sustainability at this level of LCA. Incidentally, from the total references that considered any of the indicators at the LCI level (35), there are more papers (25) using MCDA considering both LCI and LCIA as inputs to perform decisions when compared to those that only considered information from the LCI phase (10 publications). In the case of the 10 papers that exclusively considered the LCI indicator, economic dimension is present in 8 from which 3 calculated the environmental/economical social facet in the decision-making process.

The most common criteria at the LCI level is Waste Generation, in several forms as radioactive, hazardous, landfilled, non-recyclable (present in 15 papers) followed by Energy consumption (12 appearances) and Water consumption (found in 10 occasions). These aspects are present in almost any product system and have an important effect in costs for the manufacturers, whether it is expensive (or highly consumed) as energy, or because it is costly to treat (in the case of final disposal of waste). Therefore, it is not by case that those elements are present in decision-making at the LCI level. Other indicators that have shown an important presence is atmospheric emissions per substance (e.g. CO, CO_2, N_2O, PM, etc.), elements that are linked to control technologies, and in this case also gather importance by environmental regulation laws. This situation may also explain the strong presence of economical dimensions at this level of decision-making.

Regarding MCDA tools, authors have shown preference for outranking approaches with 9 papers applying methods from this family (PROMETHEE, ELECTRE and variations). Weighting Sum Approach (WSA) and Analytical Hierarchy Process have appeared 6 times each, whereas Utility-based approaches have appeared only on 4 occasions. This is a trend in MCDA studies, even more related to environmental (sustainability) decisions because outranking methods have a (partial) non-compensatory approach. WSA and AHP are considered friendly approaches (for users and decision-makers) having good presence in this survey, even though it presents compensatory behavior.

II.4.4.3 MCDA in LCIA decisions

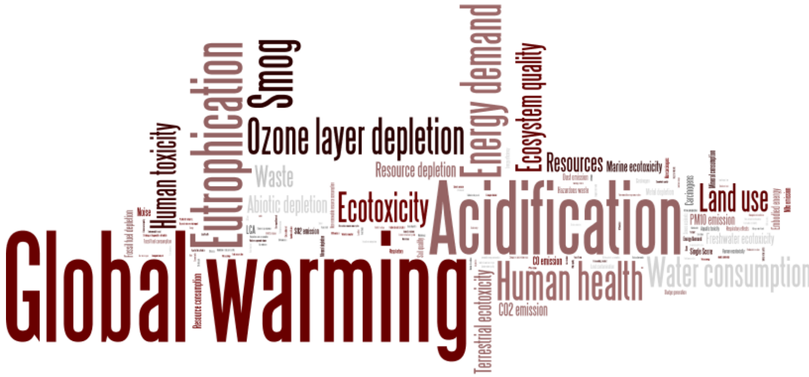
In the LCIA phase, MCDA is used to aid the interpretation of impact categories trade-offs - at midpoint and endpoint levels as exemplified in Fig. II-4. This is due to the complex nature of the impacts generated by different product systems (or alternatives), situations that have already been highlighted by Boufateh et al. (2011), “it is not obvious to distinguish the best alternative because the differences between criteria values of alternatives cannot be easily compared in regard to the impact categories, their units and their degree of seriousness”. Several authors have used MCDA to solely asses the trade-offs between LCA indicators at the midpoint level (BENETTO; DUJET; ROUSSEAUX, 2008; HERMANN; KROEZE; JAWJIT, 2007; KUMAR et al., 2016; SEDLAKOVA; VILČEKOVÁ; BURDOVÁ, 2014; VILCEKOVA et al., 2015) and at the endpoint level (MICHAILIDOU et al., 2016). Besides those aforementioned papers, in this phase, the main rationale to integrate MCDA with LCA is to deal with LCIA outcomes in parallel with economic, social and technical aspects. This is by far the most frequent use of MCDA in LCA with 43 publications (40% of our sample). For example, Petrillo et al. (2016) recently published a paper analyzing the outcomes of Ecoindicator 99 method at the endpoint level, with economic aspects (operational cost, disposal, etc.) and social indicators (health and safety, people development…) by the AHP method, to rank power generation systems. The reason behind this integration is to “support decision-makers in complex decision problems in the field of environmental sustainability” (PETRILLO et al., 2016).

The motivation for applying MCDA at this level is frequently the necessity of interpreting trade-off results and complex and uncertain information (AHMED et al., 2012; ALBUQUERQUE et al., 2013; ATILGAN; AZAPAGIC, 2016; BOUFATEH et al., 2011; CHOPTIANY; PELOT, 2014; LEE et al., 2014; LOH; DAWOOD; DEAN, 2009; SCOTT et al., 2016; VON DODERER; KLEYNHANS, 2014), communication enhancement of results (e.g. single score), multi stakeholders involvement (ATILGAN; AZAPAGIC, 2016; BASSON; PETRIE, 2007; CHOPTIANY; PELOT, 2014; LINKOV et al, 2006, LOH; DAWOOD; DEAN, 2009), a TBL consideration of aspects (LEE et al., 2014; SANTOYO-CASTELAZO; AZAPAGIC, 2014; SPARREVIK et al., 2012) and find the best choice of possibilities (ATILGAN; AZAPAGIC, 2016; PASTARE et al., 2014; SAMANI et al., 2015; SOBOTKA; ROLAK, 2009; TORRES et al., 2013). A greater number of applications of MCDA methods in the LCIA phase is somewhat expected since this is a more preferable situation than decision-making based on LCI information (i.e. environmental aspects) alone and the reason is that LCIA results expressed in potential impacts seems to better communicate with stakeholders besides giving an environmental relevance to flows. This information is calculated though characterization models (present in LCIA methods) and encompasses relations between aspects that are not always visible when a decision is made on a LCI basis, even with the aid of MCDA methods. The most present LCIA methods in our survey are ecoindicator 99, 14 times; CML 2001, 13 times and ReCiPe, 5 times.

Through analyzing the most common environmental indicators used by the authors classified in this LCA step, it is possible to note the dominance of Global Warming (present in 51 papers - 47% of the group of papers and 65% of application and case study papers), followed by Acidification and Eutrophication. The presence of these indicators is clearly the dominant pattern in the group of papers as presented in Fig. II-6. This cloud shows all environmental criteria present in the papers gathered in our survey, wherein larger words are more representative (i.e. are more recurrently applied by practitioners). Those three indicators are midpoint impact categories, which are especially recurrent in LCA studies, and generally required in Labeling programs (e.g. LEED) and by product category rules (PCRs) in environmental product declarations (EPD – programs) and are considered more robust since its characterization models are well accepted by stakeholders and the scientific community. This behavior was already indicated by Wang et al. (2009) and Herva and Roca (2013). Those authors indicate CO2 emissions, greenhouse gases or a global warming category as a key issue in a LCA/MCDA context, followed by acidifying emissions (SO2 and NOx). Other important presences in our survey are performed by common impact categories in LCA, including Land Use, Smog, Ozone Layer Depletion and Ecotoxicity (see Fig. II-6). When it comes to endpoint categories, the most used is Human Health as pointed in Fig. II-6. Although, Ecosystem quality and Resources are also noticeable in the survey since an ISO-compliance LCA study covers all three protection areas (ISO 2006a; 2006b). Finally, and noteworthy to mention in Fig. II-6, criteria at inventory level are dominated by Energy Demand, Water Consumption and Waste, three indicators subject of process efficiency control and also concern of manufacturers when it comes to environmental laws.

Besides environmental dimensions, other facets of TBL are being considered. Preferential economic criteria are related to direct costs of production/plant installation as in operational costs, raw material acquisition costs, investment costs, labor costs and generated values related to products, for instance, income or added value or gross capital. When the social dimension was considered in case studies, common criteria was generally job creation, labor safety and general acceptance of the industry (or product) of the impacted area/society. Life Cycle Costing (LCC) as a matter of methodology to raise economic criteria was also found, but only in Grillo, Frattari and Dalprá (2013), Loh, Dawood and Dean (2009) and Motuziene et al. (2016). Regarding the social dimension, Social LCA (SLCA) was found only in general propositions as in Loh, Dawood and Dean (2009) and Pettit et al. (2009).

Fig. II-6. Cloud of environmental criteria considered in MCDA and LCA studies.



When MCDA is applied at the LCIA level there is a clear preference of practitioners for WSA and AHP approaches with 16 and 15 appearances, respectively. Many authors have chosen those methods based on its simplicity (VON DODERER; KLEYNHANS, 2014) and straightforward nature (BAO; ARAMAKI; HANAKI, 2012). Similarly, when MCDA is applied at the LCI level, at the LCIA level, outranking methods have shown a recent and important presence with 11 papers, somehow confirming a trend to opt for this family of MCDA methods.

II.4.4.4 MCDA in LCIA development

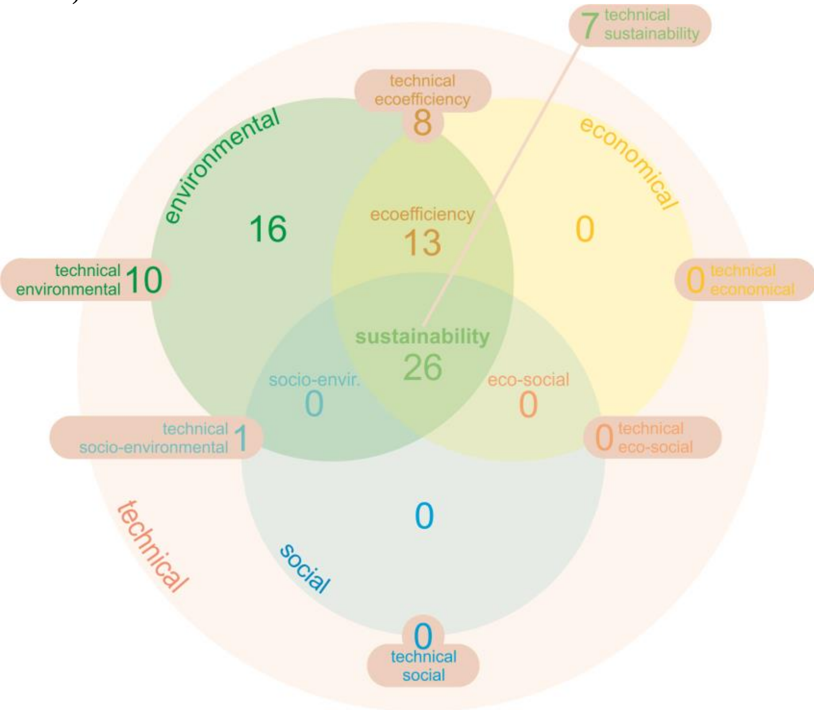
Only two papers were identified in a parallel LCA phase, Soares, Toffoletto and Deschênes (2006) and Agarski et al. (2016), both dealing with the application of MCDA to define weights for impact categories, used afterward in the weighting step. This kind of relation, even though positioned without a specific LCA stage, seeks to improve the interpretation in the LCIA phase, when a practitioner applies normalization, weighting and aggregation of LCIA results into a single score. Although controversial amongst LCA practitioners, it is an important aid in the interpretation of trade-offs in LCIA outcomes, but in a broader way, since a set of weights can be applied to any product system. In weighting, there are different methods behind the definition of a set of weights, such as distance-to-target or monetization. However, if the essence of decisions on such a broad subject is to consider all stakeholders in this process, there are surprisingly few papers on this topic. Soares, Toffoletto and Deschênes (2006) and Agarski et al. (2016) encompassed environmental and technical aspects in their MCDA approach (Fig. II-5). The first applied a panel-based AHP to elicit implications for human health, ecosystem health and natural resources (three damage categories – environmental dimension), scale, duration, reversibility, distance-to-target and uncertainty (technical sphere from impact behavior). The second, assessed ReCiPe endpoint (H) outcomes (i.e. climate change, metal depletion, etc.) as well as time, area, irreversibility and uncertainty from a technical prism through AHP and fuzzy logic approaches. Therefore, both studies have a similar MCDA basis since the used criteria are identical, duration/time, reversibility/irreversibility, scale/area, uncertainty; Impact categories are equivalent, and; AHP was the MCDA approach.

II.4.4.5 Criteria preferences

Environmental and environmental related MCDA (the green circle in Fig. II-7) represent the vast preference of studies integrating MCDA with LCA, whereas economical (blue circle) and social (yellow circle) prisms have good appearances, but are always together with environmental criteria. Environmental criteria alone were the preference of 16 papers, whereas 13 references opted for economic and environmental pillars, decisions made at the eco-efficiency level (as in FEO; MALVANO, 2012; GUMUS et al., 2015; SOBOTKA; ROLAK, 2009; and others when eco-efficiency line crosses LCIA column in Fig. II-5). The social aspect is considered integrated with the environmental aspect, but only when technical indicators are accounted altogether (as in HARBOTTLE; AL-TABBAA; EVANS, 2007). In fact, technical issues permeate all prisms raised in our survey (i.e. with environmental criteria, there is the technical-environment level; with economic and environmental criteria results in the technical eco-efficiency dimension; with social and environmental criteria reaches the technical socio-environment dimension; and even with TBL criteria, technical sustainability). This indicates the significance of such criteria for decision-makers, generally linked to product functionality/performance (e.g. efficiency of electricity plants as in MAXIM, 2014 or durability of wood lumber floors as in TSANG et al., 2014) or security (e.g. heat transmittance and thermal storage as in ČULÁKOVÁ et al., 2013). Finally, it is also possible to note in Fig. II-7 that the most common multi-criteria condition is performed by the environmental, social and economic set of papers (26), a situation where decision-making is held at the Sustainability level (BASSON; PETRIE, 2007; ROTH et al., 2009; SPARREVIK et al., 2012; and others mapped in Fig. II-5). These findings are partially aligned with the statement by Herva and Roca (2013) that "MCA methods were rarely applied to decision making that considered solely environmental criteria. Rather, they dealt with indicators from the different dimensions of sustainability". Others include technical elements, being the technical-environmental analysis as the most common, followed by technical sustainability and technical eco-efficiency.

The predominance of environmental (and environmental related) dimensions in the survey occur as only "environmental" as LCA has already been standardized. It is more robust and therefore, more widely accepted by the scientific and non–scientific communities. Because of this, environmental criteria did not show major variations (e.g. global warming was present in the major part of studies). The economic dimension is frequently considered due to costs or investments necessary to implement the alternatives or operate product systems (or scenarios) and the social dimension presented several criteria, headed by job creation (in several forms), followed by health and safety issues and acceptance of alternatives by communities. Different from the environmental dimension, criteria in social and economic spheres have shown a wide conceptual variation. In other words, and for example, even though job creation was present in most of the papers, it was also defined in many different ways such as the number of permanent jobs created, direct employment creation potential, and number of formal e-waste workers. These results may indicate opportunities for further economic and social LCIA method (or impact categories) development, since these criteria represents stakeholders' interests, and these two approaches are not yet standardized and/or well agreed upon in the scientific community. Fewer papers applied Life Cycle Costing and Social Life Cycle Assessment as methods (to perform economic and social dimensions respectively) in the interface with LCA, which demonstrates that sustainability-LCA is still not a common consideration in MCDA studies.

Fig. II-7. Criteria covered by the papers in this survey that applied or proposed a MCDA (not including reviews, general propositions, or those without defined criteria).



II.5 CONCLUSIONS

In this paper, a review was performed of the published works in the field of MCDA integrated with LCA methodology in order to assess how MCDA techniques are being applied in the LCA context to support results interpretation. The aim was to investigate the current framework of this integration and map the field for the research community concerned with improving the decision-making procedure with an expectation to enhance clarity on the subject and facilitate the path of those seeking to reduce the decision-making uncertainty based on life cycle thinking approaches.

The time evolution of the published samples demonstrates a solid and constant increase in the number of papers published following the same pattern as in other fields regarding sustainability such as LCA itself. The evolution, as well as the kind of research that were identified in the survey, indicate a field that has a growing interest based mainly on the need to have better decisions in the sense of sustainability and the need to consider several dimensions in order to make the best possible decisions.

In this group of 109 references, the most recurrent application of MCDA in a LCA is at LCIA phase, where the main goal is to assess trade-offs between different impact categories (at midpoint and/or endpoint levels) or between environmental and other dimensions (economic, social and technical criteria are considered). At this level, the most recurrent MCDA approach is WSA and AHP. However, the recent increase of the outranking family method application is a trend, mainly due to its non/partial compensatory behavior. The major part of the papers in our survey considered TBL dimensions or just the environmental aspect in this LCA step. Less common, but well represented, MCDA has shown that decisions are made in terms of aspect consumption and generation reduction at the inventory level (LCI step), where energy and water demand altogether with waste generation were the main interests in terms of criteria for the decision-making process. At this time, outranking methods are more common, although WSA and AHP maintained an important presence. Only one paper was classified in the Goal and Scope definition phase (first step of LCA standardized methodology) and applied to MCDA to define impact categories that represented the stakeholders' preferences. Despite this unusual application of MCDA in LCA, other controversial methodological options may be supported by decision aid approaches, such as the allocation approach and the inventory method. In the end, there is still a lack of studies directed to MCDA in the Goal and Scope definition, and how such integration could possibly influence or benefit an uncertainty reduction related to the LCA methodology. There is one last interface of MCDA in LCA, and it is somehow parallel to a traditional LCA, associated with LCIA development. This is the case when authors used MCDA to elicit impact category significances (or weights) to perform weighting in LCIA/interpretation of LCA results. Two papers were identified in this section. The low number of papers on this subject reflects the fact that weighting is an optional phase in a LCA study and is considered by many authors as a controversial step due to its subjectivity. However, it can be argued that interpreting LCA results without any significance related to the impact categories assigns the same importance to each impact (which may be a worse situation). Thus, there is still a need for a more in-depth research on this theme, where MCDA may play a significant role.

The wide variation in terms of choices, presuppositions and diverse outcomes in a LCA indicates that interpretation of results is still very complex and there is not a preferable methodological path to solve the final decision issue, even more when different players must participate. That is the reason auxiliary methods are needed, such as MCDA. Furthermore, besides LCA interpretation, there is a clear and increasing interest in decision-making at the TBL (sustainability) level. In this case, there is a clear necessity for the development of new methods or improvement of existing approaches, such as LCC and SLCA. One possible way to contribute to this task is to analyze economic and social criteria that already have been considered in studies like those identified in this paper.

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Capítulo III. Weighting Midpoint Impact Categories in Life Cycle Assessment with AHP-PROMETHEE II

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Abstract: Weighting is a controversial topic in LCA due to the subjectivity of the process as a whole. However, it simplifies interpretation and communication of results, often carried out with trade-off condition between indicators. Recently, the Multi-criteria Decision Analysis (MCDA) field has turned into a hot topic in LCA community, mainly due to the possibility of including stakeholders' participation and supporting the decision-making process. This relation reflects on MCDA/LCA increasing occurrence in scientific circles. Nevertheless, this interaction is still mostly used to interpret traditional LCA outcomes and rarely to weight impact categories. On top of that, value-based weighting is dependent of the overall judgment of stakeholders, what turn into necessary to investigate how impacts are weighted across the different countries or regions. Therefore, the aim of this study is twofold: (a) we weighted environmental impact categories according to main Brazilian stakeholders, and (b) demonstrated whether the different group of stakeholders' judges differently the significance of impact categories. The methodology applied was based on two panels structured through a hybrid MCDA approach formed by Analytical Hierarchy Process (AHP) and PROMETHEE II. The first panel was addressed to LCA specialists to weight criteria (according to AHP pair-wise scale) regarding environmental level of consequences, environmental consequences and possibility of treatment. The second panel was formed by Brazilian stakeholders - representatives of Academy, Government and Industry – that judged the most usual midpoint impact categories according to a specific scale for each of the criterion. The aggregation approach was based on a normalized balance of preferences (complete ranking of categories of PROMETHEE II) weighted according to the relevance of each criterion (elicited by AHP panel). Matlab, Excel and Statistic were used to perform the calculations and analysis of variance (ANOVA) to indicate whether different stakeholders have the same opinion or not. 16 LCA specialists answered the first panel, indicating 'Damage to human health' as the most significant criterion, followed by 'Damage to ecosystems', with 0.27 and 0.18 weight factors, respectively. Regarding to the impact categories, 76 stakeholders participated of the panel (returning rate of 40%) attributing to Climate Change

[7] Artigo não submetido.

the higher importance (0.185), influenced by its effects to human health, ecosystems, scale, duration and probability of occurrence. The total ranking of categories is: Ozone layer depletion (0.155), Resource depletion (0.150), Human toxicity (0.129), Land use (0.106), Acidification (0.105), Photochemical ozone formation (0.086) and Eutrophication (0.083). ANOVA results demonstrate that all stakeholders converge in terms of judgment for all impact categories exception to Resource depletion. For this category, Academy and Industry have shown statistically different mean values. This demonstrates that different stakeholders can have different preferences reinforcing the necessity of inclusion of all relevant decision-maker (DM) in this process what strengthens the application of panels into weighting process. This panel covered all relevant Brazilian institutions from Academy that develops LCA research, almost the totality of Governmental institutions that play a role in environmental DM in Brazil and several economic sectors. Thus, this set of weights for impact categories may be considered as from Brazilian reality and as an element of comparison with other weighting sets worldwide. Besides, our combined approach of AHP and PROMETHEE II was considered easy to implement regarding complexity and load of information, and allows the consideration of value judgement from decision makers.

Key-words: Life Cycle Assessment, Impact Category; Weighting; Multi-criteria-decision analysis; AHP-PROMETHEE II; Stakeholders;

RESUMO EXPANDIDO EM PORTUGUÊS

Introdução. O objetivo deste capítulo foi elicitar a significância das categorias de impacto em nível *midpoint* segundo 3 grupos de *stakeholders* brasileiros e identificar se tais grupos julgam de forma estatisticamente diferente a importância dos impactos. Apesar da ponderação ser um tema recorrentemente discutido na comunidade de ACV, em conjunto com a agregação, ela torna a interpretação menos complexa e a comunicação mais clara. Existem algumas abordagens mais usuais de ponderar impactos, dentre estas, o painel de especialistas é um dos mais indicados, por permitir a participação de todos os tomadores de decisão no julgamento. Além disso, o modo como julgamos a significância dos impactos varia de acordo com nossos preceitos, sendo válido considerar que especialistas brasileiros podem ter um julgamento diferente daqueles de outros países. Recentemente, houve um crescimento da aplicação da MCDA em estudos de ACV, principalmente devido à possibilidade de incluir as partes interessadas e facilitar o processo de tomada de decisão. A aplicação da MCDA, em específico, para auxiliar stakeholders no julgamento de significâncias, diminui a incerteza e acrescenta robustez do processo, que são reinvindicações de Finnveden et al. (2009) e Pizzol et al. (2017) para desenvolvimento de novos conjuntos de pesos.

Material e métodos. A metodologia aplicada foi baseada em dois painéis estruturados em torno de uma abordagem de MCDA híbrida formada pelo Analytic Hierarchy Process (AHP) e pelo *Preference Ranking Organization Method for Enrichment Evaluation* (PROMETHEE II). A lógica por trás desta definição levou em consideração diversos aspectos comparados sob a ótica dos métodos existentes de MCDA mais empregados e populares. O PROMETHEE II foi escolhido por ser considerado um método parcial/não compensatório, que permite um ranqueamento total das alternativas e mantém a simplicidade da aplicação com relação aos painelistas. Como o PROMETHEE assume que os critérios utilizados para comparar as alternativas já são ponderados, utilizou-se o AHP para realizar esta tarefa, resultando na abordagem híbrida AHP-PROMETHEE II.

O primeiro painel foi dirigido aos especialistas em ACV da rede de pesquisadores do CICLOG para critérios de peso (de acordo com a escala do AHP). Neste questionário, os respondentes julgaram a significância de 8 critérios: abrangência espacial, duração, reversibilidade, probabilidade de ocorrência (nível ambiental de consequências), danos à saúde humana, danos ao ecossistema, esgotamento de recursos (consequências ambientais) e possibilidade de tratamento (recuperação das consequências). Tais critérios foram definidos com base na comparação de elementos de julgamento de impactos ambientais de diversas fontes e buscaram ser o mais amplo possível na possibilidade de julgamento com o mínimo de sobreposição entre os mesmos.

O segundo painel foi formado por *stakeholders* brasileiros - representantes da Academia, Governo e Indústria – definidos com base em Zanghelini et al. (2016), Cherubini e Ribeiro (2015), Rede Empresarial Brasileira de ACV e rede de instituições ligadasao CICLOG. Os participantes avaliaram as categorias de impacto ambiental mais comumente utilizadas (em publicações sobre ACV oriundas do Brasil) de acordo com uma escala específica para cada um dos critérios. A definição das categorias de impacto se baseou nos trabalhos analisados em Zanghelini et al. (2016) e representa as 8 categorias mais recorrentes nos estudos nacionais. Foram considerados: Mudanças Climáticas, Eutrofização, Acidificação, Depleção Abiótica, Depleção da Camada de Ozônio, Toxicidade humana, Formação de ozônio fotoquímico (SMOG) e Uso de terra. Este grupo de categorias está entre aquelas recomendadas pelo EC/JRC/IES (2010) e cobrem as 3 áreas de proteção ambiental (recomendação da ABNT ISO 14044).

A abordagem de agregação foi baseada em um equilíbrio de preferências dos *stakeholders*, normalizado e ponderado de acordo com a importância de cada critério (elicitado pelo painel AHP). Os softwares Matlab, Excel e Statistic foram utilizados para realizar os cálculos e análise de variância (ANOVA) para indicar se diferentes partes interessadas têm a mesma opinião ou não.

Resultados e discussões. 16 especialistas de ACV responderam ao primeiro painel (64% de retorno), indicando como o critério mais significativo "Dano à saúde humana", seguido de "Dano aos ecossistemas", com fatores de peso de 0,274 e 0,184, respectivamente. O terceiro e quarto critérios mais significativos foram Reversibilidade e Depleção de recursos, ambos com fator 0,142. Outros critérios, incluindo Escala, Duração, Probabilidade de ocorrência e Possibilidade de tratamento foram menos significativos de acordo com os participantes. Esse padrão indica que os participantes atribuíram mais peso aos critérios associados às consequências ambientais, do que critérios relacionados ao nível de consequências ambientais, ou mesmo a possibilidade de tratamento, padrão alinhado com Soares, Toffoletto and Deschênes (2006). A análise boxplot demonstra que a variação interquartil das respostas das comparações pareadas apresetou consideráveis convergências e divergências entre os painelistas.

Em relação às categorias de impacto, 76 stakeholders participaram do painel (taxa de retorno de 40%) atribuindo à Mudança Climática a maior significância (0,185), influenciado pelos seus efeitos para a saúde humana, ecossistemas, escala, duração e probabilidade de ocorrência. O ranking total das categorias é: Depleção da camada de ozônio (0,155), Depleção de recursos abióticos (0,150), Toxicidade humana (0,129), Uso do solo (0,106), Acidificação (0,105), Formação fotoquímica de ozônio (0,086) e Eutrofização (0,083).

Os resultados da ANOVA demonstram que todas as partes interessadas convergem em termos de julgamento para todas as categorias de impacto, com exceção de Depleção de recursos. Para esta categoria, a Academia e a Indústria julgaram a significância de forma distinta, resultando em médias estatisticamente diferentes. Este painel abrangeu todas as instituições relevantes da Academia que desenvolvem pesquisas em ACV, a maioria das instituições governamentais que desempenham um papel na tomada de decisão ambiental no Brasil e em vários setores econômicos.

Conclusões. Em relação aos participantes, mesmo que o grupo quantitativo seja relativamente restritivo dos *stakeholders* (qualitativamente, este painel abrangeu instituições/grupos de várias naturezas (o que se configura em resultados sob diferentes perspectivas). Assim, este conjunto de pesos para as categorias de impacto pode ser considerado como realidade brasileira. A comparação deste conjunto de pesos com outras experiências (e.g., BEES e NOGEPA), indicam que a ponderação brasileira é semelhante em termos de magnitude e classificação das categorias de impacto, o que traz robustez para o resultado.

Resultados da ANOVA demonstram que diferentes *stakeholders* podem ter preferências diferentes, reforçando a necessidade de inclusão de todos os decisores relevantes neste processo, o que fortalece a aplicação de painéis no processo de ponderação.

O uso de abordagens de MCDA para auxiliar os tomadores de decisão na tarefa de atribuir significância a diferentes categorias de impacto foi considerado fácil de implementar em relação à complexidade e carga de informações e permitiu considerar o julgamento de valor de diversos tomadores de decisão. Em última análise, o conjunto de ponderação tem a condição de expandir as possibilidades de interpretação para a comunidade brasileira de ACV, mesmo que os padrões não recomendam o passo de ponderação na ACV.

III.1 INTRODUCTION

Life Cycle Assessment (LCA) is a pre-eminent and important tool (BAUMANN; TILLMANN, 2004; REAP et al., 2008; VON DODERER; KLEYNHANS, 2014) for estimating environmental effects of products and services during their life cycles from cradle-to-grave (GUINÉE et al., 2002; HELLWEG; MILLÀ I CANALS, 2014; ISO 2006a; SETAC, 1993; WENZEL; HAUSCHILD; ALTING, 2001). By including the impacts throughout the life cycle boundary, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection (SAIC, 2006). This concept enables many applications, generally conducted to support corporate internal decision-making, such as for eco-design of products, process optimizations, supply-chain management, and marketing and strategic decisions (HELLWEG; MILÀ I CANALS, 2014). Due to these facts, LCA and its base concept of Life Cycle Thinking (LCT) are increasingly being used in the development, implementation, and monitoring of environmental and industrial policies within both public and private sectors (EC/JRC/IES, 2010). Kalbar et al. (2016) explains that, with continuous developments, the acceptance of LCA based decision making in the policy arena gained support and strength. Accordingly, Guinée et al. (2011) affirms that Governments all over the world encourage the use of LCA, which has become a core element in environmental policy or in voluntary actions. For instance, Finnveden et al. (2009) enumerates European Directives related to LCA that are already in place. In effect, LCA application have been increasing systematically in many countries and economic sectors as demonstrated by Chen et al. (2014), Guinée et al. (2011), Hou et al. (2015), Souza and Barbaestefano (2011), Xu and Boeing (2013) and Zanghelini et al. (2016).

LCA framework has four traditional steps (ISO, 2006a) composed by: (1) Goal and Scope Definition, where the problem and the intentions of the assessment are defined, units of comparison are chosen, boundaries are established, type of impacts that should be considered are defined and data quality is outlined (FINNVEDEN et al., 2009; GELDERMANN; SPENGLER; RENTZ, 2000; HERTWICH et al., 2000); (2) Life Cycle Inventory (LCI), where all the information about emissions and resources used during the life cycle of the product is collected (HERTWICH et al., 2000) and referenced to the functional unit (GELDERMANN; SPENGLER; RENTZ, 2000); (3) Life Cycle Impact Assessment (LCIA), where these emissions are classified, characterized, and aggregated

(HERTWICH et al., 2000) to understand and evaluate the magnitude and significance of the potential environmental impacts for a product system (ISO, 2006a; 2006b); and (4) Interpretation, that seek to provide recommendations for actions and may include an assessment of uncertainties and key assumptions (HERTWICH et al., 2000).

Specifically, the LCIA step is structured around three mandatory elements (ISO, 2006b):

Mandatory within LCIA step

- Definition of impact categories: identification and selection of impact categories, category indicators, models of cause-effect chains (characterization models) and their endpoints (BAUMANN; TILLMAN, 2004; UDO DE HAES et al., 2002; ISO, 2006b).
- Classification: step where the inputs and outputs identified in the LCI are assigned to the respective impact categories (ISO, 2006b). This task is guided by the ability of each aspect to contribute to different environmental problems (EC/JRC/IES, 2010).
- Characterization: calculation of category indicator results for each impact category using characterisation factors, which are estimated using characterisation models (UDO DE HAES et al., 2002). According to Baumann and Tillman (2004) it is the calculation of the extent of the environmental impact per category.

Conventionally LCA outcomes from the mandatory LCIA steps are classified into two levels within the cause-effect network, known as midpoint and endpoint (HUIJBREGTS et al., 2017). The former is composed by variables in the environmental mechanism of an impact category between the environmental interventions and the category endpoints, (e.g. climate change, ozone depletion, and acidification) (FINNVEDEN et al., 2009; UDO DE HAES et al., 1999) and usually represent well-defined cause effect relationships (PIZZOL et al., 2017). The latter is formed by variables which are of direct societal concern (e.g. damage to human wellbeing, damage to ecosystem quality); the level of the endpoints is also called the "damage level" (UDO DE HAES et al., 1999) and represent complex processes affecting a specific target, also known as the Areas of Protection - AoP (PIZZOL et al., 2017), i.e., on Human Health, on the Natural Environment and on Natural Resources (EC/JRC/IES, 2010; FINNVEDEN et al., 2009; UDO DE HAES et al., 1999)

Both midpoint and endpoint scores are acceptable and found in LCA interpretation of results worldwide. However, there are some important aspects related to the differences between these two levels of indicators that have been extensively discussed amongst LCA specialists, as demonstrated by EC/JRC/IES (2010). Within this theme, perhaps the main issue is the uncertainty against the complexity on interpretation "battle". According to Huppes et al. (2012), the specification of endpoint effects can be much more uncertain and incomplete than midpoint modelling and generally has not been agreed upon let alone been standardized. On the other hand, endpoint results are easier to interpret in terms of relevance of the environmental flows (HAUSCHILD; HUIJBREGTS, 2015) and communicate to external stakeholders. Finnveden et al. (2009) states clearly the struggle behind this definition lies in the evaluation of whether the uncertainty in midpoint versus endpoint modelling is justified by the improved interpretation of the results. For Huppes et al. (2012) at end, LCA practitioners have preferred reliability and detailed environmental information over communication and easy to interpret results, so LCA has often become available at midpoint impact category level. Thus, the interpretation challenge remains and may jeopardize the decision-making process.

One way to support this decision is to interpret the results with the advent of the optional steps of LCIA, i.e. Normalization, Grouping and Weighting the impact categories at midpoint level (ISO, 2006b):

<u>Optional within LCIA step</u>

- Normalization: step where the magnitude of characterisated values are calculated according to a reference information (BAUMANN; TILLMAN, 2004; ISO, 2006b; UDO DE HAES et al., 2002), for instance, the total amount of pollutants emitted in a reference area or impacts caused by one person during one year (EC/JRC/IES, 2010).
- Grouping: sorting and possibly ranking of the impact categories (ISO, 2006b) in a given hierarchy (UDO DE HAES et al., 2002).
- Weighting: converting and possibly aggregating into a single indicator (UDO DE HAES et al., 2002) the results across impact categories using numerical factors based on value-choices (ISO, 2006b).

Those three elements are optional by standards because they insert a higher dose of uncertainty, to the potential biases and value choices they are respectively associated with and the consequent commercial and legal concern (PIZZOL et al., 2017). For instance, weighting is strictly forbidden in the case of “comparative assertions” for public disclosure in LCAs (KLÖPPFER, 2012; ISO, 2006b). However, and despite of all these issues, both midpoint and endpoint scores are multiple scores (HUPPES et al., 2012). Essentially, LCA results in a list of environmental impacts (or damages) (ZANGHELINI; CHERUBINI; SOARES, 2018) with a set of three to 12 impact category indicator results that describe the impact of a product system on the environment (MITTIER; SCHOLZ, 2008). Decisions and conclusions based on those outcomes are still dependent on interpretation of stakeholders, a complex task that according to Benetto, Dujet and Rousseaux (2008) is not always straightforward, especially in case of comparison between different alternative scenarios fulfilling the same function. Zanghelini, Cherubini and Soares (2018) complements indicating that this situation is aggravated when LCA outcomes show trade-offs between different scenarios, a condition that according to Gloria, Lippiatt and Cooper (2007) is more common in practice. That is the reason that many authors considered the trade-off between environmental burdens as the main factor of complexity in decision-making when impact assessments are practiced, including LCA (BOUFATEH et al., 2011; GELDERMANN; RENTZ, 2005; LE TENÓ; MARESCHAL, 1998; SEPPÄLÄ et al., 2002; SUBRAMANIAN et al., 2015). Powell et al. (1997) states that in any decision-making process, unless the outcome is obvious (which is not the case in LCA outcomes with trade-off condition), weights need to be attributed to the impacts according to their relative importance.

III.2 A GLANCE OVER WEIGHTING IN LCA

Weighting is clearly a controversial theme in LCA community as pointed by several authors (BARE; GLORIA, 2006; BAUMANN; TILLMAN, 2004; FINNVEDEN; ELDH; JOHANSSON, 2006; FINNVEDEN et al 2009; GOEDKOOP; SPRIENSMA, 1999; HERTWICH et al., 2000; SOARES; TOFFOLETTO; DESCHÊNES, 2006; UDO DE HAES et al., 2002) and discussed extensively by many others (BARE; GLORIA, 2006; CASTELLANI et al., 2016; CORTÉS-BORDA; GUILLÉN-GOSÁLBEZ; ESTELLER, 2013; GELDERMANN; RENTZ, 2005; KALBAR et al., 2016; PIZZOL et al., 2017; SOARES; TOFFOLETTO; DESCHÊNES, 2006). Nevertheless, it is still considered an open issue by Kägi et al. (2015) with supporters and non-supporters of the procedure. Those who criticize weighting, including standards, point out lack of scientific basis (BARE; GLORIA, 2006; ISO, 2006b; PIZZOL et al., 2017), value or judgment variation about impact significances (BAUMANN; TILLMAN, 2004; FINNVEDEN, 1997; HERTWICH et al., 2000; HUIJBREGTS, 1998; SCHMIDT; SULLIVAN, 2002; UDO DE HAES et al., 2002) and subjectivity (BAUMANN; TILLMAN, 2004; POWELL et al., 1997; ROGERS; SEAGER, 2009). According to Finnveden et al. (2009), those elements are understandable from the point of view that the values cannot be harmonized and there is no way to find out which values are right from a scientific point of view.

However, and even though value is really added in weighting step, one may agree with Hertwich et al. (2000) conclusions that neither LCA as a whole nor any of its steps can be "value free". For instance, the simplest choices made to outline LCA scope (e.g. boundary system definition) have also some load of judgment. This is one of the issues defended by those who see in weighting an important complement to LCA interpretation. This side indicates facilitating the interpretation of LCA results, including trade-offs (CASTELLANI et al., 2016; GOEDKOOP; SPRIENSMA, 1999; PIZZOL et al., 2017; SOARES; TOFFOLETTO; DESCHÊNES, 2006) and therefore decision-making improvement (HELLWEG; MILLÀ I CANALS, 2014) as main reasons for its application. Moreover, some weaknesses of the weighting step were explored and discussed in depth in literature. For instance, related to the non-scientific ground of weighting methods, Finnveden et al. (2009) affirms that the development of weighting methods to be used in LCA are often being benefited from developments within environmental economics and Multi-Criteria Decision Analysis (MCDA) (for instance see SOARES, TOFFOLETTO and DESCHÊNES 2006 and AGARSKI et al., 2016). This means that scientific basis is directed to create weights to LCA outcomes (as demonstrated in ZANGHELINI; CHERUBINI; SOARES, 2018) despite of the values that they may require. Actually, the simple fact of no application of significances to impact categories is even worse than the addition of the subjective element of judgment that is inherent when one attributes significance to alternatives in weighting. Several authors have argued that this is the case of assuming equal weighting factors for the considered criteria (GELDERMANN; RENTZ, 2005; KAGI et al., 2016). Situation that Johnsen and Lokke (2013) indicate that turns certain elements of decision-making to be handled in an intuitive or arbitrary manner and could lead to a severe sub-optimal allocation of resources. Ultimately, equal weighting is not science based and could be mistaken for a neutral weighting while it is not (PIZZOL et al., 2017). Thus, the simple avoidance of weighting would not be a real solution (GELDERMANN; RENTZ, 2005).

Apart of this discussion about weaknesses and strengths in weighting approach, it has become a common sense that LCA faces a major and challenging issue regarding communication of results. According to Hellweg and Milà i Canals (2014) this condition has been impelled and influenced by the demand for policymaking based on LCA. Other indicative of such behavior was noted by Corona et al. (2015) and Kalbar et al. (2016) over a tendency of Single Scores popularization in comparative assessments. This is also very clear pattern in Pizzol et al. (2017) questionnaire. Although the respondents perceived negatively when asked to perform an analysis on normalisation and weighting procedures, they answered positively for their relevance for decision making. Ultimately, the difficulty in communication in LCA was a matter of concern for Kagi et al. (2016) that stated that “if LCA is not able to deliver answers and only confuses decision-makers, it will lead to a decrease in interest in them over the long term”. Therefore, normalization and weighting are becoming an integral piece in LCA communication (KIM; JANG; LEE, 2013; ROGERS; SEAGER, 2009) and an essential part of LCA practice (KAGI et al. 2016; KALBAR et al., 2016).

III.2.1 WEIGHTING APPROACHES IN LCA

Finnveden et al. (2009) explains, “there is no objective way to perform weighting and hence, no correct set of ranks or weighting factors”. This situation according to Soares, Toffoletto and Deschênes (2006) and Myllyviita et al. (2012) turn into a difficult task select one method among others in the context of developing an LCIA method, what reflex in the several existing methods to attribute weight to impact categories in LCA (KALBAR et al., 2016). In this universe, Huppes and Van Oers (2011) segments weighting core concept into two groups. Those that are value based (i.e. focus on one aspect corresponding to one value) and those that are preference based (i.e. focus on the values behind a choice). As value based reasoning is not easily linked to complex situations, with many relevant aspects varying in different directions (HUPPES; VAN OERS, 2011) and judge environmental impacts is a complex situation, LCA weighting methods are often (or almost exclusively) based on the value-choice concept, where three different approaches predominate: monetization (found in BEES, BEPAS, ReCiPe and TRACI LCIA methods), distance to a target (DtT) or objective (as in EDIP 97 and ecological scarcity method)and panel (present in

Ecoindicator 99 and ReCiPe 2008 LCIA methods and in Soares, Toffoletto and Deschênes 2006 publication) (BAUMANN; TILLMAN, 2004; FINVEDENN et al., 2009; GUINÉE et al., 2002; HOFSTETTER, 1998; HUPPES; VAN OERS, 2011; KALBAR et al., 2016; MYLLIVIITA, LESKINEN and SEPPÄLÄ, 2013).

- Monetizing approaches focused on costs related to environmental consequences (ALROTH et al., 2011) with (a) those that are not based on willingness-to-pay (WtP) (e.g., direct cost of an activity) or (b) basis in WtP (e.g. directly expressed by individuals, revealed by individuals' behavior and society WtP) (FINNVEDEN, 1999). The former (a) is related to the direct 'price' for an activity, as the cost necessary for remediate certain damage, however it is not clear who is going to pay for it. The latter (b) is when it is a predisposition of individuals for pay for the avoidance of something (e.g. extinction of a species) (BAUMANN; TILLMAN, 2004; FINNEDEN, 1999), situation that may be grounded earlier (prevention) or later in the environmental cause-effect chain (avoidance). The rationale behind this approach is if each impact has a 'price' and they vary according to the WtP, each impact category will have a different significance where the higher price will mean a higher importance of the impact. This price may be defined with a panel, where individuals are directly asked to put values on such events (FINNVEDEN, 1999) or by revealed preferences, when market behavior dictates the value (UDO DE HAES et al., 2002) (for instance: the difference between a property that suffers with certain environmental impact over an equivalent property without any effect reveals the price of that impact). At last, society WtP derived from political and governmental decisions (FINNVEDEN, 1999), as the total costs necessary for reducing emissions to a governmental goal.

- In DtT, weighting factors are calculated with reference to a target value on the basis of a ratio between the actual impact and the target impact (BAUMANN; TILLMAN, 2004; UDO DE HAES et al., 2002). In this case, the greater the difference between both values, the greater is the factor. According to Huppes and Van Oers (2011), there are several possibilities commonly used to set a target in DtT approach as, political goals, load capacity and sustainability.

- The panel approach is based on a group of experts, representatives of different stakeholders who are invited to provide the weighting factors or judgments through other approaches (GUINÉE et al., 2002; HUPPES; VAN OERS, 2011) as questionnaires, interviews or even a group of discussions. The values are defined by the elicitation process (UDO DE HAES et al., 2002; MYLLYVIITA; LESKINEN; SEPPÄLÄ, 2013), which is a mechanism for extracting information from an individual (or individuals). Udo de Haes et al. (2002) explain that panels are differentiated by some factors, including: size and type of panelists, elicitation procedure (questionnaires, interviews, Delphi, MCDA...), question format, presentation and supporting information, response mode (rank, pair comparison...) and aggregation mode (consensus, mathematical methods...).For those reasons, much has been discussed about the subjectivity and representativeness of the panel approach (see for instance FINNVEDEN, 1999; HOFSTETTER, 1998; HUPPES; VAN OERS, 2011; METTIER; SCHOLZ, 2008; PIZZOL et al., 2017).

Amongst these three approaches, the panel has gained popularity and has been recognized as being one of the most promising ways to elicit the required category weighting factors (FINNVEDEN et al., 2002; KOFFLER; SCHEBEK; KRINKE, 2008). For instance, Ecoindicator 99, TRACI/BEES/NOGEPA and ReCiPe are LCIA methods that considered panel-based weighting procedures (BENGTSSON; STEEN, 2004; HUPPES; VAN OERS, 2011). Panels are based on stakeholders' opinions and represent collective preferences by those whose interest should be consulted, what turn it into a more straightforward process (HUPPES; VAN OERS, 2011). Soares, Toffoletto and Deschênes (2006) are aligned with that perception when states that the approach offers the possibility of a more qualitative weighting due to the qualitative nature of human perception of the severity of environmental impacts. As the elicitation is a key element in stakeholder's panel and also a complex process that must be scientific based, practitioners have been found in MCDA theory the ground for panel construction. The interface LCA/MCDA has become more popular (see ZANGHELINI; CHERUBINI; SOARES, 2018) mainly due to the elicitor support when the object to be judged or chosen represents a multi-dimensional situation.

III.2.2 WEIGHTING WITH MULTI CRITERIA DECISION ANALYSIS (MCDA) SUPPORT

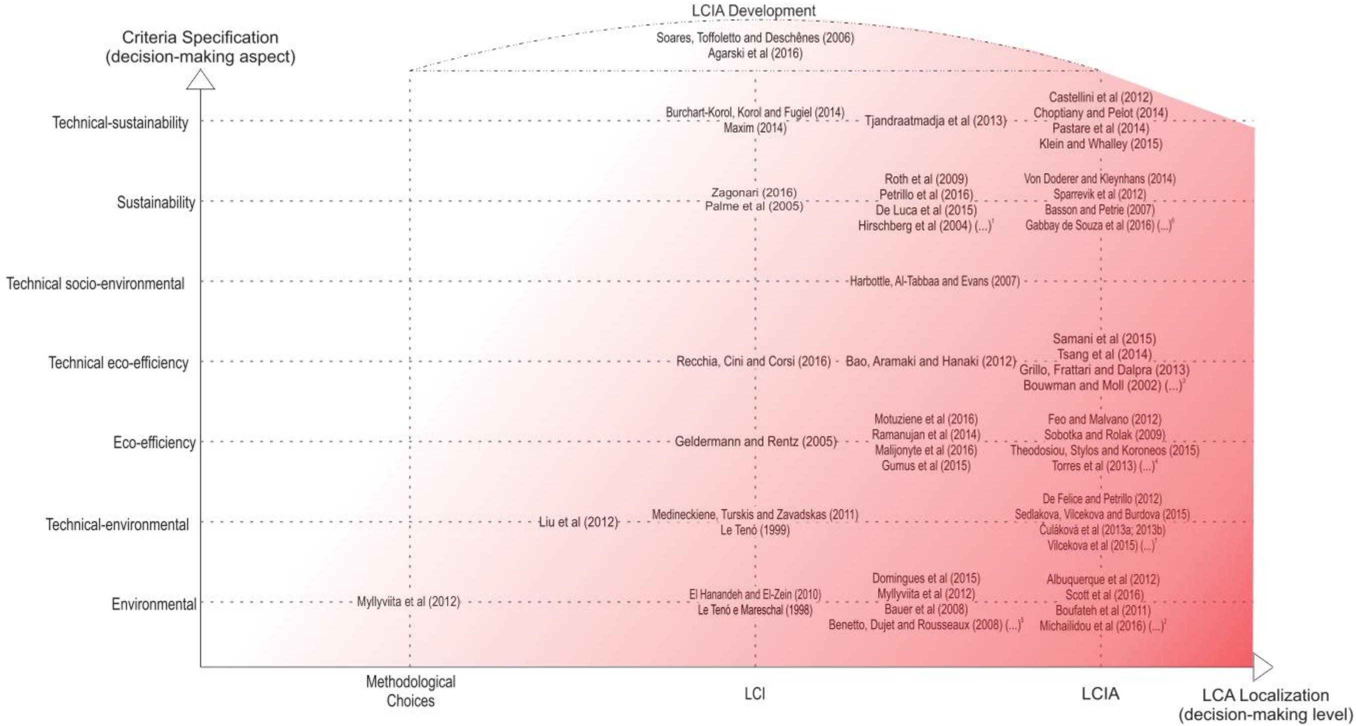
In the field of environmental decision-making, MCDA has become a widespread tool (HUANG; KEISLER; LINKOV, 2011; PIZZOL et al., 2017; ZANGHELINI; CHERUBINI; SOARES, 2018). Specially related to LCA, Zanghelini, Cherubini and Soares (2018) demonstrates that several studies have applied MCDA techniques in all phases of LCA methodology with benefits on the interpretation of results. Accordingly, other authors noted that MCDA could be applied to LCA with positive results (CINELLI; COLES; KIRWAN, 2014; GELDERMANN; RENTZ, 2005; HERMANN; KROEZE; JAWJIT, 2007; JESWANI et al., 2010; MIETTINEN; HÄMÄLÄINEN, 1997; SEPPÄLÄ et al., 2002; SOARES; TOFFOLETTO; DESCHÊNES, 2006). One of the reasons for such increase in MCDA application over LCA lies over the complexity of decision-making by stakeholders. On top of that, it allows stakeholders participation into decision-making process, situation not only preferable, but also recommended.

MCDA methods differ in the way the idea of multiple criteria is operationalized (DE MONTIS et al, 2000). For Huang, Keisler and Linkov (2011) this includes protocols for eliciting inputs, structures to represent them, algorithms to combine them, and processes to interpret and use formal results in actual advising or decision-making contexts. Thus, there are many different methods (LINKOV; SEAGER, 2011; SHIELDS; BLENGINI; SOLAR, 2011), from the simple weighted sum approach (WSA) to outranking balance of preferences. However due to these wide variation, authors highlight three as main methods: ‘Analytic Hierarchy Process’ (AHP), ‘Multi-Attribute Utility Theory’ (MAUT), and those based in Outranking (including ‘Preference Ranking Organization Method of Enrichment Evaluation’ – PROMETHEE - and ‘ELimination and Et Choice Translating Reality’ - ELECTRE) (BENOIT; RESSOUX, 2003; UDO DE HAES et al., 2002; GELDERMAN et al., 2000; HUANG; KEISLER; LINKOV, 2011; LINKOV; MOBERG, 2012). For a more detailed description on these three methods, see APÊNDICE E – MCDA Methods.

Conceptually, MCDA is introduced in the LCA framework and standards as the ‘weighting’ step to aid in LCA trade-off interpretation (ZANGHELINI; CHERUBINI; SOARES, 2018). In this combination, MCDA is generally used to weight and sum LCA results into a single index (after classification, characterization and optionally normalization) (AGARSKI et al., 2016; HERMANN; KROEZE; JAWJIT, 2007). Zanghelini, Cherubini and Soares (2018) have demonstrated that MCDA is mainly applied to interpret LCA results at Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) levels (see the heating distribution on the map of MDCA applied to LCA studies in Fig. III-1).

According to that research, significance is attributed to outcomes from LCIA methods such as midpoint impact categories (Global warming, Eutrophication and Acidification) and endpoint damage categories (Human Health, Ecosystem and Resources) at LCIA level, whereas at LCI level, weighting is directed to decide over consumptions (water, energy) and generations (waste, CO_2). Examples of the first group may be found in Kumar et al. (2016), Sedlakova, Vilčeková and Burdová (2014) and Michailidou et al. (2016) and from LCI decision-based in El Hanandeh and El-Zein (2010). Following Finnveden (1999) division of weighting procedures into case-dependents and case-independents, in Zanghelini, Cherubini and Soares (2018) the major part of the articles are case studies where weighting is case-specific or case-dependent. That is the reason that Zanghelini, Cherubini and Soares (2018) stated that weighting within the MCDA approach is still poorly addressed when the goal is to elicit significances for impact categories to create a generic weighting set (i.e. case-independent). In that survey, only two studies used MCDA to weight environmental impacts case-independently: Soares, Toffoletto and Deschênes (2006) and Agarski et al. (2016). The difference from both, in comparison from the other publications, lies on the fact that Soares and Agarski weighting proposals may contemplate any kind of LCA study. Other weighting sets constructed around MCDA for LCA are present in LCIA methods. For instance, in the Building for Environmental and Economic Sustainability (BEES) method (LIPPIATT, 2007), Gloria, Lippiatt and Cooper (2007) applied the AHP method to a panel of 19 LCA specialists to weight 12 different midpoint impact categories.

Fig. III-1. Mapping of MCDA applied into LCA studies (adapted from ZANGHELINI; CHERUBINI; SOARES, 2018).



III.3 OBJETIVES OF THE STUDY

The aim of this study is twofold: (a) we weighted environmental impact categories according to main Brazilian stakeholders, and (b) demonstrated whether the different group of stakeholders' judges differently the relevance of impact categories. Those goals are aligned with Finnveden et al. (2009) and Pizzol et al. (2017) that suggested that weighting methods for LCA should continue to be published in the scientific literature in order to improve uncertainty and robustness of LCA methodology as a whole. Also, a recent inquiry by Pizzol et al. (2017), similarly to Soares, Toffoletto and Deschênes (2006) and Ahlroth et al. (2011), stimulates the investigation on whether damages to areas of protection should be weighted the same across the different countries or regions. Such question may be answered on midpoint impact categories (that are paths to AoPs) whereas different countries/regions are also reflected in its own stakeholders. Therefore, we hope that these results may add to the (still far from end) discussion regarding weighting in LCA. In addition, the hybrid MCDA methodology AHP-PROMETHEE II is used for the first time for obtain weights for LCA traditional midpoint impact categories with the support of a panel of specialists. Ultimately, as the importance of the environmental effects is often based on a judgment (HUPPES; VAN OERS, 2011) and that specialists have a key hole on this process, the set of weights (or even the weighting approach) fills an existing gap in Brazilian LCA community a provides a guideline for LCA application when it comes to weighting, communication of final results and decision-making.

III.4 MATERIAL AND METHODS

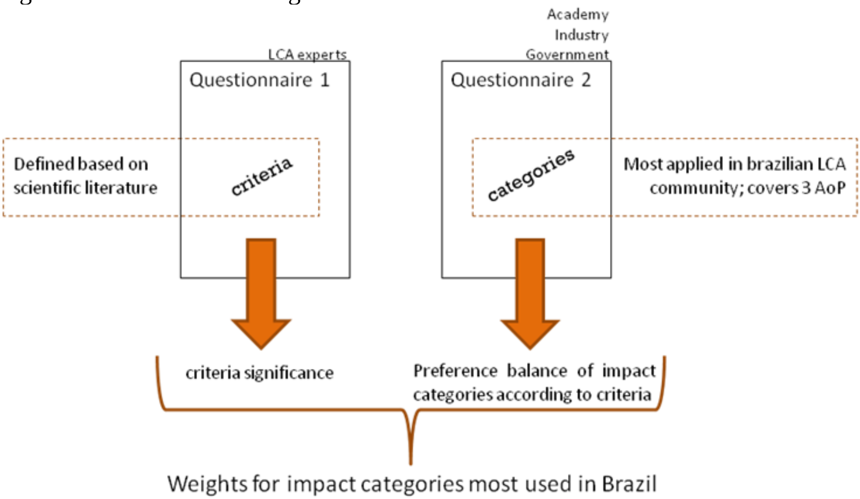
To elicit complex information from stakeholders, such as importance of impact categories, the method applied is composed by a panel structured with a combination of two MCDA methods: The Analytic Hierarchy Process (AHP) and the Preference Ranking Organisation METHod for Enrichment Evaluations II (PROMETHEE II). The former is a pair-wise comparison method developed by Saaty (1980) to support multi-criteria decision making and aimed to weigh criteria according to LCA specialists. The ladder is an outranking MCDA method proposed by Brans et al. (1984) and was assigned to obtain a final ranking of the proposed alternatives by comparing them under the influence of weighted criteria. In both cases, a panel is proposed for stakeholders' participation. The general framework of the MCDA structure in this research is presented in Fig. III-2.

The rationale behind this choice is based on the non-compensatory (or partial compensatory) nature of PROMETHEE II (CINELLI; COLES; KIRWAN, 2014; GELDERMANN; RENTZ, 2005; PRADO-LOPEZ, 2013; POLATIDIS et al., 2006; TURCKSIN; BERNARDINI; MACHARIS, 2011), desirable feature when environmental decision-making must be done (MUNDA, 2005; PRADO-LOPEZ, 2013). On top of that, PROMETHEE may be considered an 'easy-to-apply' method (BOUFATEH et al., 2011; GELDERMANN; SPENGLER; RENTZ, 2000; SEAGER et al., 2006) to a stakeholder' panel and results in a complete ranking of alternatives (BEHZADIAN et al., 2010; BOUFATEH et al., 2011; LE TENÓ; MARESCHAL, 1998), an outcome that enables on to attribute weights for the alternatives. However, as explained by Behzadian et al. (2010), Turcksin, Bernardini and Macharis (2011) and Macharis et al. (2004), PROMETHEE assumes that the decision-maker is able to weigh the criteria appropriately, so as effect, information on the relative importance of the criteria (weights) is required. Because of this condition and as AHP is a way to determine weights to be used in MCA (PASTARE et al., 2014), the combination of AHP and PROMETHEE II was complementary. A more extended and substantial comparison between MCDA methods applicable to LCA weighting and used to base the decision for the AHP + PROMETHEE II in this paper is present in APÊNDICE E – MCDA Methods.

According to Goedkoop and Spriensma (1999), the number of subjects to be weighted should be as small as possible. De Feo and De Guisi (2010) argue that the use of a large number of criteria may result in an incomprehensible questionnaire, mainly because humans have limitations on the number of criteria they can handle at the same time (METTIER; SCHOLZ, 2008). Thus, we established the number of 8 criterion for AHP and 8 alternatives for PROMETHEE II. The criteria used are defined on the following item and is deepened in APÊNDICE F – Criteria Choice, whereas alternatives (i.e. impact categories from LCA) are defined in section III.4.2 Impact Categories Set. The mathematical model behind the weighting and aggregation process present in section III.4.3 and the definition of panelists in section III.4.4 completes the MCDA model gears in this research.

Matlab and excel were used to support MCDA aggregation steps (presented in Fig. III-5) whereas Statistic software was used to test differences between practitioners affiliated to academy, government and industry, through ANOVA with Tuckey test.

Fig. III-2. MCDA structure: general framework.



III.4.1 ESTABLISHMENT OF CRITERIA

The group of criteria defined to structure the decision-making process was chosen in order to cover different and as much as possible non-overlapping aspects of environmental impact and was based on (or sought to cover) three main elements: (1) the level of environmental consequence (SOARES; TOFFOLETTO, DESCHÊNES, 2006) or dynamics of the harm (UDO DE HAES, 1994) that quantifies environmental impact; (2) the environmental consequence (SOARES; TOFFOLETTO, DESCHÊNES, 2006) or consequences of the harm (UDO DE HAES, 1994) that unlike previous criteria, it is related to the type of damage/problem caused by environmental impacts, and; (3) the possibility of recovering from the harm, criterion derived from the concept of to reduce the level of consequences and the type of damage.

Level of environmental consequences:

- Scale/Spatial coverage

Criterion referring to the area on which the impact is expected to act (VOLKWEIN; GIHR; KLOPFFER, 1996). It is assumed that environmental problems affecting a larger area (global or regional) or more significant geographic areas (protected natural areas, crowded places) are more severe than those affecting smaller areas (AGARSKI et al., 2016). According to Soares, Toffoletto and Deschênes (2006), the rationale is that the more significant the zone, the higher the probability of increased damages (since other variables contributing to the impact remain constant).

- Duration

It refers to the fact that environmental problems with a longer duration are more severe than those with a shorter duration (AGARSKI et al., 2016). It is assumed that if an action occurs over a longer period, the probability of increasing the environmental impact also becomes greater (SOARES; TOFFOLETTO, DESCHÊNES, 2006).

- Reversibility

This criterion takes into account the possibility and difficulty of reversing (artificially or naturally) the impact category itself (SOARES; TOFFOLETTO, DESCHÊNES, 2006), i.e. the ability of the system (affected environment) to return to its previous state (SÁNCHEZ, 2006). It is assumed that irreversible environmental consequences are a greater problem than those that can be remedied to restore a previous condition after a certain period (AGARSKI et al., 2016).

- Probability of occurrence

Criterion that refers to the degree of uncertainty about the occurrence of the impact. An example of a classification of extremes with respect to impacts may be: (i) high, when there is certain about the occurrence of the impact and (ii) low, when the impact is very unlikely to occur (SÁNCHEZ, 2006).

Environmental consequences:

- Damage to human Health

This criterion applies to human mortality and diseases. The impact on human health occurs for several reasons when caused by environmental impacts where the more severe the repercussions on health, the more significant the impact category (SOARES; TOFFOLETTO, DESCHÊNES, 2006).

- Damage to Ecosystems

This criterion expresses the effect on biodiversity. It applies to the disappearance or diminution of the balance of species and ecosystems (damage to fauna and flora). The more severe the repercussions on biodiversity, the more significant the impact category (SOARES; TOFFOLETTO, DESCHÊNES, 2006)

- Resource Depletion

This criterion refers to the depletion of natural reserves of raw material (renewable and non-renewable). In this case, Soares, Toffoletto and Deschênes (2006) affirms that the more severe the repercussions on its availability, the more significant the impact category.

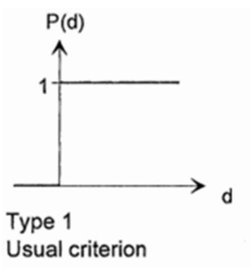
Recovering of consequences:

- Possibility of Treatment

This criterion refers to the technological availability to remedy or recover a certain area affected by a certain impact. It is assumed that an impact, for which there is no "combat" technology, represents a worse condition compared to the impact that can be addressed.

There are different preference functions under PROMETHEE II approach (BRANS and VINCKE, 1984) which covers almost all the possible criteria (ZHAO; PENG; LI, 2013): Usual, Level, Linear, V-Shape, U-Shape and Gaussian. According to Mareschal (2011), the Usual criterion is used for qualitative criteria with few evaluation levels whereas the level criterion is used for qualitative criteria when it is felt necessary to modulate the preference degree. Therefore, since the criteria in our MCDA are exclusively qualitative with evaluations levels varying from 1 to 5, the Usual criterion function was considered. In this function, the degree of preference of an alternative (a_t) compared to the other $(a_{t'})$ may vary from $p_k(d)$= 0, which means indifference along a weak preference zone to $p_k(d)$= 1 which describes a strict preference (behavior and function are presented in Fig. III-3 and Eq. III-1 respectively) (BRANS; VINCKE; MARESCHAL, 1986).

Fig. III-3. Criteria function (BRANS; VINCKE; MARESCHAL, 1986)



$$p_k(f_k(a_t) - f_k(a_{t'})) = p_k(d) \in [0;\ 1]$$

Eq. III-1. Function of Usual criteria (BRANS; VINCKE; MARESCHAL, 1986)

Where:
$f_k(a_t)$ is the evaluation of the alternative a_t with respect to the criterion f_k
$f_k(a_{t'})$ is the evaluation of the alternative $a_{t'}$ with respect to the criterion f_k

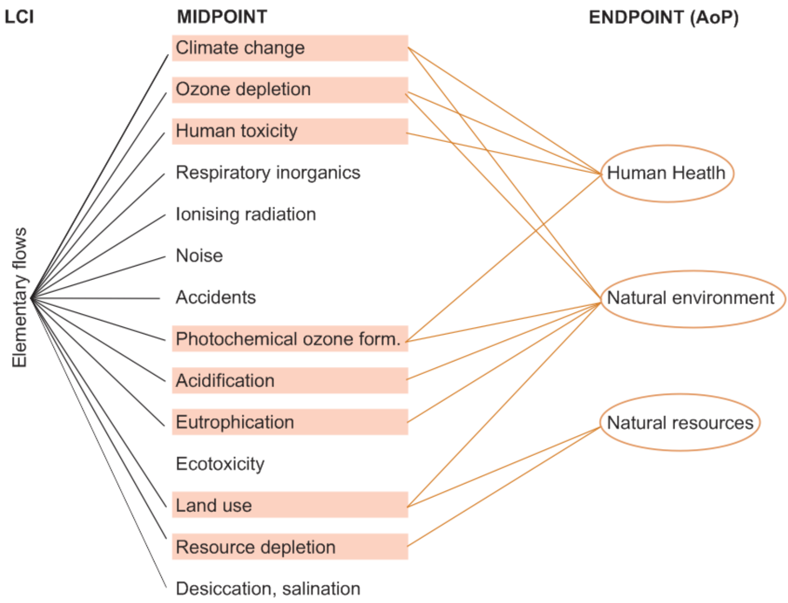
III.4.2 IMPACT CATEGORIES SET

The impact category set defined to fill the MCDA model as alternatives was selected based on three aspects: representativeness of the geography of stakeholders, quantity (to be feasible) and AoP covering.

Regarding the first aspect, “taking into account that the selection of impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration” (ISO, 2006b), the group of impact categories was defined according to Zanghelini et al. (2016) methodology and represents the most usual impact categories at midpoint level published by Brazilian LCA community. The rationale is reinforced by the fact that many LCA practitioners consider the most usual impact categories on the subject (or product system) under analyses when defining its LCA Scope. This happens due to comparability means, where obtained LCA indicators are often confronted with published values to validate the results. For instance, Zanghelini, Cherubini and Soares (2018) in their integrative review, have shown the same group of categories emerged like the most usual midpoint indicators in LCA/MCDA studies. In addition, this set is also present, with nomenclature variations, in the most popular LCIA methods as ReCiPe Midpoint (Goedkoop et al., 2009) and CML-IA (GUINÉE et al., 2002).

The quantity of alternatives is also a key factor when applying a panel-based MCDA. According to Munda (2005), a desirable property for mathematical aggregation procedures in the framework of sustainability decisions is simplicity, i.e. the use of a few parameters as possible. Thus, the number of impact categories were defined seeking for the applicability of the questioner to the stakeholders. Therefore the set of impact categories in this paper is formed by eight midpoint impact categories: Climate Change (CC), Acidification (AP), Eutrophication (EP), Ozone Layer Depletion (OLD), Photochemical Ozone Formation (POF), Human Toxicity (HT), Abiotic Depletion (AD) and Land Use (LU), which, following Finnveden et al. (2009), Pennington et al. (2004) and Udo de Haes et al. (1999) recommendation, covers the three AoP based on EC/JRC/IES(2010) framework as presented in Fig. III-4.

Fig. III-4. Considered midpoint impact categories (adapted from EC/JRC/IES, 2010).



III.4.3 MATHEMATICAL MODEL

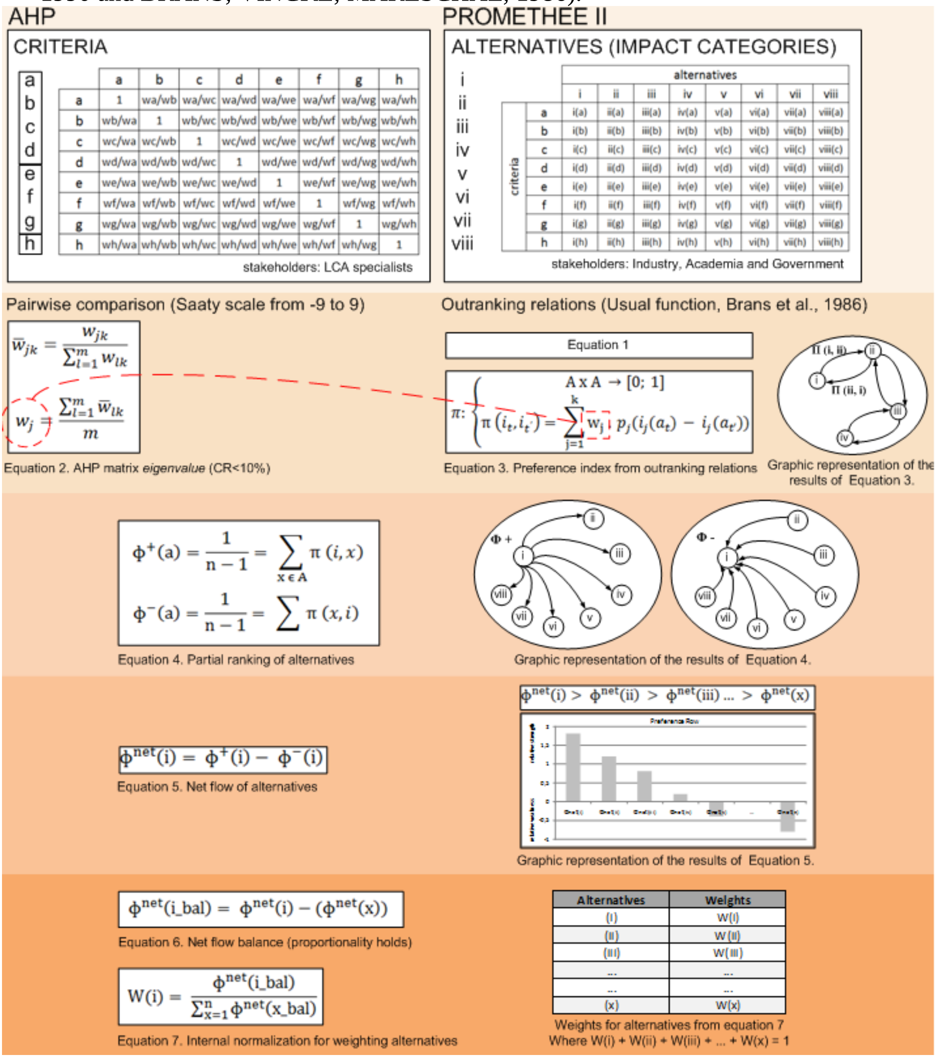
The approach is a four-step procedure based on the panel approach combined with a hybrid MCDA procedure. Similarly to Soares, Toffoletto and Deschênes (2006), panel members will not provide their direct opinion on the relative importance of the impact categories. Their value judgment will be made by the assessment of criteria and impact categories aggregated using an MCDA procedure. AHP is used to aggregate LCA specialist's opinions regarding criteria, whereas PROMETHEE II is applied to stakeholders for calculating impact categories importance.

AHP results are criteria weights given by the right eigenvector (Wj) corresponding to the highest eigenvalue (λmax), as shown in (equation 2 on Fig. III-5), based on the pair-wise comparison matrix (CRITERIA matrix in Fig. III-5) answered by each panelist. The procedure described above is repeated for all subsystems in the hierarchy. In order to synthesize the various priority vectors, these vectors are weighted with the global priorities of the parent criteria and synthesized (MACHARIS et al., 2004). According to Saaty (1987) in order to results be acceptable, consistency index must be below 10%. An inconsistency level higher than 10% means that the consistency of the pair-wise comparisons is insufficient (MACHARIS et al., 2004). Both eigenvalue (λmax) and CR (consistency ratio) were calculated with the aid of Matlab Statistical software.

PROMETHEE II procedure is based on a scale of answers of each alternative (*i*) under a criterion (*a*) that is converted in a triangular matrix for each criterion where the alternatives are confronted. This matrix represent the deviation between the evaluations of two alternatives (*i* and *ii*) on a particular criterion (*aj*) into a preference degree ranging from 0 to 1 according to a specific preference function (*Pj(i,ii)*), which is demonstrated in equation 1. Equation 3 represents an overall preference index $\pi(it,it')$ from one alternative *it* over another alternative *it'* considering the different weights calculated in AHP procedure for each criterion. The graphic representation of equation 3 results indicates the intensity of preference of *it* over *it'*. Then, the preference index is calculated. This value is based on the positive $\varphi+(i)$ and negative $\varphi-(i)$ preference flows for each alternative, which measures how an alternative (*i*) is outranking or outranked by the other alternatives (see Equation 4 and graphical representation of Equation 4). The difference between these preference flows is represented as the net preference flow $\varphi net(i)$ (Equation 5), which is a value function whereby a higher value reflects a higher attractiveness of alternative *i*. This equation results in a complete ranking of alternatives (see graphic representation of Equation 5 in Fig. III-5). The last two equations are arithmetical steps proposed to enable a weight attribution to each alternative *i*. A net flow balance (as in Equation 6) is performed, where the proportionality of each $\varphi net(i)$ holds, to bring every value into a same mathematical condition for Equation 7, an internal normalization of alternatives where their sum is equal 1.

PROMETHEE II steps were performed with the aid of excel software.

Fig. III-5. Mathematical model used in this research (based in SAATY, 1987; 1990 and BRANS; VINCKE; MARESCHAL, 1986).



III.4.4 PANELISTS

In principle, MCDA approaches cannot give an answer to the question of which type of panelists should be chosen (SEPPALA, 2003). However, Figueira, Greco and Ehrogott (2005) explains that several actors are (by definition) involved in the planning procedure and others are simply wishing to actively participate in decisions they feel they may affect their own welfare or the environment's overall stability. Thus, considering that the issue of to whom the questionnaires should be directed depends on the application and the nature of impacts (SEPPALA, 2003), and as we are dealing with environmental decision-making, every person or representative (in theory) should be consulted. However, Ji and Hong (2016) affirms that this is impossible in practice. As a result, panels consists of some experts or stakeholders. This condition generally happens due to the feasibility of the panel, but also because of an execution dilemma associated to the minimal knowledge requirement to answer such questionnaire, i.e., the accuracy of attributing weight to environmental impacts do not lies under the representativeness if the quality of the answers is misunderstanding. In this research two panels were applied (as shown in Fig. III-2 and Fig. III-5). The first one (P1) considered LCA specialists and aimed to evaluate the relevance of criteria (as defined in section III.4.1 and discussed in in APÊNDICE F – Criteria Choice. The second one (P2) was proposed to three main groups of stakeholders in environmental decision-making - academy, government and industry - to answer a questionnaire regarding the impact categories and their behavior under every criterion.

P1 was formed by LCA researchers and partner researchers (with PhD or PhD candidate on LCA) of The Life Cycle Assessment Research Group (CICLOG[8]) from Federal University of Santa Catarina. They were asked to perform a pair-wise comparison between the defined eight criteria under Saaty's scale. The questionnaire also carried a brief description on Saaty's approach and related to the meaning of each criterion as recommended by Seppälä (2003). The rationale behind the choice of this group was the relation to the experts, condition that would allow mainly an execution of a Delphi Technique if Saaty's consistency index were not reach by the first round of the panel. The choice of 10-20 specialists is in accordance with the number of experts determined by Kim, Jang and Lee (2013) if a second round of questionnaire is needed. On top of that, the criteria comparison is somehow a more technical and complex piece of the MCDA approach in this research, what would lead a difficult task for non-experts to perform.

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[8]CICLOG is one of the firsts groups studying LCA methodology in Brazil with several connections in scientific community (as shown by CHERUBINI; RIBEIRO, 2015 and ZANGHELINI et al., 2016)

Differently, P2 asked panelists to attribute an evaluation position to each of the eight criteria for each impact category according to Tab. III-1. Consistently with Seppälä (2003) statement "in the light of experience obtained from the case studies it appears very important to provide panelists with appropriate information about environmental themes", the questionnaire provided information about the environmental impacts, about the criteria and guidelines to correctly fill the form.

Tab. III-1. Scale of answers for criteria in P2.

Criteria	Scale of answers				
Scale	Global	Global/Regional	Regional	Regional/Local	Local
Duration	Long	Medium	Short		
Reversibility	Yes	No			
Probability of occurrence	Very likely	Likely	Unlikely		
Damage to human health	High	Medium	Low		
Damage to ecosystems	High	Medium	Low		
Resource depletion	High	Medium	Low		
Possibility of Treatment	There's a possibility	There's little possibility	There's no possibility		

P2 considered three groups of stakeholders, each one defined following a specific set of outlining rules and references:

- Academy: main researchers involved with LCA in Brazil based on the main authors raised in Zanghelini et al. (2016) and participants in the scientific committees of the Brazilian Conferences on Life Cycle Management (CBGCV) and Brazilian Forum of LCA (BRACV);
- Government: government organizations involved with LCA (on the basis of National LCA Program) and Governmental Research Institutions (based on ZANGHELINI et al., 2016 and CHERUBINI; RIBEIRO, 2015) and Public bodies intended to promote sustainability in several spheres, including legislative, judicial and executive.
- Industry: organizations involved with LCA or that have developed projects in this area in Brazil (based on the Brazilian Business Network for Life Cycle Assessment; ZANGHELINI et al., 2016 and CHERUBINI; RIBEIRO, 2015), including consultancies;

The rationale behind the second panel followed Soares, Toffoletto and Deschênes (2006) that verified that multiple panels could be proposed depending on their affiliation (academic, governmental or industrial). This group sough to include every entity interested in LCA in Brazil, either because practice, develop, discuss, or demands it, and still maintained a certain level of knowledge on the theme.

III.5 RESULTS AND DISCUSSION

III.5.1 LCA SPECIALISTS AND CRITERIA

The AHP panel was sent to CICLOG research network, formed by 25 specialists with PhD level on environmental sciences with emphasis in LCA. From those, 16 participants answered our survey, what represent a return rate of 64%. Similarly, and with effects of comparison, Soares, Toffoletto and Deschênes (2006) have applied an AHP-based survey to Canadian experts and counted with 14 participants to perform pair-wise comparisons to criteria related to environmental consequences and level of consequences. The average weight of the criteria tabulated from the answered questionnaires of this research is present in Tab. III-2.

Tab. III-2. Criteria pair-wise comparison matrix.

	C1	C2	C3	C4	C5	C6	C7	C8	λ max	weighting vector
C1	1.00	2.25	0.46	2.48	0.34	0.63	0.68	0.84	0.21	8.79%
C2	0.45	1.00	0.47	2.04	0.42	0.50	0.41	0.87	0.16	6.65%
C3	2.15	2.11	1.00	4.32	0.52	0.95	0.99	1.95	0.35	14.21%
C4	0.40	0.49	0.23	1.00	0.19	0.11	0.20	0.20	0.07	2.90%
C5	2.97	2.39	1.91	5.37	1.00	2.34	3.04	4.49	0.67	27.44%
C6	1.59	2.01	1.06	9.00	0.43	1.00	2.22	3.45	0.45	18.43%
C7	1.48	2.43	1.01	5.00	0.33	0.45	1.00	4.09	0.35	14.19%
C8	1.19	1.15	0.51	5.00	0.22	0.29	0.24	1.00	0.18	7.38%
Σ	**11.23**	**13.83**	**6.66**	**34.22**	**3.44**	**6.27**	**8.78**	**16.88**	2.44	100%

Where C1: Scale; C2: Duration; C3: Reversibility; C4: Probability of occurrence; C5: Damage to human health; C6: Damage to ecosystems; C7: Resource consumption; C8: Possibility of treatment

In general, panelists weighted more the consequences of the environmental impacts (C5, C6 and C7) than the level of environmental impacts (i.e., C1, C2, C3 and C4) or the possibility of treatment of its effects. One of the reasons for this behavior may be explained by Soares, Toffoletto and Deschênes (2006). According to the authors, "environmental consequences were easier for panelists to assess" whereas "the level of consequence assessment requires more knowledge on the impact categories". In other words, it is easier for panelist to understand the real damage or consequences caused by an environmental impact than its levels of severity or consequences. For instance, the former is the real impact, condition that individuals may have already witnessed (as personal perspective) and is easier to link to a real solidified situation. Thus, Soares, Toffoletto and Deschênes (2006) explains that panelists might have a tendency to rate criteria associated with level of consequences with a low score.

The consistency of the comparison matrix, and therefore criteria weights, is assured by the consistency ratio (CR). The higher eigenvalue obtained from the matrix is 8.44, which resulted in a consistency index of 0.063 and a CR of 0.045 (for a random consistency index, R.I. of 1.41 indicated for a 8 criteria matrix). Thus, panelists answered the questionnaire of criteria with 4.5% of inconsistency, value that respects Saaty's recommendation for a consistent AHP matrix. Since, consistency is lower than 10% the weighting vectors in Tab. III-2 are acceptable. According to CICLOG specialists, the most significant criterion is Damage to human health (C5) with 0.2744 of the total of 1.0 (that represents the sum of all weights of criteria), followed by Damage to ecosystems (C6) with 0.1843. This is the same behavior presented in Soares, Toffoletto and Deschênes (2006), for instance, according to the authors, "human and ecosystem health were considered by panelists as the most important criteria to assess impact category weights". The last criterion of environmental consequences, Resource consumption (C7), also represented a relevant weighting vector, with 0.1419. As a result, the criteria at environmental consequences represent around 60% of the importance of all criteria. Regarding criteria at level of environmental consequences, Reversibility rises as the most meaningful to panelists followed by Scale (C1), with weights of 0.1421 and 0.0879 respectively. Duration (C2) and Probability of occurrence (C4) completes this set of criteria with lower relevances (0.0665 for C2 and 0.029 for C4). Altogether, criteria at level of consequences represents 32.5% of the significance of all criteria. Surprisingly, the last criterion, C8, reached a higher relevance than C2 and C4, demonstrating that panelists find the possibility of treatment of an impact more important than its Duration or Probability of occurrence.

Our results have shown slightly differences between the values published by Soares, Toffoletto and Deschênes (2006) (see Tab. III-3 for proportionally adjusted values). Soares and colleagues have found weights of 0.381, 0.311 and 0.308 for Scale, Duration and Reversibility, respectively. Values 23% and 28% higher than those elicited from CICLOG specialists for Scale and Duration and 37% lower for reversibility. Regarding to environmental consequences criteria, Soares, Toffoletto and Deschênes (2006) published the same weight for damages to human health and damages to ecosystems, 0.343 and very near importance to Resource consumption with 0.314. This means that Soares's panelists considered the three criteria with almost the same importance. Differently, our panelists considered Human health more important than ecosystems (0.456 over 0.306) and both as more meaningful than Resource consumption (0.238). These variations may be justified due to the different specialist groups considered in each panel, from different realities (Canada and Brazil) and even due to the difference of 10 years from Soares, Toffoletto and Deschênes (2006) publication, conditions that may have influenced in the preferences of panelists. Although these differences in terms of magnitude are very similar for both studies.

Tab. III-3. Comparison with Soares, Toffoletto and Deschênes (2006) criteria weighting.

	C1 [1]	**C2 [1]**	**C4 [1]**	**C5 [2]**	**C6 [2]**	**C7 [2]**
Soares, Toffoletto and Deschênes (2006)	0.381*	0.311*	0.308*	0.343	0.343	0.314
Present Study	0.292**	0.222**	0.486**	0.456	0.306	0.238

1 Proportionally recalculated to represent 100% (summed) as in Soares, Toffoletto and Deschênes (2006)
2 Proportionally recalculated to represent 100% (summed) as in Soares, Toffoletto and Deschênes (2006)
* Proportionally recalculated without DtT criterion.
** Proportionally recalculated without Probability of occurrence and Possibility of treatment criteria.

As a condition of the result of the weighting vectors presented in Tab. III-2, it is possible to state the preference of panelists from a criterion over the other criteria. In a complementary way, the Fig. III-6 until Fig. III-13 demonstrate the distribution result of pair-wise comparisons within Saaty's scale. Analyzing the boxplots charts, where the values around 1 represent the equalitarian condition, it is possible to better understand panelists' criterion preferences, case-by-case, and how opinions converged or diverged. For instance, Fig. III-6 shows the distribution of opinions of the criterion 'Scale' (C1) compared to the others. In this chart it is clear the higher relevance of C1 compared to 'Duration' (C2) and 'Probability of occurrence' (C4), both with the mean result above 2 in Saaty's scale of importance. For the panelists, the size of the impact is a more important aspect than the occurrence period or the probability of occurrence. Despite of the high amplitude of values (variation of maximums and minimums) for these two comparisons, panelists have demonstrated a good convergence in terms of answers, with small interquartile ranges (IQR). Differently, the other comparisons in Fig. III-6 demonstrated the overall preference of the participants for other criteria rather than C1 and a wide IQR, reflection of a smaller convergence in specialist's opinions. Noteworthy the comparison between C1 and Possibility of treatment (C8), almost equivalents (i.e. panelists considered C1 and C8 with the same importance to environmental impacts) and with a significant variation in IQR.

Fig. III-6. Boxplot chart with C1 - Scale significances according to panelists' pair-wise comparisons.

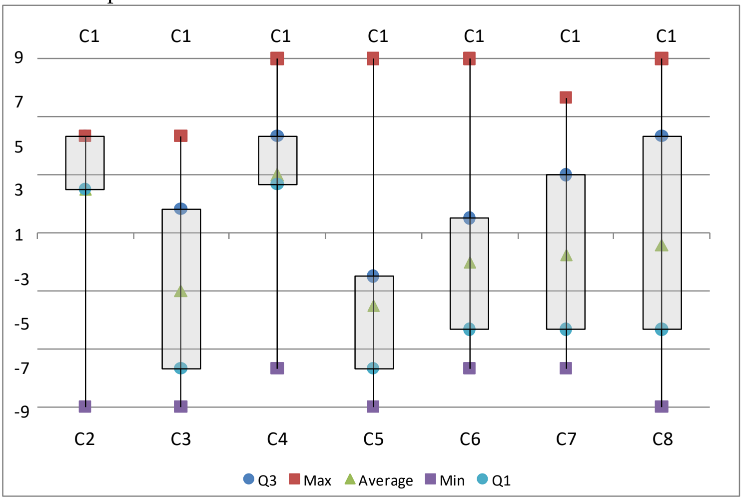


Fig. III-7 demonstrate the preference of all criteria but C4 if compared to C2. The major part of Panelists positioned C2 as one of the less meaningful criterion for the occurrence of environmental impacts. The rationale is that it does not matter the period of time that the impact occurs as long as it does not cause any damage to the 3 AoP, affect a large area or have irreversible effects. One may note that the boxplot of C2/C1 in Fig. III-7 is the opposite of the boxplot C1/C2 in Fig. III-6. This is an expected (and recurrent) condition alongside these figures, as they represent the same comparison under different perspectives.

Fig. III-7. Boxplot chart with C2 - Duration significances according to panelists' pair-wise comparisons.

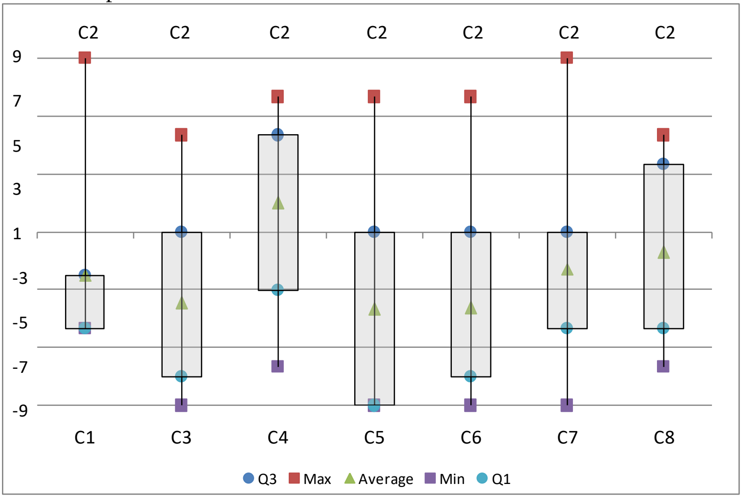


Fig. III-8. Boxplot chart with C3 - Reversibility significances according to panelists' pair-wise comparisons.

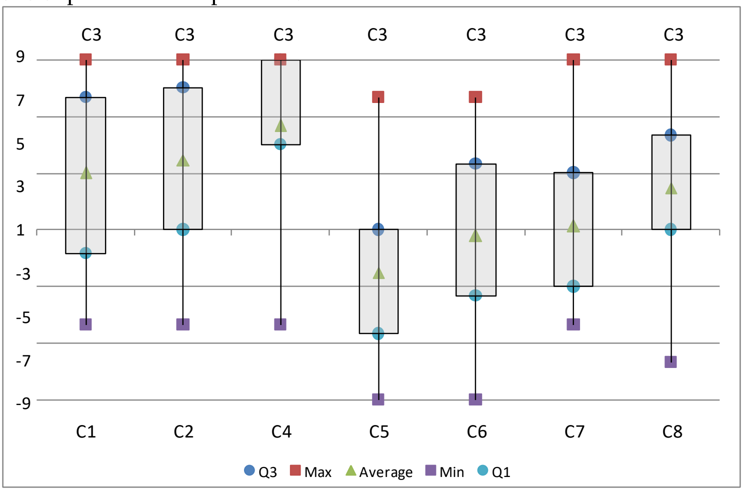
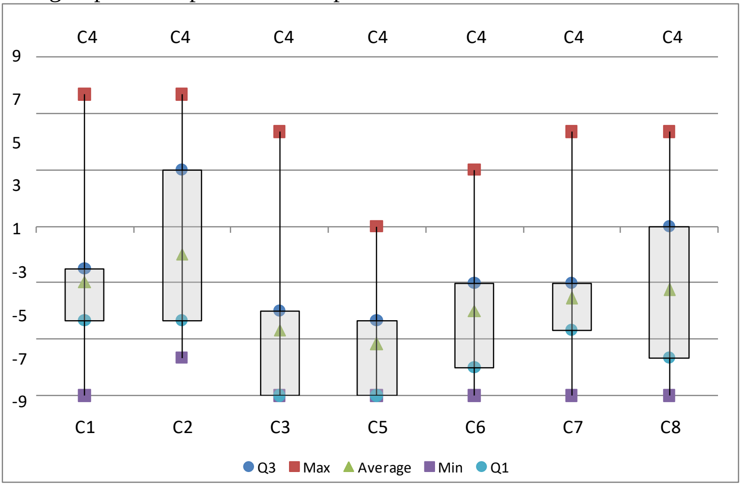


Fig. III-9. Boxplot chart with C4 – Probability of occurrence significances according to panelists pair-wise comparisons.



Panelists considered 'Reversibility' C3 as the most significant aspect among level of environmental consequence criteria. C3 is also more meaningful than C8, equivalent to C7 and almost equivalent to C6 as shown in Fig. III-8. The only strict preference is from C5 and C4 over C3. This means that only damage to human health and damage to ecosystems were considered as more important than the irreversibility condition. In fact, our judgment associates severe harm with the irreversible condition, such as extinction, desertification, death, among others. This pattern is also clear in the comparison with Soares, Toffoletto and Deschênes (2006) results in Tab. III-3. Finally, C4 is the lower weight considered by the panelists, behavior that is clearly visualized in Fig. III-9 where almost no value is above 1 (only part of IQR of C4/C2 dispersion trespassing the '1 axis'). A remarkable preference in this figure is demonstrated by C5 over C4, pair-wise comparison where panelists demonstrated a strong convergence, including an absence of maximums over the equalitarian axis.

Damage to Human Health (C5) presented the best convergence of opinions over the other criteria. Fig. III-10 plainly demonstrate panelist's preferences stated attributing higher significance to C5 (all above the equalitarian axis), resulting in the most representative value in Tab. III-2 and Tab. III-3. Transiting to Fig. III-11 and Fig. III-12 it is possible to note the same behavior but less pronounced, i.e., even though panelists indicated a preference of C6 and C7 over all criteria (aside of C5 for both plus C6 to C7), this preference was less distinct.

C8 represents a criterion that is diverse than the set composted by C1, C2, C3 and C4 (level of environmental consequences) and the set formed by C5, C6 and C7 (environmental consequences). Panelists have shown a preference of C8 over C1, C2, C4 and C7 what means that stakeholders considered the possibility of treatment of a certain impact as a more significant aspect than the affected area, duration, probability that this impact occurs and resource consumption. Reversibility was more meaningful than C8 reflecting the fact that many panelists considered that if an environmental impact is irreversible, it is not treatable at all. C5 and C6 followed the same trend as other comparisons, where participants indicated strict preference to those aspects. Noteworthy to mention the case of C8/C1 comparison. The direct comparison shows that the panelists indicated a preferential inclination to C8, but when we turn attention into the final weights (Tab. III-2), C1 is slightly more significant than C8. This occurs due the more solidified preference of C1 over C2 and C4 if compared with C8 preference over the same criteria, and even though with minimal effects to results, indicates an inconsistency in overall panelist's responses.

Fig. III-10. Boxplot chart with C5 – Damage to Human Health significances according to panellist's pair-wise comparisons.

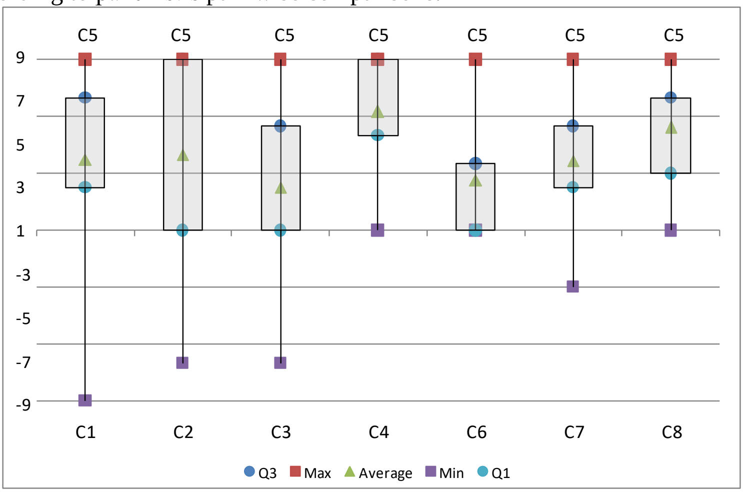


Fig. III-11. Boxplot chart with C6 – Damage to ecosystems significances according to panellists' pair-wise comparisons.

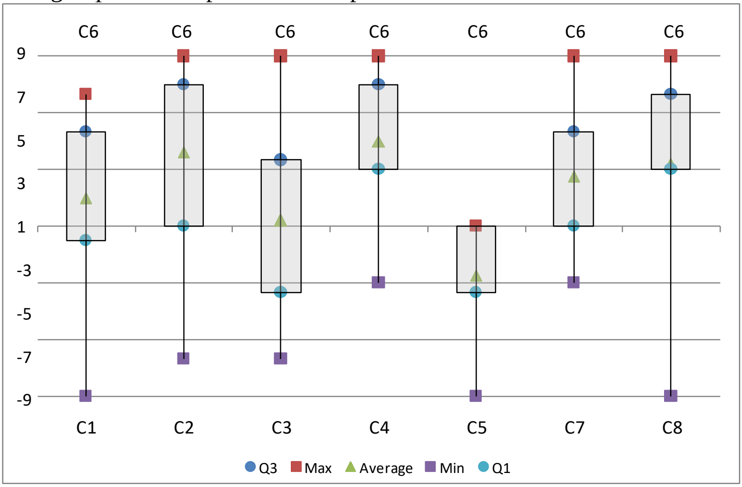


Fig. III-12. Boxplot chart with C7 – Resource depletion significances according to panellists' pair-wise comparisons.

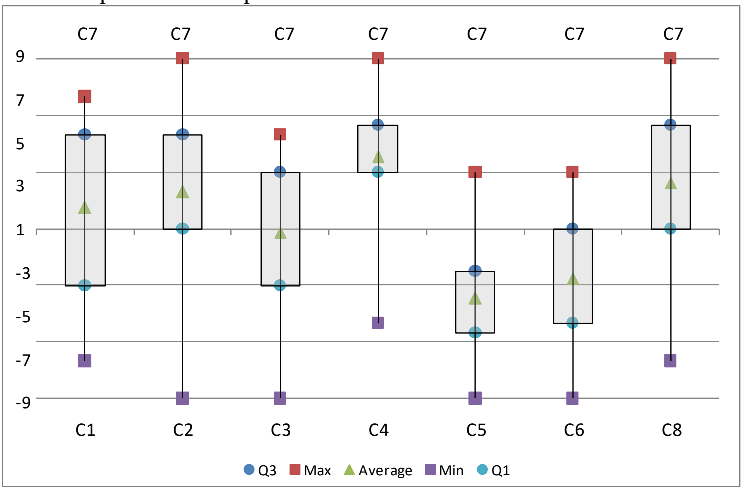
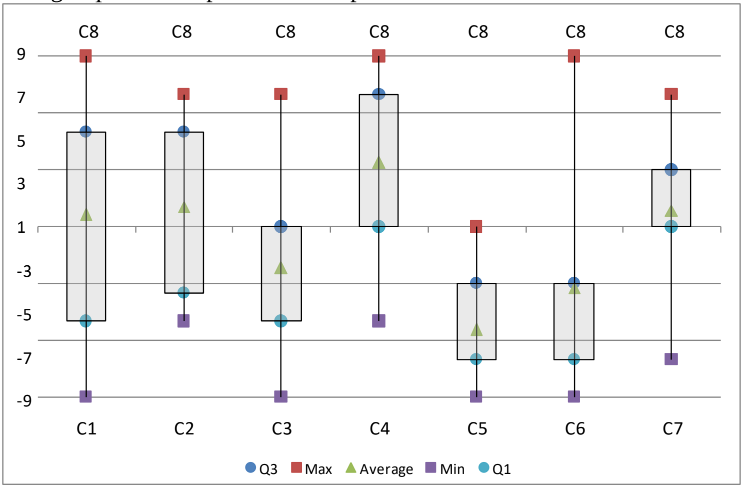


Fig. III-13. Boxplot chart with C8 – Possibility of treatment significances according to panellist's pair-wise comparisons.



III.5.2 STAKEHOLDERS AND IMPACT CATEGORIES

This panel was developed to indicate the importance of impact categories according to different stakeholders with the effect of weighted criteria calculated previously in panel 1. The mathematical rationale follows the scheme in Fig. III-5[9] based on AHP-PROMETHEE II methodology.

The panel was sent to 192 panelists divided as follows: 59 participants from Academy; 56 from Government Bodies and Institutions; and 77 representatives from Industries. After 3 months of time span on which the questionnaire was sent, and the panel and research was explained for all interested participants, the survey received a total of 76 responses, reflecting an overall return rate of approximately 39,6%. This number represents a higher coverage of stakeholders if compared to Soares, Toffoletto and Deschênes (2006), Gloria, Lippiatt and Cooper (2007) and Mittier and Scholz (2008) that applied panels to 14, 19 and 52 panelists, respectively.

From Academy stakeholder group, we obtained 26 responses (return rate of 44%) from the main Research Institutions and Universities.

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[9] Vide item I.3.2 Outranking - PROMETHEE, na página 63 para uma melhor compreensão do algoritmo de cálculo das preferencias de cada painelista e sua agregação em significâncias.

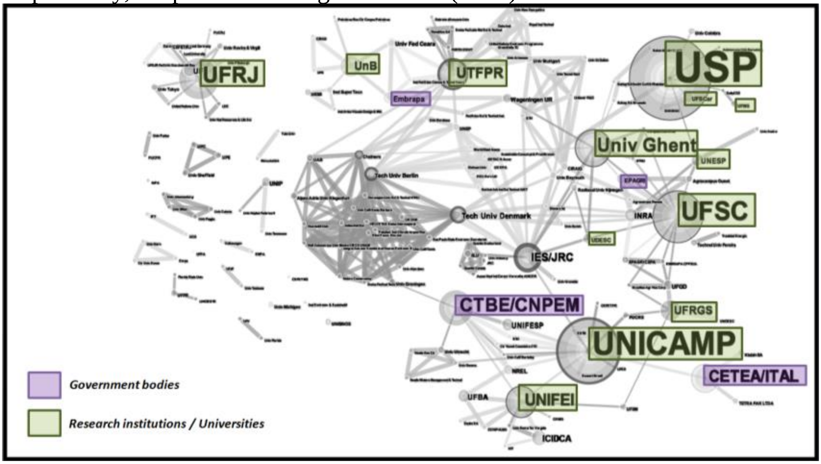
Fig. III-14 represent a co-collaboration network of Brazilian research institutions, where the green boxes indicate the coverage of Academy Bodies in this panel.

The government group participated with 25 panelists (45% of return) representing Governmental Research Institutions that develop LCA studies, Government bodies that support LCA and Government organizations that legislate, monitor, inspect and execute environmental issues. The Brazilian Ministry of Environment (MMA) and National Confederation of Industry were the representatives of public policies developers and lawmakers within environmental ambit. Regarding LCA supporters, the panel counted with the participation of two institutes, headers of the National LCA Program (PBACV): the Brazilian Institute of Information in Science and Technology (IBICT) and the National Institute of Metrology, Quality and Technology (Inmetro). IBICT is a branch of the Ministry of Science, Technology and Innovation engaged in prospecting and disseminating information in the field of Science, Technology and Innovation, e.g. initiatives to foster the LCA methodology in Brazil including the creation of the National Database of Life Cycle Inventories (SICV Brasil). Inmetro is responsible for the execution of directives from the National Council of Metrology, Standardization and Industrial Quality (CONMETRO) comprising for instance the regulation of environmental labeling (Environmental Product Declaration - EPD) that is based on LCA results.

Corresponding to technical bodies, the panel received responses from state and municipal levels. From state sphere, participated the Environmental Company of the State of São Paulo (CETESB) and the Environmental Foundation of Santa Catarina state (FATMA). At municipal sphere the agent was The Municipal Environment Foundation of Florianópolis (FLORAM). Another two organizations that replied the questionnaire were the Water and Sanitation Company of Santa Catarina State (CASAN) and the Santa Catarina State Public Ministry (MPSC). The former is responsible for municipality overall sanitation whereas the latter is an institution that acts in the defense of social and common interests, such as the right to life, health, etc.

Research stakeholders from this cluster included the Brazilian Agricultural Research Corporation (EMBRAPA) (Institution founded under the aegis of the Ministry of Agriculture, Livestock, and Food Supply) and its equivalent at district sphere (Santa Catarina State) the Agricultural Research and Rural Extension (EPAGRI), the Brazilian Bioethanol Science and Technology Laboratory (CTBE) (that integrates the Brazilian Center for Research in Energy and Materials which is qualified by the Brazilian Ministry of Science, Technology, and Innovation), and the Food Technology Institute (ITAL), (linked to the Department of Agriculture and Food Supply of the State of São Paulo). Those representatives are also identified by Zanghelini et al. (2016) and are highlighted in purple in Fig. III-14.

Fig. III-14. Research institutions/Universities (green) and Government bodies (purple) that participated as Academia and Government stakeholders respectively, adapted from Zanghelini et al. (2016).



The Industry has returned 25 questionnaires what represent a return tax of 32%. Are part of this group, representatives of industries aligned with Cherubini and Ribeiro (2015), including petrochemical, plastics and resins, cosmetics, mining, steel, metal casting, home appliances, electro-electronic, air compressors, textile, logistics, package and labeling and aviation sectors; an independent environmental labeling program organization, and; LCA consultancies that are, unavoidably, in near contact with the industry performing LCA projects to those industrial sectors.

The aggregated result of the panelists answers from PROMETHEE II without weighting criteria (i.e. with each criterion having the same importance = 1/8) are presented in Tab. III-4. At first glance, stakeholders have demonstrated similar opinions and balance of preferences. For instance, EP and AP resulted approximately the same weights for all group of panelists, with 0.082 to 0.084 and 0.102 to 0.105 respectively. CC, HT, POF and LU resulted in only one stakeholder difference. For instance, Academy considered CC less significant (0.184) than

Government and Industry (0.188 and 0.193). On the other hand, the former indicated a more meaningful value for LU (0.121) than the two latter (0.107). Other variations are identified in Industry responses. This group attribute major value to HT (0.118) and a minor importance to POF (0.070) if compared to other stakeholders. In every case, values are strictly near and differences are acceptable due to the different formation of stakeholders groups. This affirmation may also be true for the last two impact categories. However, OLD and RD have shown a more significant variation between stakeholders' groups. In the first case, three different weights were elicited, 0.154, 0.140 and 0.174 for Academy, Government and Industry respectively. On the second case, Academy and Government converged in the balance of preferences with a factor of 0.177 whereas Industry was directed a less meaningful participation of this category, with 0.151. Despite of these variations, on average, Brazilian stakeholders have indicated a more importance to CC (0.187) and RD (0.170) followed by OLD (0.153), which represent more than 50% of the significance of this weighting. LU and HT represent a weight of 0.113 each, almost the same result for AP (0.100). The last two impact categories, EP and POF represent the lower importance with 0.080 and 0.077, respectively; over the total of 1 (see Tab. III-4).

Tab. III-4. Environmental impact categories relevances (without influence of criteria weighting).

Stakeholders	CC	EP	AP	OLD	RD	HT	POF	LU
Academy	0.184	0.082	0.102	0.154	0.177	0.105	0.075	0.121
Government	0.188	0.082	0.105	0.140	0.177	0.114	0.082	0.113
Industry	0.193	0.084	0.102	0.174	0.151	0.118	0.070	0.107
Mean	0.187	0.080	0.100	0.153	0.170	0.113	0.077	0.113

The preference over Climate Change occurs due to its Scale and Duration (almost 100% of panelists considered as a global effect and long duration from the scale presented in Tab. III-1), Probability of occurrence (88% attributed high possibility of emitted GHG generates CC) and damage to ecosystems (88% interpreted as having high possibility to damaged ecosystems). One of the reasons for this high convergence in terms of opinions (regarding scale of answers) occurs due to the widespread knowledge around CC, its effects and consequences. GHG gases and Global warming is a constant theme of debate around the globe where IPCC plays a key role publishing scientific grounded reports what makes it accepted worldwide. As an effect, international cooperation pacts have been made and several countries have established reduction goals over the recent years (e.g. Paris Agreement). On the other hand, reversibility results have demonstrated a split opinion of panelists. For this category 60% of the respondents considered CC as an irreversible impact. Indeed, CC may be considered as reversible in terms of temperature, as long as emissions diminish during the years, as defended by many researchers as Wu et al. (2015) and Zickfeld et al. (2013) (that may be the rationale behind this indication by 40% of stakeholders). The other may have considered the effects of CC over the globe, including irreversible changes on sea level, polar caps melting and desertification (to cite a few consequences). Regarding damages to human health, stakeholders have shown a divided behavior. Around 40% interpreted CC as an impact that causes high damage to human health, 33% understood that the damage would be medium, whereas 27% considered a small effect over human health. Similarly, 35% indicated a high incidence over RD, 38% attributed a medium effect and 27% answered that CC would have a low influence to RD. Reasons for this results may be due to unclear direct effects caused by CC on human health and resources if compared, for instance, to damages to ecosystems (88% of convergence). At last, half of stakeholders understand that CC has a medium possibility of recovering impacted areas by available technologies. Thus, due to unanimously high scoring in C1, C2, C4, C6 and significant positioning in C3, C5 and C8, CC was considered by Brazilian stakeholders the most important impact category.

When it comes to RD, 75% of the panelists indicated this impact category as between 4 and 5 on the scale of C1 on Tab. III-1 (i.e. continental and global). Similarly, in a dominant way, 85% understand that this impact is irreversible and with long duration over the years. Regarding to C4, 66% considered RD a kind of impact with high probability of occurrence whereas for 34% of the specialists it has a medium probability to happen. Around 70% of the panelists agreed that RD has a low impact over Human health but a high impact over ecosystems (55%). The rationale here may be associated with the judgment that degradation of biomes and natural reserves (often without population presences) occurs due to extractive activities. Industry in these criteria have indicated a significant convergence for low/medium impacts (43% of industry representatives indicated low impacts of RD over ecosystems), one of the reasons that RD weight from Industry point of view have a smaller significance (see Tab. III-4). For C7, as expected, 87% of the stakeholders indicated a high potential of abiotic resource consumption, whereas the other 13% considered it at a medium level of resource depletion. Only 47% observed a low possibility of treatment of RD impacts (C8), result that was influenced by Industry. Panelists from this group demonstrated a different trend for this criterion if compared to Academy and Government, with 62% and 32% positioning RD with medium and good possibilities of treatment, respectively. In this way, RD was considered the second most meaningful category in this panel mainly due to the high scoring in C1, C2, C4, C6 and C7, but also because significant scoring regarding criteria C3.

Regarding OLD, all stakeholders answered spatial scale at global level, in accordance to Hauschild and Potting (2005), with long duration over the time span. C3 results demonstrate that panelists were divided about the reversibility/irreversibility of OLD (43% indicates that OLD is a reversible impact category and therefore 57% considers it irreversible). This behavior may occur because OLD have been re-establishing over the years (since the prohibition of CFC gases into household appliances), but at a small pace. Thus, as commented by some participants, the struggle here is at what extension OLD can be considered reversible over the pace it takes to recovery from human effects. Surprisingly, the positioning of OLD on C5 scale was not entirely dominated by ‘High’, even though the proved relation to the increasing of human risk of skin cancer, cataract and the premature aging and suppression of the immune system (EC/JRC/IES, 2010; HAUSCHILD and POTTING, 2005). Only 47% of answers positioned OLD with a High effect over human health, whereas medium and low effects reached around 34% and 20% respectively. Similarly, OLD potential to damaged ecosystem was judged equally High, Medium and Low with participations of 35%, 41% and 24% for each value of the C6 scale. Related to C7, OLD were considered by 55% of the respondents as with low effects to the consumption of abiotic resources. Finally, the majority of the panelists judged this category as without possibilities of technological treatment. As a result of this OLD conjuncture, high scores for C1, C2 and C8 and medium to highpoints related to C3, C5 and C6 positioned OLD as the third more meaningful impact category according to panelists.

The exposure of humans to environmental pollutants with toxic agents usually occurs via more than one route at the same time (HAUSCHILD and POTTING, 2005). This situation was also explicated by many panelists that explained under which conditions was considering HT when answering the panel. As a reflex, stakeholders diverge in terms of levels of environmental consequences, mainly regarding to C1 and C2. For Scale, 55% considered HT at local/regional level of occurrence, whereas 20% understood its effect only at local level. A significant share on the other hand positioned HT at regional and regional/global coverage (12% each). For Duration (C2), 15% of the participants answered 1 (short) and 3 (long) on duration scale from Tab. III-1. The remaining 70% positioned HT with a medium duration. C2 is actually a criterion that open margin for interpretation once toxic substances may have short and topical effects (as allergies) or chronicle and long symptoms (as cancer). Not by case, following the last rationale over duration, 20% of the stakeholder indicates irreversibility of HT. Relate to C4, panelists have an interesting convergence on High and medium probabilities of occurrence with 56% and 40% respectively. On the other side of these variations, the panel did not transmitted doubts about environmental consequences of HT to human health. 94% of panelists' judgment positioned HT with the higher potential to cause harm to human health (C5) and 62% considered low effect over resource depletion (C7). Unexpectedly, however, C6 had a split decision with exactly 33% of answerers for each value of the scale of damages to ecosystems. Finally, 92% of the panel considered good and medium availability of treatment (46% each) of HT effects.

EC/JRC/IES (2010) states that LU causes damage to ecosystems due to the effects of occupation and transformation of land. Thus, as a reflex, stakeholders have positioned LU with high influence (56%) followed by medium effects (36%) over the effects to C6 criterion (Damage to ecosystems). Accordingly, 77% considered LU as low effects to C5 (human health). Completing the environmental consequence criteria set, C7 (Abiotic resource depletion) reached significant meaning as LU have a strict relation to resources (e.g. mineral extraction). 50% of the panelists considered that LU would have high influence over the depletion of resources and 43% judges LU with medium effects over C7. 84% of stakeholders agreed on the reversibility of LU and the medium/high duration of its effects (67% and 24% of opinions). This means that, even though LU has a relative long period of effects and consequences, it is still enable one to reestablish near original conditions of quality (MILÀ I CANALS et al. 2007). This pattern is also perceived in C8 assessment, where 91% of panelists interpret that there would be good/medium possibilities for LU technological recovering. 70% agreed that LU represent a high possibility of occurrence, i.e. occupation and transformation of land would unavoidably have impacts on the environment. And at last, regarding space coverage, due to site-dependency of LU (BARE, 2010), 47% of the respondents indicate a preference over local/regional effects, followed by regional scale with

20%. Therefore, the significance of 0.11 related to LU comes from C4, C6 and C7 scores complemented by C2.

Panelists have demonstrated convergences and divergences in the way of judgment of AP. Results of convergent opinions are C3 (almost 100% considered this impact as reversible) and C2 (74% of the participants understand that AP have a medium duration). For all other criteria, responses were more distributed in the scale of Tab. III-1. This is at some extend acceptable if we take into account Bare (2010), Bellekom, Potting and Benders (2006) and Hauschild and Potting (2005) indications of geographical influential over effects, i.e. environmental impact due to acidification is not always the same for equal amounts of emission released at different geographical locations. Thus, related to spatial occurrence (C1) AP was classified predominantly between regional and regional/local with 70% of answers in this level. Regarding C4, 50% indicated a medium probability of occurrence, whereas for 45% the probability is high. AP is define majorly with low impact to human health (42%) and medium effects to ecosystems (55%) and resources (56%) on the environmental consequences set of criteria (C5, C6 and C7). However, noteworthy that, while the evaluation under C7 lowers AP’s rating with 33% of panelists indicating low effect over abiotic resources, the evaluation of C5 (38% indicating medium effects for human health) and C6 (42% observing a high effect over ecosystems) boost their rates up. This pattern occurs due to the judgment of the negative effects off AP over forests - increase the acidity of water and soil systems by hydrogen ion concentration (EC/JRC/IES, 2010)- and buildings due to acid rains (what may affect humans). Lastly, 62% of the panelist agreed that AP have a good possibility of treatment after occurrence. With all this rating associated to AP, this category reached a factor of 0.1 in importance, headed mainly by medium/high effects on ecosystems and human health.

According to EC/JRC/IES (2010), the heterogeneous spatial distribution of VOC and NOx sources and the hundreds of chemical species involved, makes POF on a regional scale highly non-linear and dynamic. Perhaps due to this condition of site-dependency (BARE, 2010) that expands interpretation possibilities, panelists have judged this category with less convergence of opinions. For instance, for Scale (C1), 35% of the stakeholders considered its effects at local occurrence, 38% judged at local/regional spatial coverage, and 12% and 11% respectively put POF as regional and regional/global occurrence. Even Global (5 at Tab. III-1 scale of answers) was indicated by 2% of panelists. Similarly, for C4 criterion, results demonstrate a variation in terms of opinions with 40%, 45% and 15% indicating ‘High’, ‘Medium’ and ‘Low’ probabilities of occurrence of such impact, respectively. Duration reached a better convergence where POF was positioned between short by 50% and medium by 45% of the participants. This is in complete accordance with Hauschild and Potting (2005) statement that POF generally rests for a few weeks over the atmosphere. Regarding to C3, all stakeholders agreed on the reversibility of this impact category. C5 was assessed as with high and medium effects to human health by 87% of the stakeholders. Impacts on humans arise when the ozone and other reactive compounds are inhaled and come into contact with the surface of the respiratory tract, where they damage tissue and cause respiratory diseases (EC/JRC/IES, 2010; HAUSCHILD et al. 2006). Due to its high reactivity, ozone present in POF attacks organic substances present also in plants and animals or materials exposed to air (HAUSCHILD et al. 2006). For instance, it causes oxidative damage on photosynthetic organelles of the vegetation (EC/JRC/IES, 2010). However, despite of these harmful potentials to ecossystems, C6 received majorly rating of low (44%) and medium (39%) effects. C7 received 80% of opinions positioning it as low effects to resource depletion and regarding treatment, panelists considered POF as with good possibilities.

The compilation of preferences indicates EP as the less harmful impact category (what is reflected in its weight). Regarding this category, despite of the high probability of occurrence according participants (63% indicates scale 3 for this criterion), 100% of the panelists in the three groups considered as a reversible impact, 90% understand EP as a local or local/regional impact (1 and 2 on C1 scale), 88% indicated a high possibility of treatment, 70% judged as with medium duration (the remaining 30% being for short duration). Related to the environmental consequences criteria, around 40% of the stakeholders account EP with low damage potential to human health or resources. Meanwhile the other 60% of each comparison was directed to the medium damage, generally when stakeholders made relation to the water as resource or as supply purposes to population. Damage to ecosystem is a case apart, once EP has considered impact over aquatic life. According to EC/JRC/IES (2010), these effects include the change of species composition, algal blooms and consequently oxygen depletion. Thus, stakeholders considered EP to this criterion as medium to high potential of occasioning damages. As EP have shown low score in almost every criterion, exception made to C4 and C6, it weight reached the less representative value in this weighting.

III.5.3 WEIGHTING AND GROUP BEHAVIOR

Differently from previously discussed section 5.2., in this section, 'Weighting' impact categories mean that weighted criteria are considered in the aggregation of results presented in Tab. III-5 (following the schematic on Fig. III-5). As the stated balance of preferences from panelists is unchanged, the results do not have great changes in terms of weights. The most significant impact category in this case remained CC with 0.185 of the significance followed by OLD and RD with 0.155 and 0.150 respectively. Other three categories that have resulted in values above 0.10 of significance are HT (0.129), LU (0.106) and AP (0.105). Completing the weighting set, POF represent a factor of 0.086 and EP a factor of 0.083.

Tab. III-5. Significance of impact categories considering weighted criteria.

Stakeholders	CC	EP	AP	OLD	RD	HT	POF	LU
Academia	0.184	0.083	0.101	0.156	0.161	0.119	0.084	0.112
Government	0.189	0.083	0.113	0.142	0.149	0.131	0.093	0.100
Industry	0.184	0.084	0.098	0.172	0.136	0.141	0.079	0.106
Mean	0.185	0.083	0.105	0.155	0.150	0.129	0.086	0.106

However, when comparing Tab. III-4 with Tab. III-5, it is possible to note some variations on the values what causes a different ranking of significances, positioning OLD forward RD. In this case, the greater significance attributed to C5 and C6 by AHP panel turned OLD weight more meaningful than the factor associated to RD. As shown, 70% of the Panelist has judged RD as an impact category with low effects to human health. With the contrary effect, C5is behind the increase of HT weight in this final set (12% of variation to the value from Tab. III-4). On the other side, even though, with the influence of different factor for each criterion (displaced in Tab. III-2), CC, EP, AP, and LU remained with the same significance on average if compared with Tab. III-4. This happens due a somehow balance between preferences and criteria for those categories. Taking as example CC, the criterion C6 (Damage to ecosystems, the second meaningful criterion from Tab. III-2) influenced significantly the final result as 88% of the panelists indicated high damage to ecosystems due to CC effects. However, Scale (C1), criterion where 100% of the stakeholders positioned CC as Global was considered by CICLOG LCA specialists as less meaningful than the egalitarian factor (0,88 over 0,125).

This balance for CC has resulted in a variation of only 1% between the 0,187 factor from Tab. III-4 and the 0,185 factor from Tab. III-5.

Even though, as clearly stated by Huppes et al. (2007) that the comparison between different weighting proposals are not possible in a straightforward way as these other methods have not the same basis, a brief comparison was made in order to position these significances regarding other weighting experiences worldwide. Tab. III-6 draws a comparative parallel to other weighting sets, based on panel of specialists worldwide and published in scientific literature, including the BEES panel and the EPA science advisory board (SAB) (LIPPIATT, 2007), the NOGEPA panel (HUPPES et al., 2007), the Canadian weighting proposed by Soares, Toffoletto and Deschênes (2006), the Australian experience by Bengston et al. (2010) and the 'COMbining environmental Performance indicators, LIfe cycle approach and Multi-criteria to assess the overall ENvironmental impact' (COMPLIMENT) proposed by Hermann, Kroeze and Jawjit (2007).

Tab. III-6. Midpoint weighting set comparison. Based on: Bengston et al. (2010); Gloria, Lippiatt and Cooper (2007); Huppes et al. (2007); Lippiat (2007); Soares, Toffoletto and Deschênes (2006);

	Lippiat (2007)[A]	SAB [A]	Huppes et al. (2007) [B]	Soares, Toffoletto and Deschênes (2006) [C]	Bengston et al. (2010) [D]	Hermann, Kroeze and Jawjit (2007) [E]	Present study
CC	0,29	0,16	0,32	0,182	0,19	0,42	0,185
EP	0,06	0,05	0,13	0,079 (aq.) 0,061 (ter.)	0,03	0,16	0,083
AP	0,03	0,05	0,06	0,092	0,03	0,26	0,105
OLD	0,02	0,05	0,05	0,131	0,04	-	0,155
RD	0,10 [1]	0,05 [1]	-	0,129	0,08 [5]	-	0,150
HT	- [2]	0,11 [4]	0,16 [4]	-	0,03	0,06	0,129
POF	0,04	0,06	0,08	0,068	0,03	0,09	0,086
LU	0,06 [3]	0,16 [3]	-	0,106	0,20	-	0,106

1 – Considered 'Fossil fuel depletion'.
2 – Assessed in terms of 'Human health cancerous effect' (0,08) and 'Human health noncancerous' (0,05).
3 – Considered 'Habitat alteration'.
4 – Considered 'Human health'.
5 – Considered the sum of 'Non-renewable fuels' and 'minerals'.

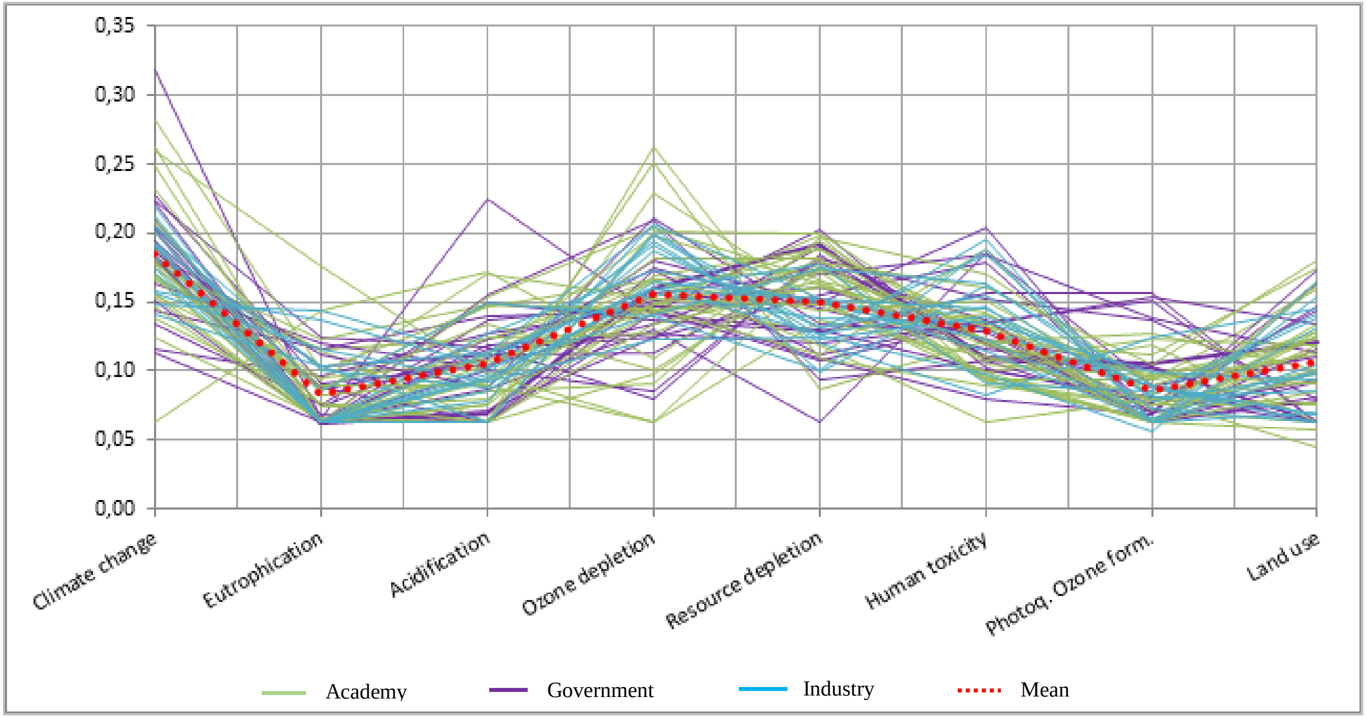
A - Lippiat (2007) and SAB also considered 'Criteria Air Pollutants' (0,09 and 0,06), 'Water intake' (0,08 and 0,03), 'Ecological toxicity' (0,07 and 0,11) and 'Indoor air quality' (0,03 and 0,11).
B - Huppes et al. (2007) also considered 'Marine Ecotoxicity' (0,08), 'Terrestrial Ecotoxicity' (0,05), 'Freshwater Ecotoxicity' (0,06).
C Soares, Toffoletto and Deschênes (2006) also considered 'Ecotoxicity' (0,085) and 'Toxic Substances' (0,066).
D - Bengston et al. (2010) also considered 'Marine Aquatic Ecotoxicity' (0,10), 'Terrestrial Ecotoxicity' (0,06), 'Freshwater aquatic Ecotoxicity' (0,10) 'Ionizing radiation' (0,02), 'Respiratory effects' (0,03) and 'Water depletion' (0,06).
E - Considered de Global perspective.

The different impact categories set from each study must be considered carefully in a comparison. As previous stated by Huppes et al. (2007), the reason is that different set of categories influence the values of each weight, once the total normalized value is divided into automatically more categories. For instance, regarding the COMPLIMENT, noteworthy that the results are related only to a global perspective what induce higher values to CC and even AP (it is possible to find regional and local weighting perspectives in this study, where impact categories with local and regional occurrence received high significances). Therefore Hermann, Kroeze and Jawjit (2007) cannot be considered as a direct comparison. Related to the other proposals, one first look at the table indicates that all sets have similar order of magnitude where CC heads as the most important impact category. Specifically, this study presents remarkable similarity to Soares, Toffoletto and Deschênes (2006), Bengston et al. (2007) and also SAB (LIPPIAT, 2007). On the other side, Huppes et al. (2007) and Lippiat (2007) have present different but proportional values and Hermann, Kroeze and Jawjit (2007) diverge more in comparison to overall weighting. This condition is exactly similar to that reported by Huppes et al. (2007) when comparing different proposals. According to those authors, the priorities resulting from weighting set, deviate sharply with those of other existing weighting methods, which also deviate substantially between each other.

The variation in terms of impact categories consideres is one of the reasons that less meaningful impact categories from Lippiat (2007), SAB (LIPPIAT, 2007), Huppes et al. (2007) and Bengston et al. (2007) have present lower values that this present study. Other characteristics as panel structure, aggregation model, stakeholders' groups, end up justifying variations found between those weighting sets. Regarding the similarity with Soares and colleagues, similar criteria may denote a condition to this near condition (see in APÊNDICE F – Criteria Choice). Nevertheless, one may note that there is an important lapse of time since 2006 and the group of stakeholders is mostly different, both geographically and in terms of country development status (including in this study other spheres but Academy).

In order to investigate the consensus degree amongst stakeholders, each participant preference profile is displayed in Fig. III-15 and stakeholders' groups are statistically represented by boxplot charts in Fig. III-16, Fig. III-17 and Fig. III-18.

Fig. III-15. Profile of balance of preferences from each stakeholder.



Analyzing the profile of answers from Fig. III-15, it is possible to note the similar behavior (in general) of preferences over local/regional impact categories such as EP, AP and POF (RD also demonstrated good convergence of preferences, but in this case, it is considered a global impact category). For these categories, despite of some outliners (e.g., the purple line that attributed the weight factor of 0.22 for AP), the overall balance of preferences shows convergence. This condition may be confirmed in Fig. III-16, Fig. III-17 and Fig. III-18, specifically for those aforementioned four impact categories, where the distribution of balance of preferences shows small interquartile ranges (IQR variation) than the other impact categories.

Fig. III-16. Boxplot chart with impact categories significances according to Academy stakeholders' balance of preferences.

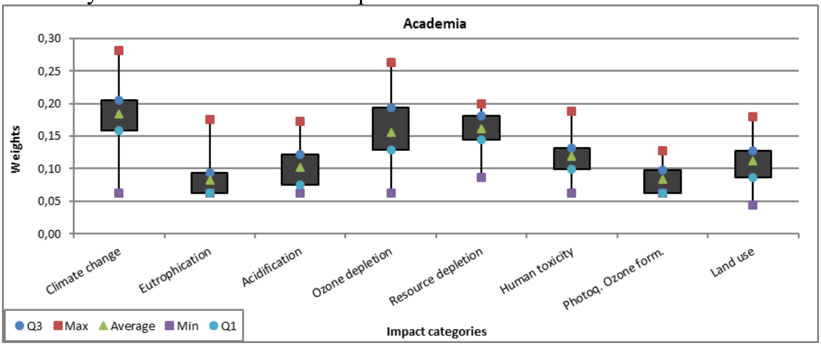


Fig. III-17. Boxplot chart with impact categories significances according to Government stakeholders' balance of preferences.

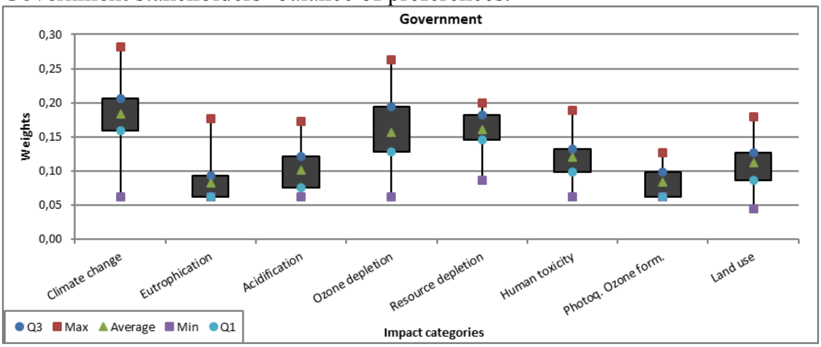
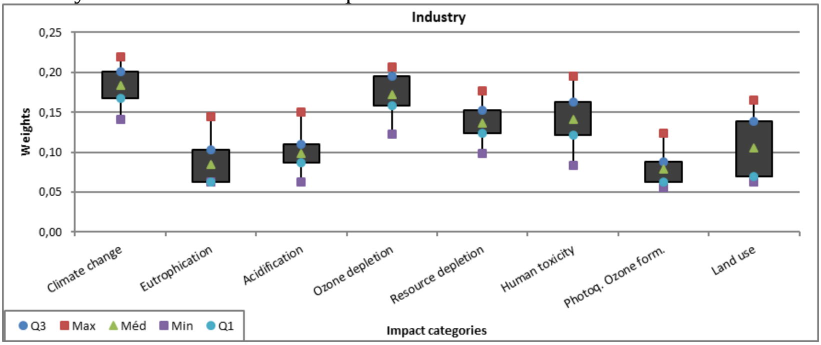


Fig. III-18. Boxplot chart with impact categories significances according to Industry stakeholders' balance of preferences.



For other impact categories, the opinion is more dispersed between panelists, situation that may be observed in the extended positioning of the lines over the 'y' axis on Fig. III-15 for CC, OLD, HT and LU. Despite of these variations, from Fig. III-15 and Fig. III-16 to 18, graphics seems to demonstrate that the dispersion of balance of preferences have a similar behavior independent of the stakeholder group.

Analyzing the groups judjement through the ANOVA (Tab. III-7), statistically, Academy, Government and Industry are convergent and have the same balance of preferences for seven of the eight impact categories: CC, EP, AP, OLD, HT, POF and LU. However, for RD, Academy and Industry diverged statistically (see bold value regarding Industry RD mean). In fact, the low significance of RD from Industry panelists is an interesting pattern since this group of stakeholders, in theory, have a straight and near relation to resources consumption in manufacturing plants. The main 'influencer' of this low score attributed by Industry, as already mentioned, was C6 (damage to ecosystems) rating (significant lower if compared to other stakeholder's groups), along with the high significance of this criterion according to LCA specialists. This result is aligned with outcomes from Huppes et al. (2007) that also found differences between sgroups of stakeholders. This variation found by the Tuckey HSD test reinforce the panel as the most indicated approach and the necessity of inclusion of all important stakeholders in a panel of specialists when the goal is to attribute significance to impact categories.

Tab. III-7. Result of the Tukey HSD test, comparing the different stakeholders weights.

Stakeholder	CC - Mean	EP - Mean	AP - Mean	OLD - Mean	RD - Mean	HT - Mean	POF - Mean	LU - Mean
Academy	0.1836[a]	0.0826[a]	0.1014[a]	0.1564[a]	0.1608[a]	0.1194[a]	0.0840[a]	0.1117[a]
Government	0.1876[a]	0.0829[a]	0.1132[a]	0.1427[a]	0.1480[a,b]	0.1317[a]	0.0930[a]	0.1008[a]
Industry	0.1836[a]	0.0844[a]	0.0983[a]	0.1723[a]	**0.1359**[b]	0.1409[a]	0.0787[a]	0.1057[a]

Different letters within the same column indicate significant differences between the weights ($p < 0.05$) according to Tukey test.

III.6 CONCLUSIONS

In this research we applied a combined MCDA approach composed by AHP and PROMETHEE II to elicit information from Brazilian stakeholders and attribute significance to midpoint impact categories used in LCA. This value-based approach was structured with two specialist panels: (1) Criteria panel, where LCA specialists (from an LCA research group network) performed pair-wise comparisons between 8 criteria and results were aggregated following AHP methodology; (2) Impact categories panel, where representatives of Academy, Government and Industry where invited to answer a questionnaire positioning each impact category into a defined criterion scale. Results were aggregated according to PROMETHEE II and criteria weight established in panel 1.

AHP panel received 16 answers, from which the most relevant criterion was associated to environmental consequences, than criteria related to the level of environmental consequences, or even the combat possibility of treatment. Regarding to the impact categories, the panel received 68 answers divided into 38% of participants from Academy, 35% representing government institutions and 27% from economic sectors, reflecting an overall return rate of 35%. According to these stakeholders, Climate Change is the most significant impact category, followed by Ozone Layer Depletion, both highly influenced by the high potential to cause damages to human health and due to its global effect. Resource depletion and Human toxicity were weighted with 0.15 and 0.13 respectively, whereas Acidification and Land Use received similar scores with approximately 0.105 each category. The lower score for Eutrophication and Photochemical Ozone Formation was mainly due to the fact that they were classiefied as local or regional impacts, with high possibility of treatment and low duration. The comparison of this set of weights with other publishing at midpoint level (and development with the application of a panel of specialists, such as BEES and NOGEPA), indicate that Brazilian weighting is similar in term of magnitude and ranking of impact categories what brings robustness to our findings.

Regarding participants, even though the relative restrictive quantitative group of stakeholders (the representativeness will never be fully comprehended), qualitatively, this panel covered all relevant institutions from Academy that research for LCA, almost the totality of Governmental institutions that play a role in environmental decision-making in Brazil and several economic sectors (what configures to results, different market perspectives). Thus, this set of weights for impact categories may be considered as from Brazilian reality and may be considered as an element of comparison with other weighting sets worldwide. Noteworthy mention that results are relative to criteria and impact categories chosen. Nevertheless this condition (that is inherent to any weighting set) it is possible to update values after a period (e.g. from 5 to 5 years) or reformulate significances expanding the panel to include a broader group of participants to already considered stakeholders groups, or even others stakeholders, such as ‘Society’. Related to stakeholders’ balance of preferences (the aggregated principle of PROMETHEE), even though results have demonstrated visually similarities between them, variance analyses (ANOVA – Tukey HSD test) have demonstrated that different stakeholders can have statically different preferences, what reinforce the necessity of inclusion of all relevant decision-maker in this process, including the aforementioned ‘Society’, and strengthens the application of panels into weighting process. The discussion on how to consider the society (as a stakeholder group) is complex and far from unanimity from MCDA community. The struggle is centralized in this specific question on "How to consider such heterogeneous group, with different levels of comprehension about environmental theme, but still keep the process straightforward and correct enough regarding value judgment?". Perhaps one way to begin to answer this question is segment this group into different levels of environmental knowledge and compares the value judgment of each part to infer the size of convergence or divergence.

This proposal, as every other attempt to weight impacts carry within certain degree of subjectivity due to choices over the process. For that and in absolute terms, there is no ideal weighting methodology. However, the use of MCDA techniques to aid Decision-makers in the task of attribute significance to different impact categories was considered easy to implement regarding complexity and load of information, and allow considering value judgment of decision makers. Ultimately, the authors consider that the weighting set have the condition to expand interpretation possibilities for Brazilian LCA community, even though standards do not recommend the weighting step in LCA.

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Capítulo IV. Discussão geral e conclusão

Diante do exposto na revisão bibliográfica e apresentado nos elementos introdutório dos capítulos II e III, pode-se afirmar que a ponderação é um elemento fundamental para auxiliar a interpretação de resultados obtidos em estudos de Avaliação do Ciclo de Vida e suportar a comunicação destes valores de forma mais clara e atrativa para diferentes *stakeholders*. Isso se deve à alta carga de complexidade que acompanha os resultados da caracterização de uma ACV, frequentemente carregando *trade offs* entre os indicadores. Adicionalmente, o envolvimento de diferentes *stakeholders* torna o processo de decisão ainda mais complexo.

De forma a ilustrar o modo como a aplicação do conjunto de pesos obtidos nesta tese gera a simplificação da decisão final, uma comparação de diferentes matrizes energéticas de diferentes países foi realizada. A razão por esta escolha foi pautada basicamente pela equalidade dos *datasets* em termos de escopo e pela representatividade em termos de *trade-off* dos resultados caracterizados em nível *midpoint*.

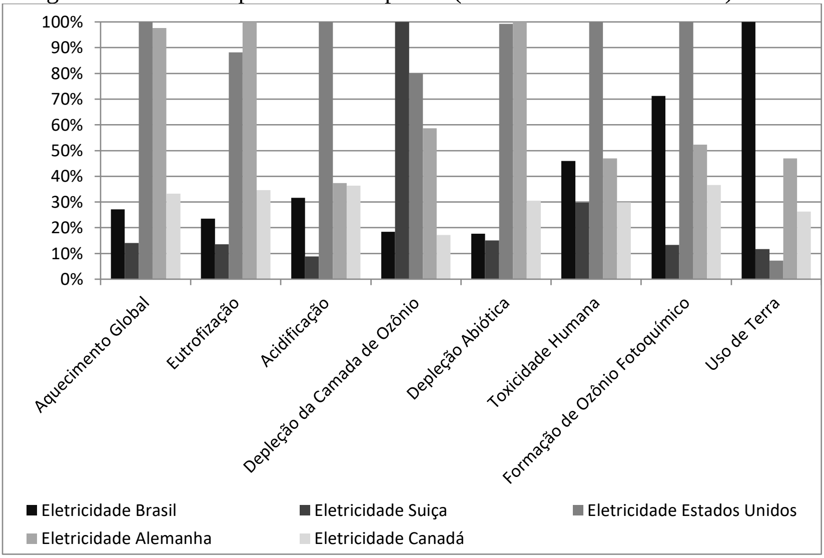
Neste exemplo foram consideradas os seguintes *datasets* para comparação[10]:

- Electricity, medium voltage {BR} | Market for | Alloc Def, U;
- Electricity, medium voltage {CH} | Market for | Alloc Def, U;
- Electricity, medium voltage {US} | Market group for | Alloc Def, U;
- Electricity, medium voltage {DE} | Market for | Alloc Def, U;
- Electricity, medium voltage {CA} | Market group for | Alloc Def, U;

A unidade funcional estabelecida foi a produção e distribuição de 100 kW.h e o método de AICV foi o CML 2000 Baseline (GUINÉE et al., 2002) (pela relação de categorias de impacto com aquelas ponderadas nesta tese). Os resultados desta ACV, normalizados internamente (i.e., relativizados para a maior emissão de cada categoria em %), estão apresentados na Fig. IV-1 enquanto que os valores da AICV estão dispostos na Tab. IV-1.

[10] Onde BR – Brasil, CH – Suiça, US – Estados Unidos, DE – Alemanha e CA – Canadá.

Fig. IV-1. Resultados da avaliação comparativa do ciclo de vida da matriz energética no mercado por diferentes países (normalizada internamente).



Tab. IV-1. Resultado da AICV comparativa por indicador de categoria.

AIVC CML BASELINE						
Categorias	Unidade	BR	CH	US	DE	CA
Aq. Global	kg CO_2 eq	17,45	9,01	64,15	62,62	21,32
Eutrofização	kg PO_4 eq	8,44E-03	4,86E-03	3,17E-02	3,59E-02	1,24E-02
Acidificação	kg SO2 eq	0,08	0,02	0,24	0,09	0,09
Dep. C.de Ozônio	kg CFC-11 eq	1,16E-06	6,28E-06	5,03E-06	3,68E-06	1,08E-06
Dep. Abiótica	kg Sb eq	0,08	0,07	0,47	0,48	0,15
Tox. Humana	kg 1,4-DB eq	4,86	3,14	10,56	4,96	3,15
For.de Ozônio Fot.	kg C_2H_4 eq	7,45E-03	1,39E-03	1,05E-02	5,46E-03	3,82E-03
Uso de Terra	m^2.a	15,16	1,78	1,09	7,12	3,98

Avaliando cada alternativa deste gráfico é possível notar claramente uma condição de *trade off* entre as categorias de impacto analisadas. Por exemplo, ao buscar a redução de emissão de gases de efeito estufa, um tomador de decisão deveria optar pela matriz alemã em detrimento à matriz americana. No entanto, se este mesmo decisor entender que seu ciclo de vida deve emitir menos nutrientes que causam a eutrofização, a opção deve ser a matriz energética americana ao invés da alemã. A escolha se torna ainda mais complexa a medida que o tomador de decisão começa a incluir as demais categorias de impacto na sua avaliação. Se sua preocupação está relacionada com a diminuição da camada de ozônio, a matriz mais impactante é a Suíça, enquanto que se o problema é diminuir a demanda por ocupação de terra, a matriz energética brasileira representa o pior desempenho em termos de m².ano.

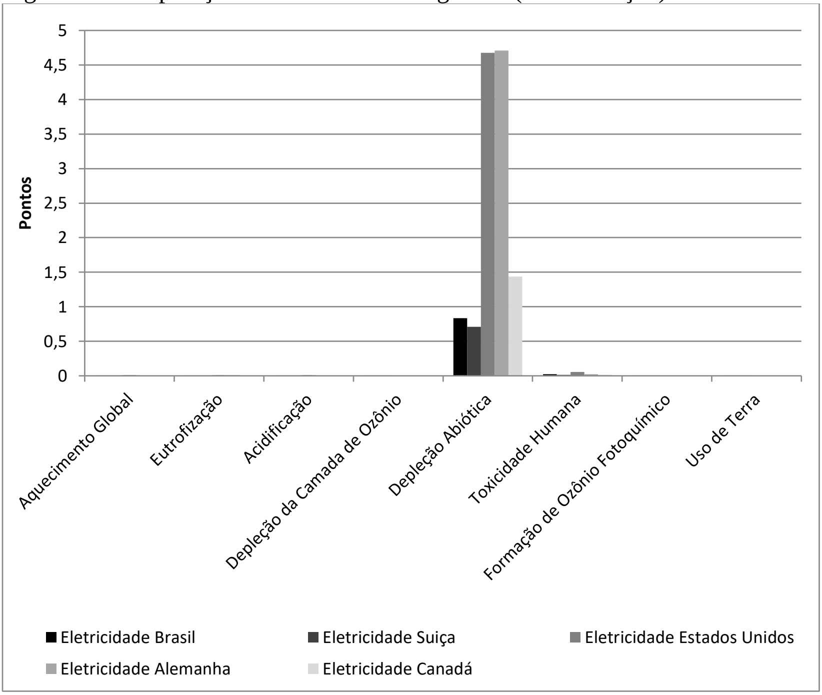
Esta é uma condição de *trade off*, que pode ter a interpretação de resultados facilitada pelas etapas opcionais da ACV. Deste modo, foi aplicada a normalização como elemento obrigatório para permitir a posterior ponderação pelos fatores calculados nesta tese. A normalização 'mista' considerou os fatores publicados por Silva (2010) para Eutrofização e Acidificação relativos à realidade do estado de São Paulo com base em emissões por habitante de 2008/2009, Benini et al. (2014) para os fatores associados ao Aquecimento Global, Depleção Abiótica, Depleção da Camada de Oxônio e Smog referentes à realidade europeia por habitante para o ano de 2010 e Sleeswijk et al. (2008) para as últimas categorias, Toxicidade humana e Uso de Terra, referente às emissões totais no ano de 2000. Com relação a estas últimas duas categorias, a correção para a população mundial no ano de 2000 foi efetuada com base em UN (2000) de forma a equalizar as unidades para um habitante no ano. Outras correções foram realizadas no tocante a uniformização das unidades entre métodos de AICV (e.g., conversão de kg P eq. para kg PO_4 eq.) com base em Owsianiak et al. (2014). O resultado desta hibridização de fatores é apresentado na Tab. IV-2, e, a despeito da inconsistência entre as coberturas de Silva (2010), Benini et al. (2014) e Sleeswijk et al. (2008), os fatores estão equalizados.

O resultado da AICV (Tab. IV-1) normalizado conforme os fatores da normalização mista (Tab. IV-2) estão dispostos no gráfico da Fig. IV-2. Neste gráfico os valores estão relativizados a uma mesma unidade, no caso pontos ou ecopontos (pt), e representam o perfil comum das matrizaes de energia, com alto valor associado ao consumo de recursos abióticos (principalmente das matrizes com fatias significativas de carvão, óleo ou energia nuclear em sua composição.

Tab. IV-2. Fatores de normalização.

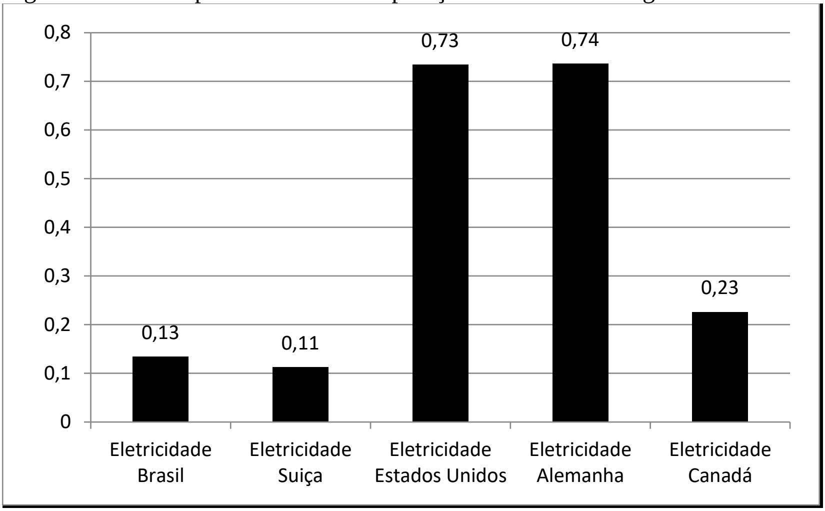
Normalização (mista)		
Categorias de impacto	Fator	unidade
Aquecimento Global	9.220,00	kg CO_2 eq/hab
Eutrofização	3,33	kg de PO_4 eq. /hab
Acidificação	32,00	kg de SO_2 eq. /hab
Depleção Da Camada De Ozonio	0,022	kg CFC-11 eq/hab
Depleção De Recursos	0,101	Kg Sb eq/hab
Toxicidade Humana	198,18	kg 1,4-DCB eq./hab
Smog	52,62	kg C_2H_4 eq./hab
Uso De Terra	3.113,93	m².year /hab.

Fig. IV-2. Comparação entre matrizes energéticas (normalização).



Este predomínio faz com que os valores das demais categorias não sejam visíveis na Fig. IV-2 embora eles estejam presentes no gráfico. Para o aquecimento global, por exemplo, os valores normalizados se posicionam na grandeza de 10E-3. De qualquer forma, a decisão neste nível ainda não é facilitada uma vez que a comparação ainda ocorre entre muti-indicadores. Ao aplicarmos os fatores de ponderação para cada categoria de impacto conforme apresentado no capítulo III, mais precisamente na Tab. III-5, e realizando a soma dos indicadores ponderados, esta comparação se torna simples. O resultado ponderado da comparação é apresentado na Fig. IV-3, posicionando a Eletricidade da matriz Alemã ligeiramente acima da matriz americana (0,74 pontos contra 0,73 pontos respectivamente). Neste resultado a matriz suíça é a menos impactante, seguida pela brasileira e pela canadense.

Fig. IV-3. Valores ponderados na comparação de matrizes energéticas.



Verificando os gráficos anteriores, a comparação ponderada fica isenta, visualmente, de *trade offs*, o que simplifica e facilita a tomada de decisão e potencializa a comunicação dos resultados. Quando os resultados se mostrarem muito díspares em termos de decisão final, esta condição deve ser analisada criticamente de modo a condicionar o tomador de decisão desta situação.

Além disso, como discutido no Capítulo II do presente documento, foi demonstrado que a aplicação de modelos de decisão multicriteriosos vêm imprimindo cientificidade ao julgamento pessoal. O uso da MCDA na ACV possui mútuo benefício, e como consequência, o campo de publicações nesta temática apresentou um crescimento importante nos últimos anos. Métodos de decisão multicritério podem ser aplicados para auxiliar à decisão em todas as etapas da ACV, desde definições controversas da etapa de Definição e Escopo, até a decisão final com relação aos resultados de uma ACV. Esta última situação inclusive é onde se encontram a mior parte dos estudos publicados. Este comportamento é claramente observado no mapeamento apresentado no capítulo II, enquanto que ainda existem poucos estudos com a aplicação da MCDA na ponderação de categorias de impacto na ACV, sendo que nenhum deles considera o julgamento dos *stakeholders* brasileiros.

Amparado pelas perspectivas descritas nos últimos dois parágrafos e justificado pela lacuna identificada no Capítulo II, no Capítulo III foram apresentados fatores de ponderação para o Brasil, desenvolvidos com base no julgamento de três dos principais grupos de tomadores de decisão nacional, estruturado na metodologia da análise de decisão multicritério. Tal estrutura considerou duas abordagens de MCDA que se demonstraram complementares: o AHP para atribuir importância aos critérios que orientam a comparação das categorias de impacto e o PROMETHEE II para agregar o julgamento dos *stakeholders* segundo um modelo não compensatório de balanço de preferências. Justamente por conta desta configuração, além do painel de *stakeholders*, o modelo contou com um painel adicional de especialistas em ACV para pesar os critérios.

Os painelistas da ACV atribuíram maior importância para os critérios associados às consequências ambientais, como saúde humana e danos ao ecossistema, possivelmente devido aos painelistas realizarem uma associação mais fácil com o dano final se comparado com critérios associados ao nível de consequência ambiental, como por exemplo, escala ou duração (SOARES, TOFFOLETTO E DESCHÊNES, 2006). A dispersão das opiniões dos especialistas em ACV indicou certa variação de julgamento entre os critérios, mas que, no entanto, seguiu um mesmo padrão geral (reflexo também no cálculo de consistência do AHP).

Com relação ao painel de categorias de impacto, como esperado, os *stakeholders* atribuíram maior significância para as categorias consideradas globais (Mudanças Climáticas, Depleção Abiótica; Depleção da Camada de Ozônio), justamente pelo alcance de seus efeitos. Os critérios pesados anteriormente influenciaram principalmente na agregação da categoria de impacto de Toxicidade humana, cujo posicionamento dos participantes para o critério de efeitos à saúde humana foi o mais alto. Consequentemente, categorias reversíveis e locais, com pouco efeito sobre a saúde humana, como a Eutrofização ou a Acidificação obteram os menores pesos. Este resultado está de acordo com todos os outros conjuntos de pesos existentes na literatura de ACV, comparação que confirmou a condição obtida pelos painelistas brasileiros em termos de grandeza e até valores para os modelos propostos por Soares, Toffoletto e Deschenes (2006), Bengston et al. (2010) e o SAB de Lippiatt (2007). Por outro lado, poderações publicadas por Huppes et al (2007) e o BEES de Lippiatt (2007) demonstraram maior amplitude entre as categorias (i.e., maior predomínio de uma categoria em específico sobre as demais), resultando em um perfil de pesos diferentes dos especialistas brasileiros. Neste sentido, estudos de ACV que considerem a etapa de ponderação em seu escopo e pretendem representar as condições do Brasil devem evitar tais conjuntos de peso.

Os *stakeholders* brasileiros demonstraram uma boa convergência de julgamentos, de forma que, estatisticamente pela ANOVA, 7 de 8 categorias de impacto obtiverem os mesmos resultados independente do grupo de especialistas envolvidos. Exceção a esta regra foi a categoria de Depleção Abiótica. Para esta categoria o grupo representativo da Indústria apresentou um balanço de preferencias estatisticamente diferente da Academia. O motivo para que a Indústria tenha atribuído menor impoprtância a esta categoria está associado a menores valores indicados para critérios como reversibilidade e duração. Curiosamente a indústria é o grupo com uma ligação mais estreita para a geração de impactos sob esta categoria, uma vez que é a grande consumidora de recursos para seus sistemas produtivos. De qualquer forma, esta única variação demonstra que nenhum grupo de tomadores de decisão pode ser desconsiderado se a intenção é alcançar a representatividade de um grupo mais amplo, como um país. Condição que nos direciona para a problemática da inclusão do quarto principal grupo de *stakeholders*, representado pela parte da sociedade 'não organizada' (elemento discutido na análise crítica item IV.1.2).

Como os elementos que formam um painel influenciam nos resultados, este trabalho considerou aspectos da análise bibliométrica como apoio à definição das categorias de impacto e dos *stakeholders*. No entanto é possível replicar o modelo para qualquer grupo de tomadores de decisão e para quantificar a relevância de quaisquer indicadores (sob os mesmos critérios estabelecidos). Esta replicação é escorada pela aplicação desta metodologia híbrida ter sido considerada de fácil assimilação pelos painelistas, obtendo importante taxa de retorno (aproximadamente 40%), totalizando 76 respondentes. Desta forma é possível criar fatores de ponderação para uma indústria em específico ou um órgão do governo, obtendo maior precisão na decisão segundo as convicções dos interessados.

Os resultados serão apresentados resumidamente de acordo com as perguntas de pesquisa definidas na presente tese em atendimento aos objetivos propostos.

IV.1 RESPOSTAS ÀS PERGUNTAS DE PESQUISA

Com relação à pergunta de pesquisa número (1) **"O conjunto de categorias de impacto ponderadas com base em consulta aos stakeholders brasileiros representará o julgamento dos tomadores de decisão? "** Pode-se responder de forma <u>afirmativa</u> que o conjunto de pesos agregados conforme a convergência de julgamentos dos *stakeholders* representa a tomada de decisão deste grupo. Desta forma a primeira hipótese, de que este julgamento é representativo do grupo consultado, está confirmada. Em termos de cobertura de *stakeholders*, este painel atende a grande maioria das instituições de pesquisa e governamentais levantadas pela bibliometria dos estudos nacionais, além de conter representantes da maioria as esferas governamentais na promoção da sustentabilidade e controle de impactos ambientais. A indústria representa o grupo de mais difícil consideração quanto a representatividade (dado que muitas companhias não revelam se desenvolvem projetos de ACV). O estudo cobriu setores econômicos de importância nacional (agropecuário, petroquímico, mineração, metais e fundição, energia, logística, papel e celulose, eletrodomésticos, motores, motobombas, têxtil, aviação, etc.).

Desta forma, considera-se que o conjunto de pesos encontrados é qualitativamente (e quantitativamente) representativo dos grupos de stakeholders consultados, fato que o torna uma alternativa importante para auxílio da interpretação da ACV no Brasil, e o posiciona como elemento de complementação da discussão sobre ponderações em nível internacional.

Para a segunda pergunta de pesquisa (2) **"O grupo de stakeholders influenciará de maneira significativa no julgamento de pesos das categorias de impacto? "** A resposta é sim, demonstrado pela ANOVA, onde a variação estatística do balanço de preferências do grupo de *stakeholders* formado pela Indústria em comparação com o julgamento do grupo formado por representantes da academia para a categoria de impacto de Depleção Abiótica. Desta forma a hipótese (2) é confirmada: cada grupo de stakeholders possui um julgamento que pode ser diferente do outro grupo.

Por fim, a pergunta número (3) **"Comparações baseadas no resultado da ponderação proposta, e agregados em um SS, simplificam a tomada de decisão?** É respondido pelo exemplo ilustrativo desenvolvido no item Capítulo IV, de forma que a resposta a esta pergunta é sim. A indicação do melhor sistema de produto é facilitada ao converter diversos indicadores em um único valor. No entanto, faz-se uma ressalva à esta resposta. O modelo proposto facilita a tomada de decisão, mas a interpretação idealmente deve ser sempre acompanhada dos resultados caracterizados.

IV.1.1 ATENDIMENTO AOS OBJETIVOS PROPOSTOS

O objetivo central desta tese, definido como "estabelecer pesos para as categorias de impacto ambiental em nível *midpoint* para o Brasil" foi alcançado através do painel de especialistas estruturado por meio da abordagem de MCDA. Com relação ao atendimento aos objetivos específicos:

(1) Mapear os *stakeholders* nacionais do governo, indústria e da academia relacionados com o desenvolvimento da ACV;

Objetivo essencial que embasou a definição de elementos estruturais para a MCDA, alcançado pela bibliometria apresentada no APÊNDICE B - A Bibliometric Overview of Brazilian LCA Research.

(2) Elicitar pesos para os critérios de comparação segundo especialistas em ACV;

Objetivo estabelecido para preencher a condição do PROMETHEE II, foi alcançado com apoio do AHP e aplicado na forma de painel à rede de pesquisadores de um gupo de pesquisa em ACV. Seu resultado é apresentado no Capítulo III, especificamente dentro do item III.5.1. LCA SPECIALISTS AND CRITERIA.

(3) Calcular o balanço de preferências ponderadas dos *stakeholders* brasileiros para as categorias de impacto de acordo com cada critério estabelecido em no objetivo específico (2);

Elemento central desta tese, os resultados foram alcançados pela implementação de uma abordagem mista de MCDA e são apresentados e discutidos no artigo "Weighting Midpoint Impact Categories in Life Cycle Assessment with AHP-PROMETHEE II" do Capítulo III, especificamente abordado nos itens III.5.2 e III.5.3.

(4) Avaliar as diferenças estatísticas no julgamento dos diferentes grupos de tomadores de decisão.

Objetivo traçado para investigar a necessidade da inclusão de diferentes grupos de *stakeholders* no processo de ponderação de categorias de impacto, foi atingido por meio da ANOVA e é apresentado com maior detalhe no decorrer do item III.5.3. dentro do Capítulo III.

IV.1.2 ANÁLISE CRÍTICA

Embora os objetivos propostos tenham sido atendidos, podem ser identificadas algumas limitações da presente tese, que devem ser entendidas como possibilidade de estudos futuros e análises complementares:

- A representatividade do painel, embora qualitativamente reflita uma cobertura ampla nas três esferas de *stakeholders*, quantitativamente esta representatividade não pode ser considerada completa (ausência da sociedade 'não organizada'). Esta condição, de fato, é inerente aos modelos de obtenção de significâncias existentes no campo da ACV, sendo que nenhum outro exercício já publicado pode ser considerado completamente representativo. Mesmo assim, os resultados alcançados nesta tese podem ser encarados como para a condição brasileira;
- A falta da inclusão do grupo de decisores formados pela sociedade 'não organizada' é uma lacuna a ser preenchida nesta tese. Partindo da premissa que o conjunto de decisores deve considerar todos os interessados e/ou atingidos pela decisão, representantes da sociedade 'não organizada' devem ser incluídos. No entanto, notadamente esta inclusão não é uma tarefa simples e quase nenhum modelo publicado a considera. Esta inclusão deve ser delicadamente avaliada e testada antes de utilizar seus resultados para garantir a consistência dos pesos. Neste caso em específico é mais importante manter a qualidade e integridade dos resultados do que aumentar a representatividade do painel;
- Os resultados deste painel são influenciados pela escolha dos critérios e das categorias de impacto, e, portanto, devem ser sempre associados aos valores elicitados;
- Para garantir a aplicabilidade do modelo, importantes categorias de impacto não foram incluídas no questionário (e.g., Demanda Acumulada de Energia Elétrica e Ecotoxicidade). No entanto, mantendo os critérios ponderados, é possível expandir (ou diminuir) o número de categorias e replicar o questionário conforme necessário (inclusive remodelando os grupos de *stakeholders*). Um exemplo seria utilizar o modelo para criar uma ponderação específica em uma dada indústria conforme o interesse de seus próprios *stakeholders*.

IV.2 CONCLUSÃO

Conclui-se que o campo da tomada de decisão ambiental com base na Avaliação do Ciclo de Vida é beneficiado pelas abordagens de Análise de Decisão Multicritério. Além de possibilitar a desestruturação de um problema complexo e posteriormente a sua estruturação de forma mais direcionada (portanto, mais fácil de compreender), a MCDA imprime a possibilidade de se abordar de forma científica, julgamentos subjetivos influenciados pela vivência de cada *stakeholder*. De forma que atribuir importância para impactos ambientais, que variam em forma, tipo, efeitos, escalas, durações, entre tantos outros critérios, podem ser facilmente avaliados, sem que o painelista perceba a complexidade de suas respostas. Como resultado, um conjunto de pesos a ser aplicado na etapa opcional de ponderação na ACV, é um agente extremamente facilitador da interpretação e da comunicação dos resultados, principalmente porque resolve a condição de *trade off* entre as categorias de impacto. Logo, simplifica a tomada de decisão pelos múltiplos *stakeholders* que devem participar deste processo.

Neste ínterim, todos os grupos de tomadores de decisão ou afetados pela decisão devem participar do processo. Esta conclusão é pautada pela possibilidade de diferentes grupos possuírem diferentes julgamentos sobre uma determinada questão principalmente dado que a ciência da decisão, quando baseada em painel, parte do princípio da covergência de opiniões. As variações de dispersão de julgamentos nos critérios e nas categorias de impacto podem influenciar na significância final agregada, como demonstrado pela ANOVA. Esta mesma condição permite o questionamento de que cada país, região, indústria ou organização deve ter sua própria matriz de julgamento de importâncias ou significâncias ambientais. Somente desta forma a decisão poderá refletir a vontade dos envolvidos.

Portanto e por fim, o conjunto de pesos calculados nesta tese é representativo e deve ser utilizado para estudos no Brasil, sobretudo no âmbito da Avaliação do Ciclo de Vida em complemento à resultados caracterizados.

Perspectivas de trabalhos futuros

Algumas lacunas são identificadas para uma melhor representatividade dos resultados da proposta de MCDA. Em especial desenvolver uma metodologia para que facilite a inclusão do grupo de stakeholders formado pela sociedade 'não organizada' no painel.

Atividade complexa, uma vez que envolve a necessidade de alcançar vários níveis da sociedade, mas que ainda assim, garanta o nível de conhecimento mínimo dos entrevistados com relação à temática da 'avaliação de impactos'. Uma possibilidade para permitir este acréscimo e mesmo assim manter a consistência dos resultados seria a participação de associações ativas na temática ambiental/sustentabilidade ou associações de moradores de determinada localidade e que estariam engajadas na tarefa de responder ao questionário (possivelmente em um workshop). Um complemento a esta inclusão seria comparar o resultado elicitado deste grupo com resultados do grupo formado pela 'sociedade leiga' de forma a verificar se a opinião da grande massa possui variação para com grupos mais direcionados.

Outras sugestões de trabalhos futuros são indicadas a seguir:

- Criar fatores de normalização para o Brasil de forma a completar as etapas opcionais de acordo com a realidade nacional;
- Variar a experiência para geografias/regiões brasileiras, biomas ou condições de contorno rural e urbana, e verificar se estas especificidades surtem efeito no julgamento dos especialistas;
- Replicar esta experiência a cada 5 anos para mantê-la atualizada e verificar a influência de possíveis novos marcadores somáticos dos especialistas;
- Considerar a possibilidade de avaliação por inferência estatística (como realizada por pesquisas de eleição ou de satisfação pública) como forma de calcular a representatividade amostral (quantitativa) do grupo de *stakeholders;*
- Criar fatores que permitam calcular pesos para as mesmas categorias avaliadas nesta tese por meio de outros métodos de ponderação (DpA ou DpP) e verificar a variação nas significâncias entre as diferentes abordagens.

IV.3 REFERÊNCIAS

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APÊNDICE A - References considered in the publishing "How Multi-Criteria Decision Analysis (MCDA) is aiding Life Cycle Assessment (LCA) in results interpretation"

Tab. IV-3. Analyzed publishing for the paper of Chapter II (chronologically and alphabetically ordered), publication vehicles, authors, publishing year, kind of research, its general context within LCA methodology, LCA and MCDA method applied, chosen criteria, etc.

N	Title	Publication	Authors	Year	Kind of paper	LCIA method	Criteria	MCDA method	Economical sector	Scenarios	Motivation	Results
1	Environmental Impacts of Fat Blends A Methodological Study Combining Life Cycle Analysis, Multiple Criteria Decision Making and Linear Programming	Environ Resource Econ	Bloemhof-Ruwaard et al	1995	Proposition and case study	Not mentioned	Environmental	AHP	Fuels	Different blends (fat and oils)	How use environmental information in guiding product development	Approach, ranking, best choice
2	Visual Data Analysis and Decision Support Methods for Non-Deterministic LCA	Int J Life Cycle Assess	Le Tenó	1999	Creation and case study	Not mentioned	Eco-efficiency	PROMETHEE	Fuels	Different sources	LCA results can be difficult to communicate to non-specialists	Method, best choice
3	An interval version of PROMETHEE for the comparison of building products' design with ill-defined data on environmental quality	Eur J Oper Res	Le Tenó and Mareschal	1998	Creation and case study	Not mentioned	Environmental	PROMETHEE I	Building	Designs for the fabrication of 100 m^2 plaster wallboards.	PROMETHEE is not able to handle interval performances	Method, ranking
4	Modelling the environmental impact of an aluminium pressure die casting plant and options for control	Environ Modell Softw	Neto et al	1998	Creation and case study	CML 2001	Eco-efficiency	Panel based and DtT	Metal Industry	Aluminium die casting plant supplying car manufacturers with aluminium	There is a need for decision-support systems, to decide on environmental control options	Method and example
5	Use of external cost assessment and multi-criteria decision analysis for comparative evaluation of options for electricity supply	Intconf on prob. safety assess. and management	Hirschberg et al	2000	Application	Published LCA results	Sustainability	WSA	Energy	Different Energy sources	MCA allows a more explicit consideration of the social dimension, which is highly important for the DM process	Ranking
6	Environmental analyses of land transportation systems in The Netherlands	Transport Res	Bouwman and Moll	2002	Application	Not mentioned	Technical eco-efficiency	WSA	Transports	Transport modes	Environmental analyses of impact from the cradle to the grave are rare	Best choice
7	Decision Analysis Frameworks for Life-Cycle Impact Assessment	J Ind Ecol	Seppälä et al	2002	Review	-	-	-	-	-	Possibilities of MADA methods in LCIA are poorly elaborated in LCA	State of the art

N	Title	Publication	Authors	Year	Kind of paper	LCIA method	Criteria	MCDA method	Economical sector	Scenarios	Motivation	Results
8	Aid for Aggregating the Impacts in Life Cycle Assessment	Int J Life Cycle Assess	Benoit and Rousseaux	2003	Review	-	-	-	-	-	Choose the most suitable MCA methods	Choice protocol
9	Sustainability of Electricity Supply Technologies under German Conditions: A Comparative Evaluation	PSI Report	Hirschberg et al	2004	Proposition and case study	Not mentioned	Sustainability	WSA, multiple-attribute function	Energy	Energy sources	Acknowledgement of the role of value judgments in DM	Ranking
10	The varied contexts of environmental decision problems and their implications for decision support	Environ Sci Policy	French and Geldermann	2005	Review	-	-	-	-	-	Explore appropriateness of the methods in relation to the different contexts	State of the art, recommendation
11	Multi-criteria Analysis for Technique Assessment Case Study from Industrial Coating	J Ind Ecol	Geldermann and Rentz	2005	Application	Not mentioned	Eco-efficiency	PROMETHEE, MAUT and AHP	Surface coating	Scenarios for coating of PVC parts (automobile industry)	Support for investment decisions on installations is rare	Ranking, best choice
12	Researching whole Life Value Methodologies for Construction	Annual ARCOM Conference	Mootanah	2005	Review	-	-	-	Building	-	Processes, methods, tools, techniques have been developed	State of the art
13	Sustainable development indicators for wastewater systems – researchers and indicator users in a co-operative case study	Resources, Conservation and Recycling	Palme et al	2005	Application	Not mentioned	Sustainability	Not mentioned	Wastewater treatment	Sludge handling options	Sustainable assessment of options	Best choice
14	Comparative environmental assessment of current and future electricity supply technologies for Switzerland	PSI Report	Bauer et al	2006	Application	Ecoindicator 99	Environmental	Not mentioned	Energy	Energy sources	Major decisions need be taken	Ranking
15	Support for Sustainable Development Policy Decisions: A Case Study from Highway Maintenance	Int J Life Cycle Assess	Elghali et al	2006	Application	CML2001	Sustainability	MAUT	Building	Road maintenance processes	Demonstrate that SD principles are addressed in service provision	Recommendations
16	Multicriteria Decision Analysis: A Comprehensive Decision Approach for Management of Contaminated Sediments	Risk Anal	Linkov et al	2006	Review and case study	Not mentioned	Sustainability	PROMETHEE	Waste Management	Reuse alternatives	Approaches do not offer a comprehensive way for incorporating the varied types of info., multi-stakeholder and public views	Recommendations, Ranking
17	Development of weighting factors in the context of LCIA	J Clean Prod	Soares, Toffoletto and Deschênes	2006	Creation	Not mentioned	Technical environmental	Panel-based	N/A	N/A	Weighting factors must take into account country specificities and policies	Weighting Method
18	A critical systems approach to decision support for process engineering	Comput Chem Eng	Basson and Petrie	2007	Application	Ecoindicator 99	Sustainability	ELECTRE TRI	Energy	Technologies for the recommissioning of an out-of-service coal-based power station	Stakeholders involvement in interactive decision processes, consideration of uncertainties	Ranking

N	Title	Publication	Authors	Year	Kind of paper	LCIA method	Criteria	MCDA method	Economical sector	Scenarios	Motivation	Results
19	A comparison of the technical sustainability of in situ stabilisation/ solidification with disposal to landfill	J Hazard Mater	Harbottle et al	2007	Creation and case study	Not mentioned	Environmental, technical	Postle et al. (1999)	Waste management	Remediation techniques	Identify the relevant criteria and address potential improvements	Method, best choice
20	Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators	J Clean Prod	Hermann, Kroeze and Jawjit	2007	Creation and case study	Not mentioned	Environmental	AHP	Paper and celulosis	Production of eucalyptus pulp	Tools are needed to assess the environmental aspects (trade-offs)	Method, best choice
21	Striving for a more sustainable Belgian dwelling stock	WIT Transactions on Ecology and Environment	Allacker et al	2008	Proposition and case study	Ecoindicator 99	Eco-efficiency	AHP	Building	Different building scenarios	A more integrated approach is required	Best choice
22	Environmental assessment of current and future Swiss electricity supply options	Int. Conf. on the Physics of React	Bauer et al	2008	Application	Ecoindicator 99	Environmental	Not mentioned	Energy	Energy sources	Decisions concerning future electricity supply in Switzerland	Ranking
23	Integrating fuzzy multicriteria analysis and uncertainty evaluation in life cycle assessment	Environ Modell Softw	Benetto, Dujet and Rousseaux	2008	Creation and case study	CML 2001	Environmental	NAIADE	Energy	Coal based electricity production	Interpretation of LCA is heterogeneous and uncertain	Modified NAIADE, ranking, best choice
24	Environmental Assessment Framework for Policy Applications: Life Cycle Assessment, External Costs and Multicriteria Analysis	J Environ Plann Man	Rabl and Holland	2008	Review	-	-	-	-	-	Confuse relation between external costs and their use for environ. policy	Framework
25	Application of Operational Research Methodology for Climate Change Mitigation Policies	EURO Mini Conference	Streimikiene and Alėbaitė	2008	Review	-	-	-	-	-	CC is a complex societal phenomenon, mitigation involve many actors	State of the art
26	Development of an Optimisation Approach for the Energy Efficient Buildings	Computing in Civil Engineering	Loh et al	2009	Creation and case study	Generic LCA	Sustainability	AHP	Building	Building materials	Difficulties to qual./quant. views of stakeholders and lack of exper. from DM	Framework, example
27	Sustainability of electricity supply technology portfolio	Annals of Nuclear Energy	Roth et al	2009	Proposition and case study	Not mentioned	Sustainability	WSA	Energy	Current and future energy technologies	A complete and transparent sustainability comparison	Ranking
28	Multi-attribute analysis for the eco-energetic assessment of the building life cycle	Technol Econ Dev Eco	Sobotka and Rolak	2009	Application	Not mentioned	Eco-efficiency	Baas and Kwakernaak (fuzzy assess)	Building	Residencial building variants	Demand for a tool to design/decide solutions for buildings	Best choice
29	The development and application of multi-criteria decision-making tool with consideration of uncertainty: The selection of a management strategy for the bio-degradable fraction in the municipal solid waste	Bioresource Technol	El Hanandeh and El-Zein	2010	Creation and case study	Not mentioned	Environmental	ELECTRE SS	Waste Management	Management strategy for the bio-degradable fraction in the municipal solid waste	The new technique is suitable for handling uncertainty resulting from multi-DMs	Ranking

N	Title	Publication	Authors	Year	Kind of paper	LCIA method	Criteria	MCDA method	Economical sector	Scenarios	Motivation	Results
30	Multicriteria analysis to evaluate the energetic reuse of riparian vegetation	Appl Energ	Recchia et al	2010	Application	Single issues (CF, ED)	Technical eco-efficiency	Not mentioned	Energy (biomass)	Operation, transport, storage conditions, utilization	Assess the possibilities to promote energy from biomass in Italy	Best choice
31	The REHMINE research project: the threefold value of São Domingos abandoned mine rehabilitation in southern Portugal	WIT Transactions on Ecology and Environment	Sardinha et al	2010	Creation	Not mentioned	Sustainability	AHP, MACBETH	Mining	-	Which socio-economic and environmental benefits are generated; stakeholders integration	Project proposition
32	Multiple Criteria Decision Making for environmental impacts optimization	Int. J of Business Perf and Supply Chain Model	Boufateh et al	2011	Application	CML2001	Environmental	PROMETHEE, ELECTRE	Textile	T-shirt fabrication	Analyse the results of LCA to help the different actors in the supply chain.	Best product, best MCDA method
33	Multiple Criteria Decision Making for environmental impacts optimization	Comput Ind Eng	Boufateh et al	2011	Application	CML 2001	Environmental	PROMETHEE I, PROMETHEE II, ELECTRE III	Textile	Different raw materials for T shirt supply chain	Dif. between criteria values of alternatives can't be easily compared	Ranking
34	Advancing Integrated Systems Modelling Framework for Life Cycle Sustainability Assessment	Sustainability	Halog and Manik	2011	Review	-	-	-	Biofuels	-	Integrated assessment crosses issues, multi-stakeholder inputs	State of the art
35	Coupling Multi-Criteria Decision Analysis, Life-Cycle Assessment, and Risk Assessment for Emerging Threats	Environ Sci Technol	Linkov and Seager	2011	General proposition	Generic LCA	Sustainability	-	-	-	Generate decision criteria, rank alternatives, deal with uncertainty and manage trade-offs	Framework
36	State-of-the-art sustainability analysis methodologies for efficient decision support in green production operations	Int J of Sustainable Engineering	Liu et al	2011	Review	-	-	-	-	-	New concepts, strategies, frameworks and systems have been developed to tackle SD issue	State of the art
37	Life-Cycle Analysis of a Sustainable Building, Aplying Multicriteria Decision Making Method	8th Int. Conf Env. Engineering	Medineckiene et al	2011	Application	Inventory level	Sustainability	COPRAS	Building	Flat dwelling house and loft type apartment	Find the best option in terms of sustainability	Best choice
38	Sustainable management of urban pollution: an integrated approach	Build Serv Eng Res T	Pettit et al	2011	Creation	Generic LCA	Sustainability	Simple ranking method, AHP, CP	Several	MSW, Electricity generation	Sust. Manag.requires a more integrated approach	Method
39	Integrating Life Cycle Assessment and Other Tools for Ex Ante Integrated Sustainability Assessment in the Minerals Industry	American J of Appl Sciences	Shields et al	2011	Review	-	-	-	-	-	Decision methods are no longer adequate to capture the complex issues and trade-offs	State of art, recommendations
40	"Describing the elephant": A framework for supporting sustainable development processes	Renew Sust Energ Rev	Sinclair	2011	Creation	-	-	Not mentioned	-	-	There is a need for a more integrated and systematic approach to DM	Framework
41	Enhanced Assessment of the Air Transportation System	Air transp Systems	Weiss et al	2011	Creation and case study	Generic in the framework	Sustainability	TOPSIS	Air Transpo. System	Low noise aircraft configurations	Allows the assessment of different simensions	Ranking

N	Title	Publication	Authors	Year	Kind of paper	LCIA method	Criteria	MCDA method	Economical sector	Scenarios	Motivation	Results
42	The potential role of biochar in combating climate change in Scotland: an analysis of feedstocks, life cycle assessment and spatial dimensions	J Environ Plann Man	Ahmed et al	2012	Application	Hammond et al. 2011	Technical eco-efficiency	GIS-MCDA	Agriculture	Different features in pyrolysis biochar system chain	Various factors are weighed up and traded-off against one another to show optimum locations	Best choice
43	Optimisation of the Environmental and Financial Cost of two Dwellings in Belgium	International J Sus Dev Plann	Allacker and De Troyer	2012	Creation and case study	Ecoindicator 99	Technical eco-efficiency	WSA	Building	Different dwellings	Integrated life cycle design could enhance the overall performance	Method, best choice
44	Towards life cycle sustainability assessment: drawing on the NEEDS project's total cost and multi-criteria decision analysis ranking methods	Int J Life Cycle Assess	Bachmann	2012	Review	-	-	-	-	-	Integration of social, economic and environmental criteria into decision making	Discussion SLCA using NEEDS principles
45	Assessment of stakeholders' preferences towards sustainable sanitation scenarios	Water Environ J	Bao et al	2012	Application	GWP	Technical eco-efficiency	AHP	Wastewater treatment	Wastewater treatment systems options	Decision is complex, with inherent trade-offs among sdimensions	Ranking
46	A multicriteria approach for measuring the sustainability of different poultry production systems	J Clean Prod	Castellini et al	2012	Application	Ecoindicator 99	Technical sustainability	ELECTRE I	Livestock	Poultry production	Few studies have compared the global perform. of this system	Ranking
47	Green Policy in a Manufacturing System	Com, Computing and Control Appl.	De Felice and Petrillo	2012	Application	Eco-indicator 99	Eco-efficiency	ANP	Metal mechanic	Energy sources	Need for assessment tools that go beyond the usual analysis	Best choice
48	Technical, economic and environmental analysis of a MSW kerbside separate collection system applied to small communities	Waste Manage	Feo and Malvano	2012	Application	Ecoindicator 99	Technical eco-efficiency	SimpleAdditive Weighting	Waste management	MSW kerbside separate collection systems (var. the size of the municipalities)	Separate collection systems are designed to only under technical and economic aspects	Best choice
49	Combining risk assessment, life cycle assessment, and multi-criteria decision analysis to estimate environmental aspects in environmental management system	Int J Life Cycle Assess	Liu et al	2012	Creation and case study	-	Eco-efficiency	-	Waste Management	SEM of waste tretatemt plant	When evaluating the severity of an envir. impact, most lack a sound theoretical basis and tend to be over-subjective	Method
50	Assessing environmental impacts of biomass production chains e application of life cycle assessment (LCA) and multi-criteria decision analysis (MCDA)	J Clean Prod	Myllyviita et al	2012	Application	ReCiPe	Environmental	SMART	Biomass for Biofuel and Pulp (paper)	Biomass production chains producing biodiesel and pulp	A method for weighting the importance of environmental impacts in LCA is lacking	Impact category definition, impact category weights, best scenario
51	Measuring and mitigating the environmental impact of earthworks and other geotechnical processes	Engineering Geology Special Publications	O'Riordan and Phear	2012	Review	-	-	-	Eartwork	-	There is an enormous variety in terms of plant, materials, cost, effectiveness and risk	State of the art

N	Title	Publication	Authors	Year	Kind of paper	LCIA method	Criteria	MCDA method	Economical sector	Scenarios	Motivation	Results
52	Use of Stochastic Multi-Criteria Decision Analysis to Support Sustainable Management of Contaminated Sediments	Environ Sci Technol	Sparrevik et al	2012	Application	ReCiPe	Sustainability	PROMETHEE II	Waste Management	Sediment management alternatives	Sustainable manag. of contaminated sediments requires decisions that consider TBL	Best Choice
53	Aggregating sustainability indicators: Beyond the weighted sum	J Environ Manage	Rowley et al	2012	General proposition	-	-	-	-	-	Ensure that MCDA is consistent with value/info	Guide
54	Strategic and Tactical Evaluation of Conflicting Environment and Business Goals in Green Supply Chains	Transactions on Systems, Man, and Cybernetics	Albuquerque et al	2013	Creation and case study	GWP	Environmental	Goal programming	Food industry	Variations on production line	Envir. indicators are often odds with business goals	Method, best Scenario
55	An integrated approach to assessing the environmental and health impacts of pollution in the urban environment: Methodology and a case study	Process Saf Environ	Azapagic et al	2013	Creation and case study	CML 2001	Environmental	-	Cities	Different industrial, domestic and transport sources	Integrated approaches to urban environmental manag. are recognised as necessary to improve legislative compliance	Method, best choice
56	Multi-criteria Analysis of Material Compositions of External Walls	Advanced MatResearch	Čuláková et al	2013	Application	Not mentioned	Technical-environmental	WSA, IPA, CDA and TOPSIS	Building	Material compositions of external walls	It is important to take into account embodied energy	Best choice
57	Multi-Criteria Analysis of Material Selection in order to Reduce Environmental Impacts	Chem Engineer Trans	Čuláková et al	2013	Application	Not mentioned	Technical-environmental	WSA, TOPSIS	Building	Material selection during the design stage of building	Material can affect the perform./sustainability of the building	Best choice
58	Economic and environmental evaluation via an integrated method based on LCA and MCDA	Procedia - Social and Behavioral Sciences 99	De Felice et al	2013	Proposition and case study	Ecoindicator 99	Sustainability	ANP	Industry (bearing)	Energy sources	Support managers in suggesting/selecting best solutions for eco./environ. improvement.	Approach, best choice
59	Review of combined approaches and multi-criteria analysis for corporate environmental evaluation	J Clean Prod	Herva and Roca	2013	Review	-	-	-	-	-	Ensure that relevant issues were not being disregarded	State of the art
60	Industrial Estate Retrofitting: Selection of sustainable strategies using MCA	CESB 13 Prague	Grillo et al	2013	Application	Not mentioned	Technical eco-efficiency	WSA	Building	Solutions for energy retrofitting in industry	Assess sustainability of design options	Best design proposition
61	Electronic waste management approaches: An overview	Waste Manag	Kiddee et al	2013	Review	-	-	-	Waste Management	-	E-waste consists of different materials	State of the art
62	Environmental Impact Assessment of Road Asphalt Pavements	Modern Applied Science	Moretti et al	2013	Proposition and case study	Not mentioned	Environmental	WSA	Building (road)	Asphalt concrete mixes	Calculate environmental impact of road construction is difficult	Approach, best choice
63	The Incorporation of Results of Non-aggregated Life Cycle Assessment in Decision Making: Evidence from a Case Study in Local Waste Management in France	Waste Biomass Valori	Schlierf et al	2013	Review and case study	-	-	-	Waste management	-	How to ensure ‘‘satisfactory’’ incorporation of LCA results in the DM process	Orientations on LCA and MCA for public policy

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64	A Decision Support Methodology for Integrated Urban Water Management in Remote Settlements	Water Resour Manage	Tjandraatmadja et al	2013	Application	Not mentioned	Technical sustainability	PROMETHEE	Wastewater treatment	Service and treatment technologies options	Multi-faceted dimensions increase the complexity; stakeholder participation	Best choice, Ranking
65	Microalgae-based biodiesel: A multicriteria analysis of the production process using realistic scenarios	Bioresource Technol	Torres et al	2013	Application	Ecoindicator 99	Eco-efficiency	Geometric mean of the ratios for pair-wise comp	Biofuels	Different harvesting and oil extraction and transesterificatio	Environmental and economic behavior depends on several variables	Ranking, best choice
66	A comparison of carbon accounting tools for arable crops in the United Kingdom	Environ Modell Softw	Whittaker et al	2013	Review and case study	-	-	Not mentioned	Agriculture	CF tools	Need has been identified for access to farm relevant GHG calculators	State of the art, comparison of CF tools
67	Development of Eco-Efficiency Evaluation with Multicriteria Analysis for Steel Production	Metal 2014	Burchart-Korol et al	2014	General proposition	Not mentioned	Technical sustainability	Generic in the framework	Steel	Steel production variants	MCA application are not sufficiently documented	Approach, Framework
68	A Multicriteria Decision Analysis Model and Risk Assessment Framework for Carbon Capture and Storage	Risk Anal	Choptiany and Pelot	2014	Creation and case study	Not mentioned	Technical sustainability	Based on Utility function	Energy	Amine scrubbing, pos combustion CO_2 capture technology on a coal power plant	Tech. complexity, range of envir/social/econ. impacts, stakeholders, long time spans	Method, example
69	An Interdisciplinary Perspective on Carbon Capture and Storage Assessment Methods	J Ind Ecol	Choptiany et al	2014	Review	-	-	-	-	-	Studies assessing CCS, focus mainly on detailed, single disciplines	Set of criteria and recommendations for CCS
70	A Combined Economic and Environmental Performance Framework for Railway Infrastructure Maintenance	Asset Management Conference 2014	Lee et al	2014	Application	CML 2001	Eco-efficiency	SMART	Transports	Different asset maintenance plans	Economic and environmental decision support model is lacking	Best choice
71	Sustainability assessment of electricity generation technologies using weighted multi-criteria decision analysis	Energ Policy	Maxim	2014	Application	Inventory level	Technical sustainability	SWING	Energy	Energy sources	Environ. degradation due to the expansion of energy demand requires a balanced approach	Ranking
72	Impact of normalisation, elicitation technique and background information on panel weighting results in life cycle assessment	Int J Life Cycle Assess	Myllyviita et al	2014	Review and case study	Not mentioned	-	SMART, AHP, SWING	Building	Different Houses	Different panel weighting methods, normalisation and background information infl. the result	Recommendations
73	Sustainable Use of Macro-Algae for Biogas Production in Latvian Conditions: a Preliminary Study through an Integrated MCA and LCA Approach	Environmental and Climate Technologies	Pastare et al	2014	Application	IMPACT 2002	Technical sustainability	AHP, TOPSIS	Energy	Algae-based biogas production scenarios	Application for Latvian conditions should be investigated more thoroughly	Ranking
74	Prioritizing Design for Environment Strategies Using a Stochastic Analytic Hierarchy Process	J Mech Design	Ramanujan et al	2014	Creation and case study	Ecoindicator 99	Technical-environmental	AHP	Mining	Various levels of DfE strategies	No individual expert can be representative of the ground truth	MCDA based tool

N	Title	Publication	Authors	Year	Kind of paper	LCIA method	Criteria	MCDA method	Economical sector	Scenarios	Motivation	Results
75	Sustainability assessment of energy systems: integrating environmental, economic and social aspects	J Clean Prod	Santoyo-Castelazo and Azapagic	2014	Creation and case study	CML 2001	Sustainability	MAVT	Energy	Dif. technologies, electricity mixes, CC targets	SD of energy systems requires consideration of TBL	Method, ranking
76	Concepts and Tools for Comprehensive Sustainability Assessments for Tourism Destinations: A Comparative Review	J Sustain Tour	Schianetz et al	2014	Review	-	-	-	-	-	-	State of the art
77	Evaluation of Structures Design Concept of Lower Structure from Embodied Energy and Emissions	Chem Engineer Trans	Sedlakova et al	2014	Application	IBO ecological construction comp catalogue	Technical-environmental	WSA, IPA, TOPSIS and CDA	Building	Building materials	Assess structures from environmental indicators and embodied energy	Best choice
78	Benefits and Risks of Emerging Technologies: Integrating Life Cycle Assessment and Decision Analysis to Assess Lumber Treatment Alternatives	Environ Sci Technol	Tsang et al	2014	Application	TRACI	Technical eco-efficiency	MAVT	Building	Lumber Treatment Alternatives	Trade-offs across benefits and risks are difficult to quantify given limited and fragmented information	Best choice
79	Determining the most sustainable lignocellulosic bioenergy system following a case study approach	Bioresource Technol	Von Doderer and Kleynhans	2014	Application	CML2001	Sustainability	AHP	Energy	Lignocellulosic bioenergy systems	The complexity and conflicting nature of criteria	Ranking
80	Multicriteria Analysis of Coal Mine	Int M Scientific Geo Conference SGEM	Bogacka	2015	Creation and case study	ReCiPe	Sustainability	Not mentioned	Mining	-	In order to analyze the environmental impact, we must take into account all relevant aspects	Method, best choice
81	Multidisciplinary and innovative methodologies for sustainable management in agricultural systems	Environ Eng Manag J	De Luca et al	2015	Proposition	Generic LCA	Sustainability	AHP	Agriculture	Agricultural ecosystems	Optimize the management of soil, water and energy macro-systems of crops	Ranking
82	Social Life Cycle Assessment and Participatory Approaches: A Methodological Proposal Applied to Citrus Farming in Southern Italy	Integr Environ Asses	De Luca et al	2015	General proposition	Not mentioned	Sustainability	AHP	Agriculture	Crop systems of citrus growing	Increase knowledge in this area	Ranking
83	Applying Multi-Criteria Decision Analysis to the Life-Cycle Assessment of vehicles	J Clean Prod	Domingues et al	2015	Application	CML2001	Environmental	ELECTRE TRI	Vehicles	Vehicles (engine and combustion)	The need to consider multiple environmental impacts	Ranking
84	Components and structures of the pillars of sustainability	J Clean Prod	Duic et al	2015	Review	-	-	-	Several	-	Interest to practitioners in various industries	State of the art
85	Integrating expert weighting and multi-criteria decision making into eco-efficiency analysis: the case of US manufacturing	J Oper Res Soc	Gumus et al	2015	Creation and case study	From literature	Eco-efficiency	WSA	Industry	US manufacturing sectors	Environment versus profit questions brings complexity to the DM for eco-efficiency evaluation	Framework

N	Title	Publication	Authors	Year	Kind of paper	LCIA method	Criteria	MCDA method	Economical sector	Scenarios	Motivation	Results
86	Comparing the sustainability of U.S. electricity options through multi-criteria decision analysis	Energ Policy	Klein and Whalley	2015	Proposition and case study	Published LCA results	Technical sustainability	WSA	Energy	Options for new US electricity generation	Energy DM requires comparisons between environ. and other criteria	Approach, ranking
87	Towards More Holistic Environmental Impact Assessment: Hybridisation of Life Cycle Assessment and Quantitative Risk Assessment	22nd CIRP conf on Life Cycle Engineering	Kobayashi et al	2015	Review	-	-	-	-	-	Provide knowledge	Recommendations
88	A sustainability assessment of advanced materials for novel housing solutions	Build Environ	Samani et al	2015	Application	ReCiPe	Technical eco-efficiency	PROMETHEE II	Building	XPS 30 core composite sandwich panel; building	Identify the best alternative within defined aspects	Ranking
89	Analysis of material solutions for design of construction details of foundation, wall and floor for energy and environmental impacts	Clean Techn Environ Policy	Sedlakova et al	2015	Application	IBO ecological construvtion component catalogue	Technical-environmental	WSA, TOPSIS, IPA and CDA	Building	Variants of the construction details of foundation, wall and floor	Find the best option in terms of sustainability	Ranking
90	Review of decision analytic tools for sustainable nanotechnology	Environ Syst Decis	Subramanian et al	2015	Review	-	-	-	Nanotechnology	-	Support DM with respect to the risks, impacts, costs and benefits	State of the art
91	Integration of the environmental management aspect in the optimization of the design and planning of energy systems	J Clean Prod	Theodosiou et al	2015	Application	Ecoindicator 99	Eco-efficiency	Not mentioned	Energy	Energy sources	Due to the multi-parameter nature of the design procedure	Best choice
92	Energy and Environmental Evaluation of Non-Transparent Constructions of Building Envelope for Wooden Houses	Energies	Vilcekova et al	2015	Application	IBO ecological construction componente catalogue	Technical-environmental	WSA, IPA, TOPSIS and CDA	Building	Building materials	Low energy design and buildings requires consideration of a wide range of factors	Best choice
93	Fuzzy multi-criteria-based impact category weighting in life cycle assessment	J Clean Prod	Agarski et al	2016	Creation and case study	ReCiPe	Technical-environmental	AHP	Waste Management	Incineration, bio-gasification, composting, landfill	How to use subjective impact category weighting factors	Ranking, hotspots
94	Sustainability assessment framework for low rise commercial buildings: life cycle impact index-based approach	Clean Techn Environ Policy	Al-Nassar et al	2016	Creation and case study	TRACI	Sustainability	WSA	Building	Alternatives for low rise commercial building construction	Integrate LCT into building construction to minimize its TBL impacts	Method, best choice
95	An integrated life cycle sustainability assessment of electricity generation in Turkey	Energ Policy	Atilgan and Azapagic	2016	Application	CML2001	Sustainability	MAVT	Energy	Different electricity matrix	Choice depend on stakeholder views on each aspect	Ranking
96	Sustainable Development Factors in Pavement Life-Cycle: Highway/Airport Review	Sustainability	Babashamsi et al	2016	Review	-	-	-	-	-	Lack of consensus on a methodology to guarantee sustainability	Recommendations

N	Title	Publication	Authors	Year	Kind of paper	LCIA method	Criteria	MCDA method	Economical sector	Scenarios	Motivation	Results
97	Sustainability assessment and prioritisation of e-waste management options in Brazil	Waste Manage	De Souza et al	2016	Application	CML 2001	Sustainability	Probabilistic Preferences (CPP)	Waste management	Collection and treatment of e-waste	There are still few LCA applications in Brazilian WMS; lack of database	Approach, best scenario
98	Sustainability evaluation framework for building cooling systems: a comparative study of snow storage and conventional chiller systems	Clean Techn Environ Policy	Kumar et al	2016	Application	TRACI	Environmental	PROMETHEE II	Building	Different building cooling systems	Minimizing energy use and GHG emissions is one priority goal	Best option
99	Life Cycle Assessment and Optimization-Based Decision Analysis of Construction Waste Recycling for a LEED-Certified University Building	Sustainability	Kucukvar et al	2016	Application	Not mentioned	Eco-efficiency	Not mentioned	Building	Best recycling strategy	Optimization-based decision support framework has not been addressed	Best choice
100	Life cycle assessment capacity roadmap (section 1): decision-making support using LCA	Int J Life Cycle Assess	Laurin et al	2016	Review	-	-	-	-	-	Current methods are limited to inform decision-makers	Recommendations and Roadmap
101	Waste treatment: an environmental, economic and social analysis with a new group fuzzy PROMETHEE approach	Clean Techn Environ Policy	Lolli et al	2016	Proposition and case study	IMPACT 2002	Sustainability	PROMETHEE	Waste Management	Traditional incinerator and an innovative integrated plant	Most complex decisions involve several stakeholders	Approach, best choice
102	Methodology for determining the mixing ratio of selected solid recovered fuels	Agronomy Research	Malijonyte et al	2016	Proposition and case study	Not mentioned	Eco-efficiency	TOPSIS	Fuels	Fuel mix compositions	Benefits should be balanced with energy inputs, envir.impacts, costs	Approach, best choice
103	Life Cycle Thinking used for assessing the environmental impacts of tourism activity for a Greek tourism destination	J Clean Prod	Michailidou et al	2016	Proposition and case study	Ecoindicator 99, CML 2001	Environmental	Not mentioned	Tourism (hotels)	Operational use of Hotels	Estimate the environmental load in areas of considerable tourism activity	Hotspots
104	Construction solutions for energy efficient single-family house based on its life cycle multi-criteria analysis: a case study	J Clean Prod	Motuziene et al	2016	Proposition and case study	IMPACT 2002	Eco-efficiency	AHP, COPRAS	Building	Masonry, Log and Timber frame building	Need for assess a complex system of criteria	Ranking
105	Sustainability assessment tools – their comprehensiveness and utilisation in companylevel sustainability assessments in Finlan	Int J Sust Dev World	Myllyviita et al	2016	Review	-	-	-	-	-	Few of the studies have addressed utilization of these tools at the company level	State of art
106	Life cycle assessment (LCA) and life cycle cost (LCC) analysis model for a stand-alone hybrid renewable energy system	Renew Energ	Petrillo et al	2016	Application	Ecoindicator 99	Sustainability	AHP	Energy	Power generation system	Support DM in complex decision problems in the field of environmental sustainability	Ranking

N	Title	Publication	Authors	Year	Kind of paper	LCIA method	Criteria	MCDA method	Economical sector	Scenarios	Motivation	Results
107	Can Carbon Nanomaterials Improve CZTS Photovoltaic Devices? Evaluation of Performance and Impacts Using Integrated Life-Cycle Assessment and Decision Analysis	Risk Anal	Scott et al	2016	Application	TRACI	Eco-efficiency	MAUT	Energy, Nanomaterials	Different nanomaterials	Related impacts remain uncertain, resulting in challenges to decisions	Best choice
108	Decision making in renewable energy investments: A review	Renew Sust Energ Rev	Strantzali and Aravossis	2016	Review	-	-	-	Energy	-	Trends in methods and application areas	State of art
109	Four Sustainability Paradigms for Environmental Management: A Methodological Analysis and an Empirical Study Based on 30 Italian Industries	Sustainability	Zagonari	2016	Creation and case study	Not mentioned	Sustainability	MAUT	Several	Interdependent industries in Italy	Methodology to consistently compare alternative sustainability paradigms	Method

APÊNDICE B - A Bibliometric Overview of Brazilian LCA Research

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Abstract:
Purpose We bibliometrically evaluated the scientific literature outlined around Brazilian life cycle assessment (LCA). Our aim is twofold: (1) Analyze the Brazilian scientific literature on LCA, forming a current view of how the LCA methodology is applied in the country; (2) within this view, trace the evolution of themes, characterize institution collaboration and indicate major influences in Brazilian LCA community.
Methods Data were outlined around academic production and publications, from 1993 to 2015, indexed by the Institute for Scientific Information (ISI- SCIE and SSCI) through a specific group of keywords. Initially, a temporal evolution and projection of papers, PhD and Master Theses was performed. In sequence, indexed papers were analyzed through performance indicators (i.e. number of authors, impact factor, among others), content evaluation (for instance, major addressed themes). Finally, a mapping of science was performed, with the aid of Cite Space software application, where co-word (and evolution), co-collaboration (and evolution) and co-citation maps were created.
Results and Discussion The survey identified 429 documents divided among international and national papers, PhD and Master Theses. From those documents, 165 were indexed. In terms of production and performance, the results indicate an undeniable evolution of the Brazilian LCA research, as affirmed by relations solidified through time. The main research field is 'LCA

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application' with 84% of papers, whereas 'LCA methodology' completes the framework. In LCA applications, 25% of publications are related to Biofuels - divided into bioethanol and biodiesel - which makes it the current dominant LCA research area in Brazil. The collaboration network demonstrates three main institution groups, whereas evolution through the years indicates that this situation may further improve. Influential authors are linked to LCA of Biofuels, general LCA guidelines and methodological LCA developments.
Conclusions Brazilian LCA research has been growing and more complex relations between themes and institutions denotes that further developments can be expected. Co-collaboration indicates three main clusters, led by USP, Unicamp and UFRJ. 'Biofuels' is the main research area where sugarcane ethanol and biodiesel from different sources are the domain product systems. Co-citation analysis solidifies this statement, pointing to Isaias Macedo (and other biofuel researchers) as the main author in Brazilian LCA after ISO and Mark Goedkoop.

Keywords: Brazil, LCA research, Bibliometrics, Networks, Trends.

1. INTRODUCTION

Publications on life cycle assessment (LCA) have been growing exponentially since its standardization in 1997 (current ISO 14040, 2006) (CHEN et al., 2014; HOU et al., 2015); the same trend is observed with other LCA-related initiatives and programs (RACK; VALDIVIA; SONNEMANN, 2013; SOUZA; BARBASTEFANO, 2011). This development can also be explained, at least partially, by a clearer understanding of a significant part of modern society regarding the consequences of its activities on the environment. The growing public awareness of environmental issues and widespread acceptance of sustainable development have been highlighted by many authors (CHEN et al., 2014; CHERUBINI; RIBEIRO, 2015; GUINÉE et al., 2011, HOU et al., 2015; XU; BOEING, 2013). Hou et al. (2015) clearly identified the acceleration profile of this development, with the number of LCA publications per year increasing from 38 in 1998 to 1104 in 2013; this finding means that the rate of LCA publication grew by 2,905% during this period.

One of the reasons for the popularity of LCA lies in its characteristics. Often used as a tool in the decision-making process, LCA considers a systemic approach and provides quantitative results related to potential impacts on humans, ecosystems and resources. All of these features are essential for process management at any level for any goal, achievement, or objective, which allows practitioners to apply the methodology to products, processes and services. In this sense, the tool has a close relation to the activities carried out in both public and private sectors, where its application is frequently mandated by important economic developments. This geographical influence is an expected and symptomatic behavior, not only in LCA but also in other fields of technological development. For instance, considering the Brazilian economic profile, Willers and Rodrigues (2014) asserted that Brazil offers many possibilities for the application of LCA in both industrial and agro-industrial sectors. Confirming this position, Cherubini and Ribeiro (2015) showed that LCA research is spread in different sectors such as the biofuel industry, agriculture and livestock, the civil construction sector, the steel industry, and other main economic activities in Brazil. Complementary to its economic features, assessment of those sectors through LCA is critical for Brazil to achieve its environmental goals (e.g., Brasil, 2009), and it is also important for many other countries that are commodity consumers.

Nevertheless, if LCA diffusion is an important step in the development of the methodology itself, for the improvement of inventory databases and life cycle management, in the other hand, the recent spread of LCA and the flexible nature of LCA steps (that enable practitioners to make different choices regarding scope), raises difficult questions related to this research field. The purpose of finding those answers lies in the analysis of insights regarding 'how LCA evolution is being conducted', 'how LCA is being associated with public administration and industries', or even 'in what ways LCA preferences in the determination of products guide policy making', among others. One way to understand these topics is by analyzing the past to allow one to assess the present and predict the future. This issue can be analytically addressed from an overview of scientific production performed through statistical analysis of written publications under an approach known as bibliometrics.

The use of bibliometric techniques in scientific research is considered to be a widespread practice, having already been widely applied to many disciplines of science and engineering (XIE; ZHANG; HO, 2008). White and McCain (1989) define Bibliometry as "the quantitative study of literatures as reflected in bibliographies", where "its task is to provide evolutionary models of science, technology, and scholarship". Considering a certain number of published studies, a bibliometric evaluation of publications is regarded by many researchers as an alternative and innovative way to connect various aspects of scientific findings and reveal global trends (ESTRELA, 2015; XU; BOEING, 2013).

Despite the clear importance of indicating research patterns, tendencies and paths in academic evolution, there are few efforts into systematic, chronological, and synthesizing studies to map LCA research (CHEN et al., 2014). To date, few papers have been published that apply bibliometry to LCA (e.g., BJORN et al., 2013; CHEN et al., 2014; SOUSA; BARBASTEFANO, 2011; HOU et al., 2015; QIAN, 2014; XU; BOEING, 2013). Still in the same theme but on another approach, Estrela (2015) have analyzed the methodology proposed by Chen et al. (2014) and Hou et al. (2015). On top of that, while these studies implemented bibliometric analysis on a global scale (CHEN et al., 2014; HOU et al., 2015), to a specific research field (as Biofuels assessed by XU; BOEING, 2013) or to a specific topic, such as global LCA networks (BJORN et al., 2013; De SOUSA; BARBASTEFANO, 2011) and co-citation maps (QIAN, 2014), this paper is outlined around a geographic scale group of bibliometry.

In this study, we attempted to bibliometrically evaluate the scientific literature on Brazilian LCA since its beginning. Our aim is twofold: (1) Analyze the Brazilian scientific literature on LCA, forming a current framework of how the methodology is applied in the country; (2) within this framework, trace the evolution of themes, characterize institution collaboration and indicate major influences in Brazilian LCA community. These findings enable future projection, improve understanding of the Brazilian LCA community, and provide a useful reference for other studies; in addition, the study may stimulate further research. The results may also be used to strengthen LCA applications and improve decision-making processes regarding Brazilian LCA-related institutions and those of developing countries with relatively recent LCA engagement.

2 MATERIALS AND METHODS

2.1 DATA

The data sources and technology for the bibliometric research are bibliographies and bibliographic databases (GLÄNZEL, 2003). The data for this paper were gathered into two groups whose purpose was to provide different insights related to both scientific production and scientific publication. The first group comprised several types of scientific production and represents a broader range of databases — e.g., Master and PhD theses from the Brazilian 'National Database of PhD and Master Theses' and papers published in indexed journals from the Institute for Scientific Information (ISI) Web of Science (WoS) – and non-indexed journals. The second group covers only papers indexed in the ISI database, where Science Citation Index Expanded (SCIE) and Social Sciences Citation Index (SSCI) were considered. Conference papers, reports and other technical documents were not included in the scope of this study. Noteworthy to mention that conferences proceedings were not considered in our research despite of Estrela (2015) recommendation for global mapping of LCA research. The rationale for establishing these boundaries comprised two assumptions: (1) WoS did not cover all conferences and performance analysis would not be feasible; and (2) PhD theses, Master theses and papers (generally) have a more robust scientific background.

To compose the scientific production group, we considered both SCOPUS and Web of Science as international databases. These decisions were made due to the proper characteristics of those data sources and the high incidence of access in academic and scientific fields. Complementarily, other bibliometric studies noted that Web of Science is widely used for analyses of this nature (see HOU et al., 2015; QIAN, 2014; SOUZA; BARBASTEFANO, 2011 and XU; BOEING, 2013). In addition, the Science Citation Index (SCI) database has been the most common way to trace papers in bibliometric research (MING; TE; YUH, 2009). For national research, we use the databases of SCIELO, the National Database of PhD and Master Theses by the Coordination for the Improvement of Higher Education Personnel (CAPES) and the Brazilian Digital Library of PhD and Master Theses by the Brazilian Institute of Information in Science and Technology (Ibict). The research in these three databases represents complete coverage because it includes both national periodic and national theses indexes.

For the scientific publication group, our surveys were restricted to articles indexed in the ISI WoS database (SCIE and SSCI). WoS represents the preference of several authors in bibliometric studies related to LCA (CHEN et al., 2014; SOUZA; BARBASTEFANO, 2011; HOU et al., 2015; QIAN, 2014; XU; BOEING, 2013) because it enables the extraction of vital information for bibliometry, including cited references. WoS was also used as a reference for the development of indicators for scientific production worldwide; it was associated with the creation of one of the main journal impact factors (IF), the Journal Citation Report (JCR) (SOUZA; BARBASTEFANO, 2011), which allows analysis at the level of importance of a publication during a specific period.

2.2 DATA OUTLINING

Data outlining was performed in the following three steps. In the first step, the research was conducted with regard to a set of keywords. Following recommendations made by Estrela (2015), in addition to specific keywords – such as "LCA" and "life cycle assessment" (the preferred term in ISO) – some other correlated acronyms – as LCI and LCIA – have also been considered in the research.

For the Brazilian databases, we searched for "Avaliação do ciclo de vida*", "Avaliação de ciclo de vida*", "ACV", "Avaliação de Impacto de Ciclo de Vida*", "Avaliação do impacto de ciclo de vida*", "AICV", "Inventário de ciclo de vida*", "Inventário do ciclo de vida", "ICV", "life cycle assessment*" or "LCA", in the search fields of (title), (keyword) and (subject). For the SCOPUS database the survey was conducted for "life cycle assessment*", "LCA", "life cycle impact assessment*", "LCIA", "life cycle inventory*" or "LCI" in the (keywords) field AND "Brazil or Brasil" in the (affiliation country) field AND "Article" as (Document type). Finally, in the ISI Web of Science, we used the terms "life cycle assessment*", "LCA", "life cycle impact assessment*", "LCIA", "life cycle inventory*" or "LCI" in the (title) field AND "Brazil or Brasil" in the (address) field. To include all Brazilian research within the previous scope, the time span for all databases was from 1993 – as the publishing date of SETAC's Guidelines for LCA (SETAC, 1993) - to December 2015.

As a second step, we used a variation of the snowballing method (BEZERRA et al., 2014; JALALI; WOHLIN, 2012) in which the most relevant Brazilian researchers and study supervisors in the databases have been selected. The relevance criterion was defined as the number of articles or studies supervised by each person. Using the Lattes Platform (http://lattes.cnpq.br, the Brazilian database that integrates the curriculum vitae (CV) of all researchers in the country), a second search was performed on the CV of these researchers by searching for scientific publications not covered by direct search in the databases.

The third step comprised a screening analysis of the results from the first step to select the papers that met the scope definition - i.e., research conducted or with collaborative participation of Brazilian researchers on LCA topics.

2.3 BIBLIOMETRICS

2.3.1 Performance Analysis

The performance analysis aims to determine the characteristics of the publications, such as their types, languages, journals, and countries, based on bibliometric analysis, resulting in concluding trends or hotspots for specific research areas (HOU et al., 2015). Performance analysis included the following fields: number of papers (NP), number of authors (NA), number of pages (NPg), author reference count (NR), number of times cited (NC), journal IF , year published, subject category and journal name. For subject category, a general normalization of keywords was applied to enable main domain theme analysis. For instance, 'Poultry', 'Swine' and 'Cattle' were classified into the 'Livestock' domain area. Other research topics were similarly categorized.

The correlation between the number of papers published and Master and PhD theses (hereinafter also referred to as academic research) was analyzed through a non-parametric method, the Spearman's correlation coefficient. Then, in an attempt to predict trends for future LCA works in terms of numbers of publications, the data was extrapolated through a second order interpolation.

2.3.2 Mapping of the Science

Three different analyses were performed to map the current state of LCA research in Brazil. Cognitive maps about collaboration, co-citation and co-word networks were produced to support the examination.

The co-citation allows the establishment of a framework for the research field through pairs of documents that are commonly cited together (COULTER; MONARCH; KONDA, 1998) to find the degree of relationship between papers as perceived by the population of citing authors (SMALL, 1973). Co-word analysis measures the association strengths of representative terms in relevant publications or other texts produced in a technical field (COULTER; MONARCH; KONDA, 1998), where the clusters represent groups of textual information that can be understood as semantic or conceptual groups of different topics treated by the research field (COBO et al., 2011). The co-word network uses keywords to evaluate the influence of each word based on the number of appearances in the papers, where the node size indicates the importance of each term, the links represent how they are connected (one citation means one link), and the clusters outline the domain research areas. Note that the cluster also refers to a group of co-cited references with tight connections within the same cluster, which can be observed as a specialty in a certain domain (CHEN et al., 2014).

The interpretation of bibliometric maps can be performed through analytic and visual assessment of the results with the aid of specific software applications (CHEN et al., 2014) available to assist researchers in such analysis. For this research, we opted to use CiteSpace (CHEN, 2014) that allows temporal analysis to indicate research field evolution during a time span as well as the creation of collaborative groups. This tool has recently been used in LCA bibliometric studies to generate co-citation and co-word networks, identify similarities (applying keywords) and analyze the temporal evolution of each topic based on the year and influence of each publication (CHEN, 2014). The software application demanded a standardized input format. Therefore, and in order to deal with possible bias in affiliations raised by Estrela (2015), the data were standardized, including keywords, institutions (first affiliation), authors and citations. For instance, similar terms were aggregated into a single term (e.g., lca, life-cycle-assessment, life-cycle assessment, LCA and life cycle assessment were standardized into the single term “LCA”).

Noteworthy to mention that normalization was possible due to the relative small number of papers in our survey (if compared to CHEN et al., 2014 or HOU et al., 2015). Difficulties found to perform bibliometry studies are highly linked to lack of standardization on how indexation information is made and mistakes made in citations by the authors. In this sense, Estrela (2015) conclusions are reinforced both in clarity of bibliometric outlining and indexing of the papers. Other possible problems are related to mistakes on how articles are cited

3. FINDINGS

3.1 DATA

The survey on all databases and publication groups in our scope identified 524 documents which have been classified as international and national papers (248), Master theses (213) and PhD theses (63). Post-graduate studies addressing LCA started in 1998. Since then, we could see an erratic growth in terms of the number of concluded projects. From previous years until 2012/2013, there were positive peaks of academic works interlaced with negative drops where publications decreased. Even with fluctuations, we have identified that until 2012, there was a slight production growth trend per year. However, this behavior has changed during the 2013/2015 period. As can be seen in Fig. IV-4, in the last three years, Brazilian academic research related to LCA is facing a considerable reduction, from 32 concluded projects in 2012 to only 9 in 2015.

Regarding the published papers, it is possible to observe an exponential growth with a noteworthy variation during the period of 2009/2011. The number of papers grew by 316% between 2009 and 2010 and then fell to 175% in 2011. Nevertheless, after 2011, we can confirm continued and clear growth to date (Fig. IV-4) with the number of publications per year increasing from 9 in 2011 to 67 in 2015.

The reasons for the peak in publications in 2009/2010 are not quite clear. One possibility is the increase of Master and PhD theses in 2007/2008; in Brazil, many courses has a demand for publications as a prerequisite to reach the Master and PhD degrees, but most academic works, especially Master theses, require additional time to achieve the maturity level necessary to be published. This assumption is based on the positive correlation between the variables Master+PhD theses and papers published (rs = 0.81).

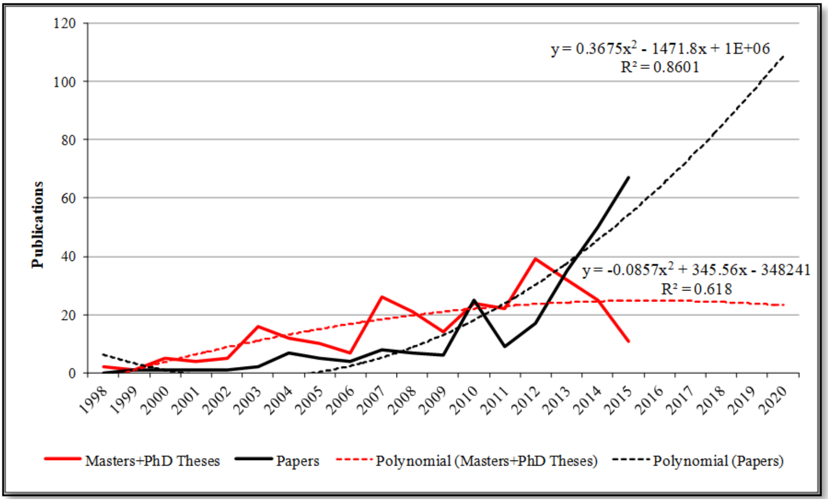
A trend analysis of data from Fig. IV-4 suggests that the decrease in Master and PhD theses observed after 2012/2013 could lead Brazil toward a reduction in international publications in the near future. However, it should further be considered that despite the positive correlation between the variables and its potential influence to decrease articles publishing, the projection shows that it can be expected an substantial growth of papers (black dotted line on Fig. IV-4 - R2 = 0.8601). Some of the reasons for this contradictory behavior can be due to the delayed update of national PhD and Master Theses databases, but also due to the recent interest and application of LCA methodology by research institutions (e.g. CTBE from 2013; Embrapa from 2010). The interest of research institutions has a major influence in papers production without necessarily increase the number of PhD theses and Master theses. In addition, LCA was just recently introduced as a research field in Brazil (Fig. IV-4). Therefore, it is a plausible assumption that the quality of overall Brazilian academic work in the field reached an international publication level only in the past few years.

This sudden reduction in academic research is different from that which occurred (almost periodically) in other years. Currently, the LCA research field is more structured in Brazil, which is reflected in national maturity regarding comprehension of the methodology. This condition was reached previously to 2013, in which the main research driver comprised LCA applications and case studies. For some time, LCA applications aroused worldwide interest; however, they are currently rarely original, and LCA is facing new challenges in methodological evolution. LCA research is being addressed to solve methodological bottlenecks as indicated by Reap et al. (2008a; b) and illustrated by Finnveden et al. (2009) and Guinée et al. (2011). These issues include the development of different approaches such as Life Cycle Costing, Social Life Cycle Assessment (GUINÉE et al., 2011), and hybrid LCA applications with other tools, such as the Multi-criteria Decision Analysis approach.

Brazilian academic research is following this tendency; therefore, even though the number of academic projects has been reducing, it is possible to expect more influent results in years to come. This prediction is enhanced by several efforts that have been made in collaboration with international institutions (e.g. UDESC, Ghent University and JRC related to natural resource accounting based on exergy approaches (ALVARENGA et al. 2013; TAELMAN et al., 2014); USP and Technical

University of Denmark related to the regionalization of characterization factors for impact categories), as well as collaborative working groups that are dealing with databases, adaptation of LCIA factors, among others.

Fig. IV-4. Evolution over time of Brazilian scientific production (academic works and published papers) and projection.



For the analysis of the second group of papers, 165 articles were indexed in ISI WoS. A comparison with Hou et al. (2015), restricting the period to the same time span applied by those authors (i.e., 1998 – 2013), indicates a higher quantity of papers from this research (128 against 94 identified by those authors). This difference may be explained due to the use of other keywords in our query, while Hou et al. (2015) applied solely “life cycle assessment”. These findings would increase the Brazilian scientific production by 36% relative to that study, hence, confirming that the metrics applied to quantify the publishing group (e.g., different keywords) play a significant role in bibliometric results.

The first Brazilian publications on ISI occurred in 2003 (2 papers), and - as shown in Tab. IV-4 - this profile is quite similar to the total number of papers (Fig. IV-4) along the temporal series under analysis, although in minor scale (48 papers were published in 2015). During the lifetime of LCA research, it is possible to outline two well-defined periods - from 2003 to 2009, in which publishing was incipient (3.7 papers/year), and from 2009 to date (34.2 papers/year), in which occurred the growth mentioned before. This statement is reinforced by indicators in the performance analysis as number of authors, pages and references per paper (see 3.2. Perform Analysis).

3.2 PERFORMANCE ANALYSIS

In terms of performance, the data in Tab. IV-4 indicate an upward trend in the total number of authors of Brazilian LCA papers, from 5 to 239 during the studied time frame. In relative terms, the number of authors per published paper has also shown a slight increase, remaining at approximately 3.7 authors/(paper.year) on average. This value is very similar to the values found by bibliometric studies of worldwide LCA publications obtained by Hou et al. (2015) and Xu and Boeing (2013), respectively of 3.9 and 3.5 a/(p.y). The number of papers (NP) and number of authors (NA) have grown exponentially; however, the small variation of (NA/NP) in the time span means that both increases were almost linear. This performance suggests that each new LCA author has a positive but constant influence on scientific production, indicated by the number of papers. This occurred for two main reasons in Brazil: there are more institutions (and therefore authors) researching LCA, which is driven by industry interests, government promotion and international collaboration; and there are better research conditions with regard to data, experiences and knowledge. On top of that, interest in LCA from developing countries has been growing along with conventional Brazilian product systems (such as grain, meat and ethanol) because they are often related to specific impacts on biodiversity.

The number of pages (NPg) and the summed IF values exhibited the same behavior; there was a considerable growth until 2015 in absolute terms, which is dampened with regard to the number of papers. Apart from the year 2005 (which recorded only one paper published), the NPg has doubled in the time span – from 5.5 to 9.39 (Tab. IV-4). Hou et al. (2015) and Xu and Boeing (2013) presented 10 and 9.9 pages per paper, respectively, revealing consonance between international and Brazilian studies regarding this indicator. One may say that NPg is influenced by publishers' guidelines, which limit the lengths of papers (generally in terms of the number of characters). Although that might be true, it is undeniable that the group of papers experienced a slight increase in NPg/NP.

The ratio of IF to NP has evolved from 1.0 to 3.9 with an average performance of 2.25. Even at less expressive levels, an increase in the ratio (IF/NP) indicates a positive trend because this indicator represents an increase in quality and relevance of those papers, as well as LCA research.

Tab. IV-4. Characteristics of Brazilian publications from 2003 to 2015.

Year	NP	NT	NT/NP	NA	NA/NP	NPg	NPg/NP	NR	NR/NP	NC	NC/NP	IF	IF/NP
2003	2	2	1.0	5	2.5	11	5.5	35	17.5	35	17.5	2.1	1.0
2004	3	7	2.3	9	3.0	24	8.0	84	28.0	52	17.3	2.1	0.7
2005	1	5	5.0	2	2.0	14	14.0	8	8.0	8	8.0	0.8	0.8
2006	3	4	1.3	11	3.7	21	7.0	60	20.0	48	16.0	3.2	1.1
2007	5	8	1.6	17	3.4	44	8.8	183	36.6	263	52.6	8.5	1.7
2008	6	7	1.2	19	3.2	45	7.5	104	17.3	60	10.0	8.9	1.5
2009	6	6	1.0	19	3.2	58	9.7	126	21.0	115	19.2	18.2	3.0
2010	17	25	1.5	78	4.6	147	8.6	512	30.1	607	35.7	41.4	2.4
2011	8	9	1.1	40	5.0	81	10.1	303	37.9	166	20.8	26.0	3.2
2012	11	17	1.5	41	3.7	102	9.3	452	41.1	95	8.6	32.5	3.0
2013	24	35	1.5	117	4.9	270	11.3	1029	42.9	222	9.3	79.0	3.3
2014	31	52	1.7	147	4.7	335	10.8	1542	49.7	78	2.5	112.3	3.6
2015	48	67	1.4	239	5.0	554	11.5	3261	67.9	36	0.8	186.7	3.9
Average	12.7	18.8	1.70	57.2	3.75	131	9.39	592	32.2	137	16.8	40.1	2.25

*NP = number of papers indexed in ISI; NT = total number of papers; NA = number of authors; NPg = number of pages; NR = number of references; NC = number of citations; IF = Impact Factor (at publication's year).

The way in which the number of references (NR) varied also reaffirms the progress of LCA research in Brazil. Tab. IV-4 shows the progressive average growth of references per paper (NR/NP). According to Hou et al. (2015), "the progressive increase of publications and references indicated a growth trend and an increasing level of communication in the field of LCA research during the past years". Conversely, Brazilian articles are facing a decline in citations per produced paper (NC/NP). An exception is made in the years 2014 – 2015, which are too recent to represent a real number of citations; since 2011, it is possible to note a decrease, even though there were more papers produced with more consistency during the same time span. This behavior could have many causes: Brazilian LCA research to date has been primarily produced as case studies, which have less citation appeal than other topics (this fact has become even more true recently, as mentioned previously); there is a possible lack of novelty or originality in the research; paper conclusions might be too specific to warrant citation; national and South American periodicals (or databases) are hardly indexed by ISI.

From the 165 articles, approximately 84% are dedicated to LCA applications. The other 16% are particularly noteworthy and address methodological issues, i.e., adaptation and improvement of LCIA methods, particularly related to land use and biodiversity, development of social life cycle impact assessment (S-LCA) and life cycle inventory

(LCI) (Tab. IV-5 and cluster (4) in Fig. IV-5).The development of the 'land use' impact category as a main methodological topic is not a surprise owing to the economic activities practiced in Brazil pertaining to richness of biodiversity and the occurrence of deforestation. This mix of themes represents some of the main areas of interest from international and national organizations, which can be observed in co-authorship of recent papers such as Alvarenga et al. (2013; 2015) and Souza et al. (2013).

Even though it was classified as methodological, the group in Tab. IV-5 represented by "LCA promotion and state-of-the-art" does not exactly refer to methodology development but rather indicates important paths for its development (e.g., RUVIARO et al., 2012, whose authors compiled LCA studies related to agriculture and indicated paths to methodological improvements: "develop specific methodologies for both Life Cycle Inventory and Life Cycle Impact Assessment"). In this group, it is not possible to consolidate into common topics because there is a varied set of studies. Two other important methodological topics are LCI (e.g., MOURAD et al., 2007), where authors elaborate a methodological approach for representing agricultural products in terms of LCI, and S-LCA (e.g., RAMIREZ et al., 2014), which proposes evaluating subcategories in S-LCIA.

Tab. IV-5. Methodological research areas of LCA in Brazil.

Themes	Publications	Participation*
LCIA	12	44%
LCA promotion and state-of-the-Art	8	30%
LCI	3	11%
S-LCA	3	11%
Ecodesign	1	4%

* Participation is related to the percentile apparition of each theme in Methodological topic.

Regarding LCA applications, the publication profiles in terms of research areas are depicted in Tab. IV-6. The dominance of fuels and biofuels in Brazilian LCA research was already anticipated (CHERUBINI; RIBEIRO, 2015; ZANGHELINI et al., 2014a) because of the national production of sugarcane and ethanol explained by Ometto and Roma (2010). Additionally, biofuel-related research has generated interest worldwide, even more through LCA in the sense that it verifies, explores and exposes some commonsense axioms, including 'renewable-based products are less influential on the environment than fossil ones'; 'bio-based products are more attractive owing to carbon neutrality'; and 'renewable-based products preserve or cause no harm to the environment'.

Tab. IV-6. Major research areas of LCA application in Brazil.

Sector	Publications	Participation
Biofuels/Fuels	35	25%
Energy	23	17%
Agribusiness	21	15%
Construction	13	9%
Waste Management	13	9%
Chemical and Petrochemical	8	6%
Vehicles	5	4%
Furniture and Wood	4	3%
Services	3	2%
Packaging	2	1%
Steel	2	1%
Miscellaneous	9	7%

Some of the themes displayed in Tab. IV-6. are hot topics worldwide, showing that Brazilian LCA research is aligned with the international trend noted by Chen et al. (2014) assessing LCA publishing in the period of 1998 – 2013 - "biofuel, process design, solid waste management, and livestock production-related LCA studies are the main areas where interest is surging" - and by Xu and Boeing (2013), who mapped the biofuel field from 1991 to 2012 - "LCA is an increasingly popular method for biofuel research". In order to better explain the results they were aggregated in fuel/biofuel produced from sugarcane (69% of the papers were on this topic) and other sources such as palm (25%), soybean (22%), algae (6%), jatropha (3%) and cooking oil (3%). Although the product system is classified as fuels/biofuels, those papers also have a straight connection to energy owing to its function with regard to agriculture because some of the research on biofuels uses raw materials based on sugarcane, palm and soybean (e.g., SEABRA et al., 2011; SILVA et al., 2014; RODRIGUES et al. 2014). Hence, it is possible to state that the main LCA research field in Brazil is crop-oriented production for fuel and energy purposes.

The top 6 main journals account for 58% of Brazilian LCA publications during the time period, and 49% were published in only three journals: Journal of Cleaner Production (JCP), The International Journal of Life Cycle Assessment (IJLCA), and Resources, Conservation and Recycling. Tab. IV-7 shows that 22% of Brazilian scientific production has been published in the JCP and another 20% occurred in the IJLCA. The concentration in these vehicles is explained by the high adherence of these journals to the theme (as postulated by Chen et al., 2014). Other journals are specific to energy and fuels, which corroborate our outcomes related to the main areas of LCA application displayed in Tab. IV-6.

Tab. IV-7. Top 6 most productive Web of Science journals that published Brazilian researches.

Journal	IF 2014	Publications
Journal of Cleaner Production	3.844	37
The International Journal of Life Cycle Assessment	3.988	33
Resources, Conservation and Recycling	2.564	12
Energy	4.844	5
Biofuels, Bioproducts & Biorefining	4.263	5
Renewable Energy	3.476	5

The concentration in general LCA journals may denote a twofold condition. The Brazilian LCA community invests in the development of 'LCA for LCA' in the sense that LCA acts as the central focus of the research (i.e., LCA is central in paper) - rather than being a way to explore a new dimension and/or alternative (i.e., LCAs are performed to support further analysis). Brazilian LCA research has demonstrated few technical or scientific partnerships with other scientific areas to conduct collaborative work. However, the tendency toward specifically focused themes such as biofuel is changing this behavior, indicating that Brazil is becoming an authority on this subject (see also XU; BOEING, 2013).

3.3 NETWORKING AND RELATIONS

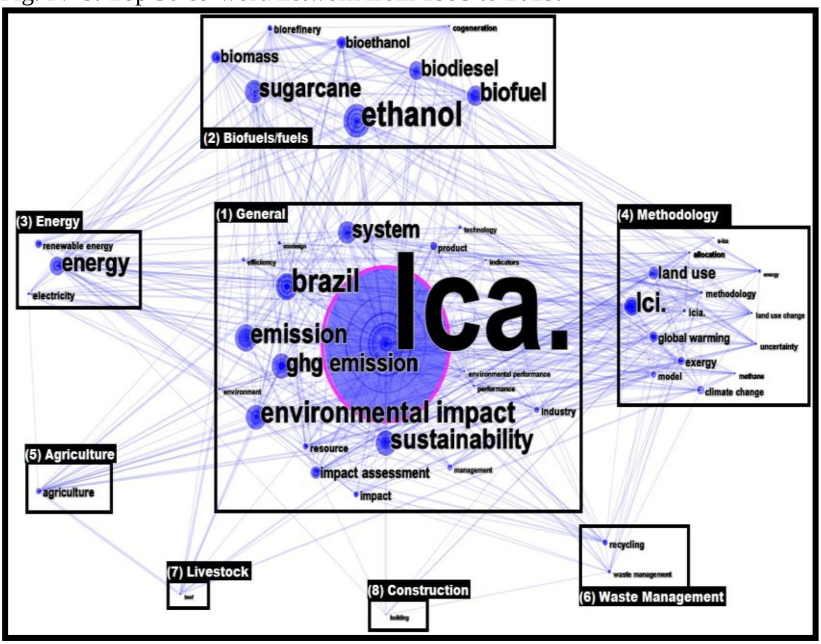
3.3.1 Co-word

In the 165 papers under examination, exactly 1600 keywords were registered after normalization. Of this total, 212 keywords appeared repeatedly, and other 447 were unique, appearing only once in the sample. Analyzing the major clusters, it is possible to classify LCA research into 8 groups (Fig. IV-5): (1) general, (2) biofuel/fuel, (3) energy, (4) methodology, (5) agriculture, (6) waste management, (7) livestock, and (8) construction. In this framework, clusters (1), (2), (3) and (4) represent some of the main Brazilian LCA research areas, not necessarily in that order. These outcomes show that Brazil is following world trends with regard to recent LCA developments based on three of the four domain areas identified by Hou et al. (2015): energy, bio (biofuels, biodiesel and bioethanol) and analytical methods.

From the selected papers, the most frequent keyword is 'Life Cycle Assessment' (129 repetitions), followed by 'Ethanol' (32 repetitions) and 'Brazil' (28 repetitions). The frequency of use of the term 'ethanol' reinforces this topic as the main theme in Brazilian LCA research.

A general domain was created to simplify the interpretation of the results. According to this approach cluster 1 included keywords related to the general LCA methodology (e.g., 'system', 'impact assessment' and 'emissions'), and others related to environmental concerns ('sustainability', 'industrial ecology', etc.). Because of its general nature and interdisciplinary content, those words are linked to several other domain areas - i.e., 'GHG emissions' (cluster 1) to 'biodiesel' (cluster 2) or 'beef' (cluster 7). Although this cluster cannot indicate a specific research area, such keywords are important to LCA propagation, allowing readers to relate a broader view into the article or theme.

Fig. IV-5. Top 50 co-word network from 1993 to 2015.



With 32 records, 'ethanol', classified in cluster 2, is certainly the major product system assessed by the Brazilian LCA community. The high prevalence of ‘sugarcane’ (23 indications) in this domain is due to the source of ethanol production. Citations of ‘bioethanol’ and ‘biorefinery’ (14 and 9 appearances, respectively) corroborates this conclusion; the first one refers to ethanol from biological sources (including sugarcane), and the other is due the ethanol production plant. Another important word in cluster 2 is ‘biodiesel’ (20 records). Co-word relations to this fuel indicate that Brazilian biodiesel has sources other than soybean or palm. These outcomes highlight biofuel as the main domain of scientific LCA development in Brazil, making both biodiesel and bioethanol the fuels of interest. Hence, it is not a coincidence that the proper keyword ‘biofuel’ is an important theme from this cluster (with 24 records).

Fig. IV-5 also denotes a strong connection between clusters 2 and 3 indicating that the biofuels/fuels and energy domain areas are interlaced. The link between ‘energy’ to ‘sugarcane’ and ‘biomass’, could be related to the use of sugarcane bagasse as biomass energy in cogeneration plants that are associated with ethanol production. There is an important connection between clusters 2 and 4 provided by sugarcane and land use change (LUC); the rationale for this link is the use of area originally occupied by native forest. Moreover, ethanol fuel produced from sugar crops in tropical settings appears to be by far the most efficient of these categories from a land use perspective (VON BLOTTNITZ; CURRAN, 2007). Von Blottnitz and Curran (2007) showed that the development of biofuels aroused interest worldwide, and studies on this theme continue to be conducted. In addition, biofuel was also the main cluster identified by Chen et al. (2014).

LCA of biofuels in Brazil started in 2007 with incipient studies (Fig. IV-6 B). The first studies on ethanol and biodiesel occurred in 2009, and publications related to biodiesel sharply increased in 2011. Along the period from 2011 to 2015, the studies of LCA related to bioethanol and biodiesel increased significantly, as is possible to see by the node growth (particularly in 2014 and 2015 colors) and increasing relationship between words, as sugarcane and ethanol (Fig. IV-6 C). Hou et al. (2015) also noticed this booming behavior of bioethanol while analyzing consecutive and equivalent time series. From 2003 to 2005, they identified three publications about LCA of bioethanol; from 2006 to 2009, there were 15 publications; and from 2010 to 2013, exactly 46 articles related to the theme have been recorded.

The second main thematic area is the methodological development of LCA (cluster 4 in Fig. IV-5). Three of the most frequent keywords from this group were ‘land use’, ‘land use change’ (LUC) and ‘s-lca’ (social life cycle assessment). Souza et al. (2013) and Ramirez et al. (2014) are recent examples of publications on such themes. Other keywords, such as 'LCI' (25 records), do not necessarily represent a methodological development; they could only indicate a characteristic of the study (e.g., RIBEIRO; SILVA, 2010). On the other hand, LCI may represent a good indicator of available data in those papers, especially if they were connected to 'industry' (cluster 1), which could also indicate a primary data source. LCI is connected to a wide range of words (e.g., biodiesel, energy, recycling, and others) suggesting that inventories are developed and published in several domain areas.

'Energy', another hot topic of LCA studies (HOU et al., 2015), with 24 records in the query represents the third most important field of research in Brazil. In cluster 3, other expression indicates the source of energy production - 'renewable energy' (8 records) whereas a connection to 'biomass' (16 records) can be highlighted. Both are correlated words used in reference to biomass as the main biobased source for energy production. This link enhances the relation to cluster 2 because sugarcane and bagasse were applied to energy production. Research on energy production began in 2003 (see COLTRO; GARCIA; QUEIROZ, 2003) at the inventory level, which it is illustrated by the purple connections in Fig. IV-6 A. In 2007, the first connections with energy can be observed (orange links in Fig. IV-6 A), while other energy sources started to be studied, such as solar and hydroelectricity (PACCA; SIVARAMAN; KEOLEIAN, 2007; PACCA, 2007, respectively). Subsequently, this domain area involved sugarcane as an energy source. More recent efforts were published by Guerra et al. (2014) and Silva et al. (2014).

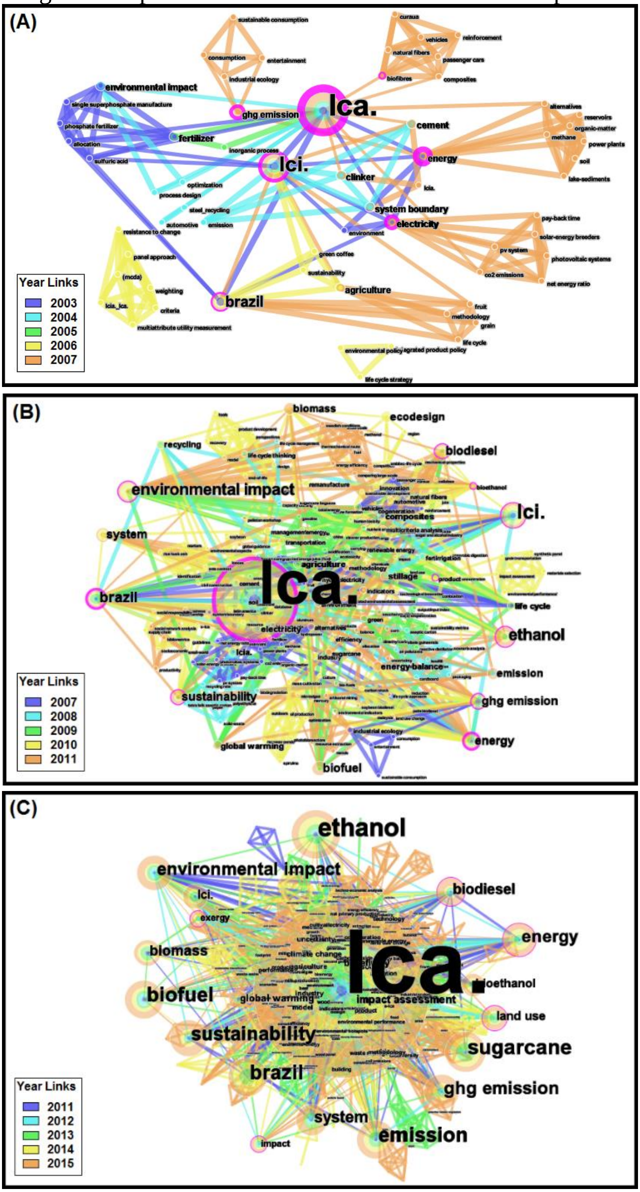
Agribusiness has a unique status owing to its wide domain area that covers from crop production to livestock systems. Thus, keyword repetition is unlikely even when studies represent the same research field. In this sense, with the normalization of the keywords, this area becomes the fourth most active research field in Brazil. Clusters 5 and 7 from Fig. IV-5 show the agribusiness domain area, which is divided into agriculture systems and livestock, respectively. In the agriculture cluster, 'agriculture' (11 records) is the unique keyword appearance within cut criteria (i.e., top 50 keywords). Analyzing other relations in this cluster we find 'cultivation' and 'maize' (also called corn) and 'fertilizing' as topics. Connections between agribusiness and other clusters explain its uses, including biodiesel (i.e., soybean, palm and others), electricity, and ingredients for animal feed (connected to beef).

Livestock cluster is represented by the three main animal productions in Brazil: ‘cattle’, ‘poultry’ and ‘swine’. In addition to its connection with the agricultural cluster, a link with climate change was noticed in cluster 4. This behavior occurs due the fact that agribusiness are potential GHG emitters, being LCA studies on this field frequently directed to its quantification (for instance, CHERUBINI et al., 2015 and LÉIS et al., 2015).

Cluster 6 is related to waste management with two keywords, ‘recycling’ (8 indications) and ‘waste management’ (6 indications). In this case, we could observe connections between this cluster and cluster 8 (buildings) that indicates a research on construction and demolition waste management.

The overall evolution presented in the three established time spans of Fig. IV-6 demonstrates the gradual strengthening of LCA in Brazil, mainly in terms of the scientific basis and research maturity. Some nodes can be noticed in the early stages of this trajectory, which were identified as border research areas (i.e., small islands on Fig. IV-6 A). Conversely, the subsequent spans demonstrate a gradual increase in interrelationships culminating in one tangled scenario (Fig. IV-6 C), with various and different words being connected.

Fig. IV-6. Co-word evolution during the time span separated into three periods: (A) 2003–2007, (B) 2007–2011 and (C) 2011–2015. Periods were divided equally during the lifespan to allow a better visualization of temporal evolution.



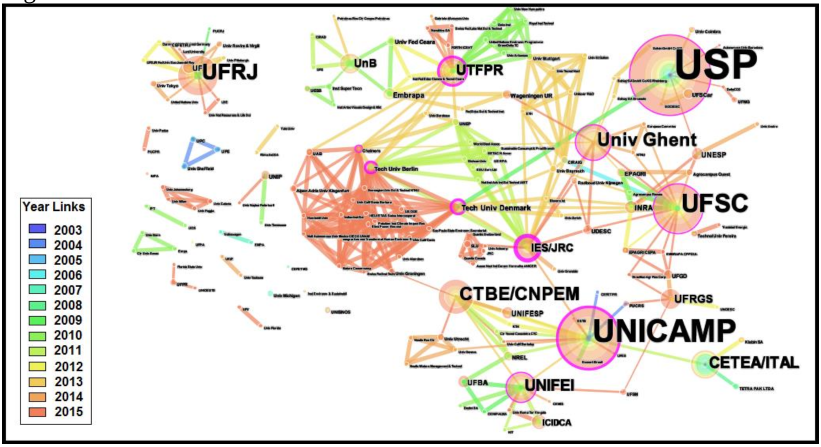
3.3.2 Co-collaboration

The relation between institutions indicated three main clusters (Fig. IV-7) with important international collaborations, headed by University of São Paulo (USP), University of Campinas (Unicamp) and Federal University of Rio de Janeiro (UFRJ). A time evolution analysis clearly shows a significant increase in collaborative research since 2003 (Fig. IV-8) although some recent LCA research groups are still isolated as can be observed in the single lines of Fig. IV-7.

The first international collaboration based on published papers was made by Pernambuco University (UPE) and Universitat Autonoma Barcelona in Spain through the paper from Josa et al. (2004). This particular relation corroborates a statement made by Hou et al. (2015), in which the authors suggests that LCAs researched by Spanish institutions are particularly interinstitutional. Meanwhile, for national collaboration on LCA research, our results place Unicamp as a pioneer with the partnership established in 2004 with the Pontifical Catholic University (PUC-RS) and the Federal Center of Technological Education (CEFET-PR) (BAUER; FILHO, 2004; UGAYA; WALTER, 2004).

According to Fig. IV-7, the major collaboration group is headed by USP and Federal University of Santa Catarina (UFSC). USP and UFSC have already been indicated as two of the main research organizations of LCA in Brazil (CHERUBINI; RIBEIRO, 2015; ZANGHELINI et al., 2014a). USP played a key role in the early steps of Brazilian LCA (Fig. IV-8) with one of the first publications in 2003 (SILVA; KULAY, 2003) and the first research group dedicated to LCA, the Group of Pollution Prevention (GP2). However, the connection between both universities is made by a single international institution (i.e., Technology University of Denmark) and one national institution (UNESP), which means that although both are in the same collaboration net, they have not worked together to date. In fact, other than single collaborations (i.e., University of Coimbra and Autonomous University of Barcelona), the Technology University of Denmark and UNESP are the only connections from USP to the other two clusters from Fig. IV-7. The presence of Technology University of Denmark in this diagram is not a coincidence; this university is at the center of the collaboration network among the top 30 productive institutions worldwide in LCA (HOU et al., 2015).

Fig. IV-7. Brazilian co-collaboration network from 2003 to 2015.

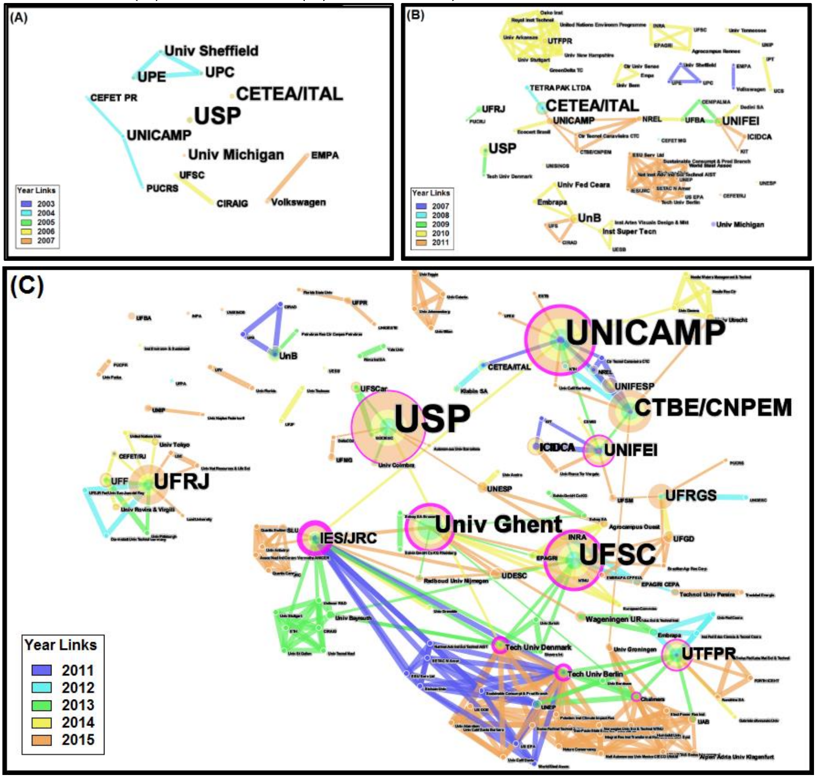


UFSC was responsible for the second international collaboration of LCA in 2006 (SOARES; TOFFOLETTO, DESCHÊNES 2006), with Ecole Polytech from Canada (Fig. IV-8). Thereafter, the university has created a closer connection with agricultural research institutions, such as French National Institute for Agricultural Research (INRA) in France and Santa Catarina Rural Extension and Agricultural Research Enterprise (EPAGRI) in Brazil, mainly because of the regional economy sector in Santa Catarina state, which is based on agribusiness. Recently, Ghent University has created a strong collaboration with USFC through collaborative work with Alvarenga (SOARES; TOFFOLETTO; DESCHÊNES, 2013). Three other Brazilian organizations highlighted in the same collaboration cluster are the Brasília University (UnB), the Federal Technological University of Paraná (UTFPR) and Brazilian Agricultural Research Corporation (Embrapa). UnB has developed relations with Embrapa and Petrobrás to develop LCA of fuel derivatives (CALDEIRA-PIRES et al., 2013) and Agro-industrial production systems (Figueirêdo et al., 2014). Meanwhile, UTFPR is the most important institution in Brazil with regard to international collaboration with partnerships involving the United Nations Programme (UNEP) and the Joint Research Centre (JRC). This collaboration was unsurprising because Professor Cássia Ugaya from UTFPR represents the Brazilian LCA community in those institutions and in the International LCA Academy. Cherubini and Ribeiro (2015) also described the importance of the above institutions in LCA development in Brazil. These universities represent the affiliations of the main researchers and professor responsible for national and international publications and for academic supervising in terms of the development of Master and PhD theses.

Unicamp led the second largest collaboration network group (Fig. IV-7) with a strong connection to the National Laboratory of Science and Technology of Bioethanol (CTBE) and the Brazilian Institute of Food Technology (CETEA/ITAL) and was responsible for important developments in the domain areas of biofuels and packaging. Meanwhile, the UFRJ is a more recent Brazilian network group, performing LCA research in the fields of energy and fuel.

The results of the collaboration network showed a similar behavior in the analysis of networks within domain areas (Fig. IV-6), which have evolved over time since 2003. From 2003 to 2007, there were isolated studies (Fig. IV-8 A) with minor networking. In a second span from 2007 - 2011, some partnership were established even without strait links (Fig. IV-8 B). More recently, from 2011 to 2015, a more robust network comprising industry, academia and government with international and national connections, has been established (Fig. IV-8 C). Cherubini and Ribeiro (2015) also reported the participation of government institutions - ITAL, Embrapa and CTBE - and industry - Petrobras - that have created collaborative works between those actors, such as Mourad et al. (2008), which involved industry and government, and Cavallet et al. (2013), which results from a partnership between academia and government. The current intellectual structure also demonstrates the evolution of LCA in Brazil, which is reflected in better-quality publications and is reinforced by the growing impact factor of articles as shown in Tab. IV-4.

Fig. IV-8. Evolution of collaboration between institutions in three periods: (A) 2003–2007; (B) 2007–2011; (C) 2011–2015).



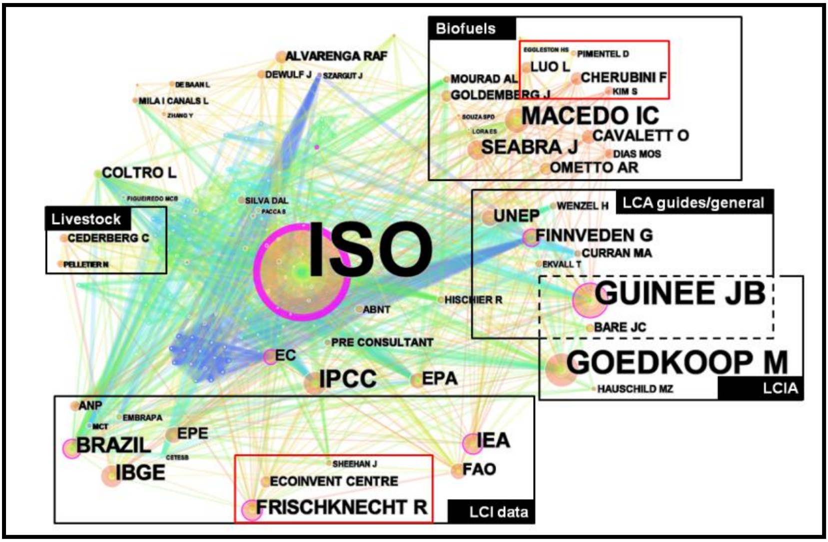
3.3.3 Co-cocitation

The co-citation network identifies the main papers or authors in a determined research area with regard to citations and demonstrates how authors and papers are connected. Fig. IV-9 depicts the authors/institutions with major influence in the group of analyzed papers. From that result it is possible to identify ISO as the most cited institution (157 records, when summed over all standards). This finding was to be expected since ISO is cited to indicate methodology paths and to justify choices, such as allocation.

Regarding international authors, Mark Goedkoop is the most cited (55 citations), followed by Jeroen B. Guinéé (47 citations). Both are important LCA researchers that have being developing the LCA methodology; the most cited works from those authors are respectively the ReCiPe (GOEDKOOP et al., 2009), Eco-indicator´99 (GOEDKOOP; SPRIENSMA, 1999) and the Handbook on Life Cycle Assessment (Guinée et al., 2002). The first two reports are related to LCIA methods, as can be seen in the cluster from Fig. IV-9, while the Handbook is cited as a LCA guide, but also as the reference for CML-IA method.

The productions from Göran Finnveden (24 citations) can also be highlighted in the LCA guides/general cluster (Fig. IV-9). Among these, Finnveden et al. (2009) is the most expressive to point out a general picture of the developments of LCA methodology. Other authors have minor number of citations but also influence Brazilian LCA research to indicate general statements (e.g. UNEP, 2009).

Fig. IV-9. Main co-citation network in Brazilian LCA research from 2003 to 2015.



An analysis addressing specific research fields stands out the importance of the publications from Isaias C. Macedo (48 citations) for the LCA of biofuels. Macedo, Seabra and Silva (2008) is the third publication most cited (24 citations) by the LCA publications in Brazil and it is the most influential work in the Biofuels cluster (Fig. IV-9). The high frequency of citation of this paper is not a surprise once Biofuels is the main topic in Brazilian LCA research. Other important Brazilian researchers in the Biofuels cluster are Joaquim E. A. Seabra, Otávio Cavalett and Aldo R. Ometto, respectively with 35, 28 and 25 citations.

In this cluster, the international most influent authors are Francesco Cherubini with 26 citations distributed by 13 publications (in which, CHERUBINI; STRØMMAN, 2011 and CHERUBINI; ULGIATI, 2010, are the most cited) and Lin Luo with 19 citations mainly from Luo, Van Der Voet and Huppes (2009), the sixth most cited paper from all the Brazilian researches (15 citations). Other three international authors complete the red box inside the Biofuels theme.

Due to the high dependency of LCA studies on data information, it could be noticed a set of other highly cited authors/institutions related to LCI data, production information and general statistics. In this cluster, the red box (Fig. IV-9) is related to data from international databases, whereas outside the red box but still in LCI data cluster, it is possible to identify important international governmental institutions (e.g., FAO, IEA) as well as Brazilian's sources of statistical data (e.g., IBGE, EPE, and Brazil itself, when referring to laws and official reports). This cluster highlights the importance of the ecoinvent® database, cited 17 times as Ecoinvent Centre, but also referenced by the authors of the ecoinvent data reports, such as Frischknecht et al. (2007a; b) with 13 and 7 citations, respectively. Another LCA topic that is influenced by Rolf Frischknecht is related to the LCIA method.

Finally, regarding to livestock production, Christel Cederberg plays an important role, appearing 22 times as reference in the sample of papers, and Cederberg, Meyer and Flysjö (2009) dealing with LCI in Brazilian Beef production represents the most cited publication.

4 CONCLUSIONS

LCA has been demonstrated to be a valuable tool to provide environmental perspectives in decision making. It is a consensus among scientific community that LCA has not only spread very widely in the scientific media but has also been developed in industrial sectors. In effect, the rapid growth can complicate some important analyses as the identification of an emerging research area or even which is the main topic addressed by a specific scientific community. This paper performed a bibliometric review of LCA papers indexed in ISI from Brazil or developed by Brazilian researchers, and it was demonstrated that Brazilian LCA research has evolved in recent years, namely in terms of relations between areas, institutional networking and researcher connections. Based on 165 articles that respected the outlined methodology, we sought to provide a current and precise overview of Brazilian LCA research.

Despite the limited scientific production, there is an undeniable evolution of Brazilian LCA research in the last 10 years, which follows international patterns in this field. This affirmation is supported by the growing number of published papers, the increased complexity of the relationships between keywords (which can be assumed to be an improvement in interdisciplinary study or just an increase in practitioners) and the clear growth of networking groups and collaboration nets since 1998. Moreover, the IF (annual average) of indexed papers demonstrated a constant rise, which reinforces LCA as a growing topic worldwide. PhD and Master Theses projects have been going through a severe reduction since 2012/2013; this may be a matter of concern in terms of scientific production because of its relation with the publishing process.

In contrast, Brazilian industry and government institutions seem to be more involved in LCA. This finding may explain the growth on publications despite the reduction on academic projects. Another example of this involvement regarding government is the National Policy on Waste Management (2010) that indicates shared responsibility for products life cycle amongst its production and consumption chain and have already influenced recent publications related to vehicles and end-of-life of electrical electronic equipment (e.g., Zanghelini et al., 2014b). This may generate a demand for LCA studies that could result in LCI with a high level of data quality and new unexplored sectors - an important incentive for future publishing.

Currently, the main domain of Brazilian LCA is biofuels, in which bioethanol from sugarcane and biodiesel from crops with different energy potentials are the main drivers. About 25% of all Brazilian LCA publications are related to the theme. Other important areas are energy, LCA methodology - which gained prominence in the ‘land use’ impact category within ‘LCIA’, ‘S-LCA’ and ‘LCI’ - and ‘agribusiness’ (crop and livestock systems). Recently, the Brazilian Programme on Life Cycle Assessment (PBACV) and The Brazilian Business Network on Life Cycle Assessment defined a priority list of LCI that will be developed for the national database, including, for instance, industrial base sectors as electricity, cement, and petrochemicals, among others. Because the current domain areas do not match those priorities, the list could lead to an evolution in those fields within the near future and drive the trends for the next steps in Brazilian LCA development.

The network of collaboration among institutions led by USP, Unicamp and UFRJ demonstrates internal improvement in existing clusters. However, certain relationships are still lacking between these same groups. Therefore, there is a wide margin to reinforce Brazilian collaborative research and increase international partnerships with foreign institutions. This profile may contribute somewhat to the knowledge economy, as experiences and primary data are exchanged between organizations. In this sense, improvement of the network is mandatory for LCA strength and development in Brazil.

Regarding to the influence for Brazilian LCA research, ISO emerges as the main reference due to standards followed by Mark Goedkoop and Jeroen B. Guinée. The latter two authors are highly cited because of LCIA method application (i.e. ReCiPe, Ecoindicator 99 and CML-IA) and general guidelines (LCA handbook), respectively. However, Isaias C. Macedo is the main reference inside the main theme (i.e. biofuels), and because of this feature, perhaps he is the most influential author in Brazilian LCA research.

Future challenges may be addressed to identify barriers in Brazilian LCA research. Mapping those bottlenecks would be valuable information to plan future actions and promote further developments. In this path, a comparison to other countries and regions might be a first step. Comparing indicators and networks found in this paper to other countries (i.e. formers of BRICS as China or India), to Latin America, or even to a developed country (as USA or Germany) may indicate where Brazilian LCA research is placed in comparison to other engaged nations. Understanding how those countries dealt with their barriers would indicate a secure path to implement LCA as business and national policy tool and for further publishing.

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APÊNDICE C – Questionário 1 - Critérios

Este é o questionário 1 do modelo de MCDA aplicado nesta tese, referente aos critérios utilizados para avaliar impactos ambientais e enviado aos pesquisadores especialistas em ACV da rede do CICLOG.

ORIENTAÇÕES

A sua participação consistirá em ponderar esses critérios por meio do Processo de Análise Hierárquica (AHP).. Essa ponderação é feita comparando-se os critérios par a par, definindo-se o nível de importância que um critério tem sobre o outro segundo a escala de Saaty (Tab. IV-8). Para maiores informações acerca dos critérios, exemplos e explicações, veja o glossário nas páginas 3 e 4. Caso você tenha interesse em saber um pouco mais sobre esta pesquisa, a página 5 contém uma breve explicação deste trabalho.

Tab. IV-8. Escala de importância de Saaty.

Escala	**Descrição da escala**	**Explicação da escala**
1	Igualmente preferível	Os dois critérios contribuem igualmente para o objeto
3	Importância pequena de uma sobre a outra	A experiência e o julgamento favorecem levemente um critério em relação ao outro
5	Importância grande ou essencial	A experiência e o julgamento favorecem fortemente um critério em relação ao outro
7	Importância muito grande ou demonstrada	Um critério é muito fortemente favorecido em relação ao outro; sua dominação de importância é demonstrada na prática
9	Importância absoluta	A evidência favorece um critério em relação ao outro com o mais alto grau de certeza

Com base na escala de Saaty, você deverá preencher a "***Tabela para preenchimento***" (na página 2) conforme o exemplo hipotético da Tab. IV-9.

Tab. IV-9. Exemplo de preenchimento da tabela.

Pesquisador: Gustavo Kuerten										
COMPARAÇÃO DE CRITÉRIOS – ESCALA DE SAATY										
1º Critério	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	2º Critério
Abrangência espacial			X							Duração
Abrangência espacial									X	Reversibilidade
Abrangência espacial		X								Probabilidade de ocorrência
Abrangência espacial					X					Impacto para a saúde humana

Para este exemplo, o pesquisador voluntário considera que o critério "abrangência espacial" representa uma importância grande se comparado ao critério "duração" de um impacto ambiental. Ele julga que a área de ação de um impacto é mais relevante do que a duração que ele eventualmente possa ter. Já quando comparados os critérios “abrangência espacial” com “reversibilidade” o pesquisador considera o segundo critério de importância absoluta em relação ao primeiro, julgando que o fato de existirem consequências irreversíveis oriundas de um impacto ambiental é de absoluta importância quando se compara à área que porventura este impacto possa atingir. Na sequência o pesquisador acredita que a amplitude geográfica representada pela “abrangência espacial” é de importância muito grande comparado a “probabilidade de ocorrência”. Aqui ele julgou que a amplitude do impacto representa uma relevância dominante sobre a possibilidade de ele ocorrer. Por fim, “abrangência espacial” e “impacto para a saúde humana” possuem a mesma importância, entendendo que ambos possuem a mesma significância em termos de impactos ambientais. Assim, segue a “***Tabela para preenchimento***” que deverá ser preenchida por você para contribuir com essa pesquisa.

Tab. IV-10. Tabela para preenchimento (Questionário 1)

Pesquisador:										
COMPARAÇÃO DE CRITÉRIOS – ESCALA DE SAATY										
1º Critério	**9**	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**	2º Critério
Abrangência espacial										Duração
Abrangência espacial										Reversibilidade
Abrangência espacial										Probabilidade de ocorrência
Abrangência espacial										Impacto para a saúde humana
Abrangência espacial										Impacto para o ecossistema
Abrangência espacial										Recursos Naturais
Abrangência espacial										Tecnologia para o tratamento
Duração										Reversibilidade
Duração										Probabilidade de ocorrência
Duração										Impacto para a saúde humana
Duração										Impacto para o ecossistema
Duração										Recursos Naturais
Duração										Tecnologia para o tratamento
Reversibilidade										Probabilidade de ocorrência
Reversibilidade										Impacto para a saúde humana
Reversibilidade										Impacto para o ecossistema
Reversibilidade										Recursos Naturais
Reversibilidade										Tecnologia para o tratamento
Probabilidade de ocorrência										Impacto para a saúde humana
Probabilidade de ocorrência										Impacto para o ecossistema
Probabilidade de ocorrência										Recursos Naturais
Probabilidade de ocorrência										Tecnologia para o tratamento
Impacto para a saúde humana										Impacto para o ecossistema
Impacto para a saúde humana										Recursos Naturais
Impacto para a saúde humana										Tecnologia para o tratamento
Impacto para o ecossistema										Recursos Naturais
Impacto para o ecossistema										Tecnologia para o tratamento
Recursos Naturais										Tecnologia para o tratamento

GLOSSÁRIO DE CRITÉRIOS

I. ABRANGÊNCIA ESPACIAL (MAGNITUDE/ESCALA): critério referente à área sobre a qual o impacto é esperado para atuar (VOLKWEIN; GIHR; KLOPFFER, 1996). Este aspecto parte do princípio que os problemas ambientais que afetam uma área maior (global ou regional) ou áreas geográficas mais significativas (áreas naturais protegidas, lugares populosos) são mais graves do que aqueles que afetam áreas menores (AGARSKI et al., 2016). Ou seja, quanto mais significativa for a zona de ocorrência, maior a probabilidade de aumento de danos (SOARES; TOFFOLETTO, DESCHÊNES, 2006). Alguns exemplos de impactos com relação a este critério são: em escala global as mudanças climáticas (e.g. seus efeitos acarretam no degelo das calotas polares e aumento do nível dos oceanos); em escala local pode-se citar a eutrofização (seus efeitos podem causar a diminuição de oxigênio dissolvido em um corpo hídrico, refletindo na mortandade de peixes).

II. DURAÇÃO: o critério "duração" refere-se ao julgamento de que os problemas ambientais com uma duração mais longa são mais graves do que aqueles que têm uma duração menor (AGARSKI et al., 2016). Este critério sugere que quanto mais longa for a ação, mais representativa será sua repercussão no meio ambiente. Parte-se do princípio que se uma ação ocorre durante um período de tempo mais longo, a probabilidade de aumentar o impacto ambiental também se torna maior (SOARES; TOFFOLETTO, DESCHÊNES, 2006). Por exemplo, a eutrofização que ocorre nos rios da grande São Paulo, como o rio Pinheiros, já perdura por vários anos (duração longa), enquanto que a eutrofização que ocorre nos rios do norte da ilha de Florianópolis (e.g. Rio do Braz em Canasvieiras) acontece no verão quando há excesso de carga orgânica devido ao aumento populacional nas férias (duração média).

III. REVERSIBILIDADE: este critério deve levar em consideração a possibilidade e a dificuldade de reversibilidade (artificial ou natural) do impacto (SOARES; TOFFOLETTO, DESCHÊNES, 2006), ou seja, a capacidade do sistema (ambiente afetado) de retornar ao seu estado anterior (SÁNCHEZ, 2006). Parte-se do princípio de que as consequências ambientais irreversíveis são um problema maior do que aqueles que podem ser remediados para restabelecer uma condição anterior após um determinado período (AGARSKI et al., 2016). Um exemplo de impacto irreversível pode ser a Mudança Climática, cujos efeitos podem causar a desertificação de determinada área, condição que não pode retornar ao estado original. Um exemplo de impacto reversível pode ser a eutrofização, quando cessada a carga orgânica e de nutrientes, o corpo hídrico tem a capacidade de depuração e restabelecimento de sua condição natural.

IV. PROBABILIDADE DE OCORRÊNCIA: refere-se ao grau de incerteza acerca da ocorrência do impacto. Um exemplo de classificação de extremos com relação a impactos pode ser: (i) alta, quando não há dúvida sobre a ocorrência do impacto e (ii) baixa, quando é muito pouco provável a ocorrência do impacto em questão (mesmo assim não pode desprezar esta possibilidade) (SÁNCHEZ, 2006). Um impacto que reflete uma alta probabilidade de ocorrência pode ser a eutrofização. É quase certo que uma alta carga orgânica lançada em um corpo hídrico causará uma proliferação de algas e consequentemente uma redução no oxigênio dissolvido. Por outro lado, uma emissão de substância acidificante nem sempre causará uma chuva ácida, deste modo a probabilidade de ocorrência da acidificação pode ser menor do que a eutrofização.

V. IMPACTO PARA A SAÚDE HUMANA: este critério aplica-se à mortalidade e às doenças humanas. Quanto mais graves as repercussões na saúde, mais significativa é a categoria de impacto (SOARES; TOFFOLETTO, DESCHÊNES, 2006). Diferentemente dos critérios anteriores, este (e os próximos dois) é um critério relacionado ao dano causado pelos impactos ambientais. O impacto para a saúde humana ocorre por diversos motivos quando originados por impactos ambientais. Por exemplo, o Smog causa danos respiratórios diretos à população, a toxicidade atua diretamente causando doenças (e.g. hepáticas e nervosas), o aquecimento global acentua a incidência de infartos, catarata, etc.

VI. IMPACTO PARA O ECOSSISTEMA: este critério expressa o efeito sobre a biodiversidade. Aplica-se ao desaparecimento ou diminuição do saldo das espécies e dos ecossistemas. Quanto mais graves as repercussões sobre a biodiversidade, mais significativa é a categoria de impacto (SOARES; TOFFOLETTO, DESCHÊNES, 2006). Os impactos ao ecossistema ocorrem em virtude dos danos causados à fauna e flora. Por exemplo, a acidificação quando ocorre na forma de chuva ácida afeta diretamente a vegetação atingida. Outro exemplo, a eutrofização causa a mortandade de fauna aquática pela redução de oxigênio dissolvido na água.

VII. RECURSOS NATURAIS: este critério diz respeito ao esgotamento nas reservas naturais de matéria-prima (renovável e não renovável). Quanto mais severas as repercussões na sua disponibilidade, mais significativa é a categoria de impacto (SOARES; TOFFOLETTO, DESCHÊNES, 2006). Este critério tem relação com danos ao esgotamento de recursos. Por exemplo, a categoria de impacto de consumo de metais afeta diretamente nas reservas de minérios no planeta.

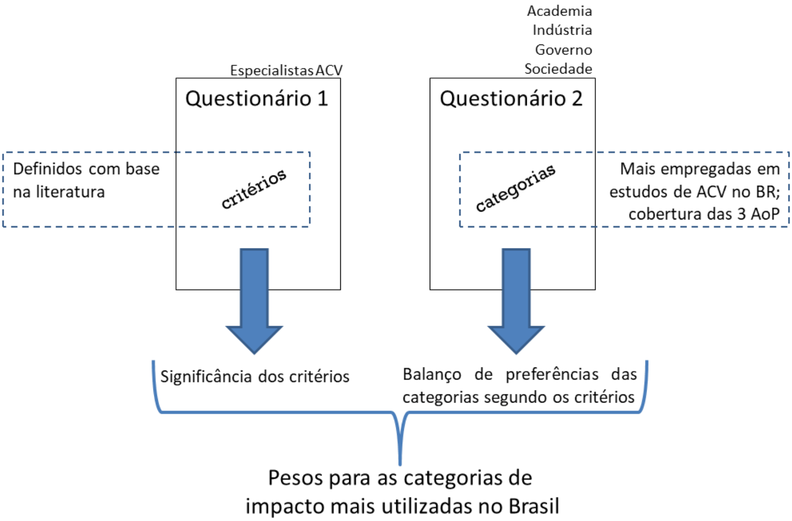
VIII. TECNOLOGIA PARA TRATAMENTO/RECUPERAÇÃO: este critério refere-se à disponibilidade tecnológica para recuperar os danos que determinado impacto possa causar. Parte-se do princípio que um impacto, para o qual não exista tecnologia de “combate”, representa uma pior condição se comparada ao impacto que pode ser tratado. Por exemplo, existem sistemas de tratamento de efluentes que podem tratar a carga orgânica em ambientes eutrofizados, ou aeradores que podem acelerar o processo de depuração do corpo hídrico. Desta forma pode-se considerar que a eutrofização possui tecnologias para sua recuperação. Com relação à acidificação, não existe uma tecnologia para recuperar a fauna atingida por chuva ácida (a não ser sua recuperação natural). Desta forma não há tecnologia de recuperação.

QUANTO À PESQUISA

Sabemos que a interpretação dos resultados de uma ACV nem sempre permite a decisão com absoluta certeza. Situações na qual ocorrem *trade-offs* entre diferentes categorias de impacto quando analisamos diferentes cenários ou alternativas é muito comum em estudos de ACV. Para estes casos, a ponderação (apesar de opcional) é um bom caminho no auxílio à interpretação e a tomada de decisão.

A ponderação é baseada no modo como entendemos a importância (ou significância) dos impactos e para tanto partimos de julgamentos. Como diferentes pessoas julgam de formas distintas diferentes situações, entendemos que um conjunto de pesos voltados para o Brasil poderia melhorar o desenvolvimento e aplicação da ACV (e pode ser mais ajustada para a condição nacional do que os conjuntos de pesos já existentes), atuando no aumento de consistência dos resultados, na comunicação e no entendimento das partes interessadas (diminuindo o uso frequente do “depende” dos resultados de uma ACV). Para auxiliar na “extração” deste julgamento por parte dos *stakeholders* nacionais, utilizaremos a abordagem de análise de decisão multicritério pelo emprego do método AHP-PROMETHEE II. Este primeiro questionário busca extrair a significância dos critérios que serão utilizados na comparação das categorias de impacto (segundo questionário), conforme esquema ilustrativo abaixo.

Fig. IV-10. Fluxograma básico do modelo MCDA aplicado nesta tese (Q1).



O conjunto de critérios contemplados neste primeiro questionário foi definido com base em revisão bibliográfica em estudos de MCDA para tomada de decisão ambiental e buscou contemplar elementos associados com a probabilidade de aumento da magnitude das consequências (escala, duração, reversibilidade, probabilidade de ocorrência), com as consequências ambientais nas áreas de proteção (saúde humana, ecossistemas e recursos) e com a possibilidade de tratamento/recuperação (Tecnologia de tratamento).

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APÊNDICE D - Questionário 2 – Categorias de Impacto

Este é o questionário 2 do modelo de MCDA aplicado nesta tese, referente às categorias de impacto *midpoint* usuais da ACV e enviado aos *stakeholders* nacionais formadas por representantes da indústria, do governo e da academia.

ORIENTAÇÕES

A sua participação consistirá em preencher as tabelas que correlacionam cada critério frente aos impactos ambientais, de acordo com as definições de escalas de respostas apresentadas individualmente, conforme exemplo a seguir:

Tab. IV-11. Exemplo para preenchimento do questionário 2.

ABRANGÊNCIA ESPACIAL				
Escala de resposta	**Alternativas**			
	A	**B**	**C**	**...**
Global	X			...
Global/regional				...
Regional		X		...
Regional/local				...
Local			X	...

Para este exemplo, o respondente considera que a categoria de impacto de “A” possui efeito Global para o critério Abrangência espacial (ex. efeitos dos seus impactos atuam em todo o globo). Para este mesmo critério, o participante considerou que a categoria “B” possui enquadramento regional (ex. efeitos ocorrem em nível da região norte do Brasil) enquanto que “C” possui efeito local (ex. um corpo hídrico em um determinado município).

Com estas orientações, nas páginas seguintes encontram-se as tabelas para preenchimento que deverão ser preenchidas por você para contribuir com essa pesquisa. Uma breve explicação acerca deste trabalho, com objetivos e metodologia é apresentada ao final deste documento. Além disso, e caso haja a necessidade de se compreender ou relembrar os critérios e as categorias de impacto, um glossário é apresentado nas páginas seguintes ao questionário com definições e exemplos.

PREENCHIMENTO

ABRANGÊNCIA ESPACIAL

Considere que um impacto é **Global** quando afeta localidades de forma independente do ponto onde ocorre podendo ser caracterizados como os impactos com efeito espacial de um ou mais continente(s) (ex. Ásia, América Latina) ou de países continentais (ex. Brasil, China). Para o nível **Regional**, a abrangência é de tamanho "estadual" (ex. Paraná) ou interestadual (ex. região sudeste no Brasil). Por fim, em nível de **Local**, entende-se impactos que afetam municípios (ex. cidade de São Paulo). Considere as escalas intermediárias como impactos que oscilam entre duas classificações para a abrangência espacial (ex: local/regional para um impacto que atinge alguns municípios em um estado).

Tab. IV-12. Quadro do critério Abrangência Espacial.

ABRANGÊNCIA ESPACIAL								
Escala de resposta	Alternativas							
	Mudanças Climáticas	Acidificação	Eutrofização	Diminuição da camada de ozônio	Toxicidade humana	Diminuição de Recursos Abióticos	SMOG	Uso e ocupação de terras
Global								
Global/regional								
Regional								
Regional/local								
Local								

DURAÇÃO

Entende-se por um impacto de **Longa duração** aquele com efeitos permanentes ou por período de tempo indefinido e/ou superior a uma geração humana (ex. >100 anos); de **Média duração** os impactos que perduram por período de tempo de até uma geração humana (ex. 1 – 100 anos); e de **Curta duração**, os impactos que causam efeitos somente durante a ação que os causou (<1 ano).

Tab. IV-13. Quadro do critério Duração.

DURAÇÃO								
Escala de resposta	Alternativas							
	Mudanças Climáticas	Acidificação	Eutrofização	Diminuição da camada de ozônio	Toxicidade humana	Diminuição de Recursos Abióticos	SMOG	Uso e ocupação de terras
Longa								
Média								
Curta								

REVERSIBILIDADE

O impacto **Irreversível** é aquele que causa efeitos permanentes ao local afetado, sendo que a condição natural não pode ser mais restabelecida (mesmo com ações corretivas). Um impacto **Reversível** por outro lado é aquele cujos efeitos podem ser corrigidos de forma a estabelecer uma condição similar à de antes da ocorrência, ou seja, consegue restabelecer as funções e qualidade ambiental do meio.

Tab. IV-14. Quadro do critério Reversibilidade.

REVERSIBILIDADE								
Escala de resposta	Alternativas							
	Mudanças Climáticas	Acidificação	Eutrofização	Diminuição da camada de ozônio	Toxicidade humana	Diminuição de Recursos Abióticos	SMOG	Uso e ocupação de terras
Irreversível								
Reversível								

PROBABILIDADE DE OCORRÊNCIA

Um impacto é classificado como **Muito provável** de ocorrer quando existe a certeza (científica ou por casos semelhantes) de que, havendo a causa (ex. emissão de um aspecto) acarretará em efeitos danosos (ex. impacto ambiental na flora). **Provável** é o impacto com boa condição de acarretar determinado efeito na área atingida (mas nem sempre acarretará em danos). **Pouco Provável** é o impacto que dificilmente ocorrerá em detrimento a uma determinada ação (aspecto) (ex. mesmo havendo uma emissão atmosférica, o impacto causado é muito pouco provável de ocorrer).

Tab. IV-15. Quadro do critério Probabilidade de ocorrência.

PROBABILIDADE DE OCORRÊNCIA								
Escala de resposta	Alternativas							
	Mudanças Climáticas	Acidificação	Eutrofização	Diminuição da camada de ozônio	Toxicidade humana	Diminuição de Recursos Abióticos	SMOG	Uso e ocupação de terras
Muito provável								
Provável								
Pouco provável								

DANOS À SAÚDE HUMANA

Entende-se como um **Grande** dano à saúde humana, impactos que eventualmente acarretam na morte prematura ou em danos irreversíveis à saúde dos seres humanos (ex. AVC, cegueira, etc.) ou permanecem na cadeia genética causando efeitos negativos na saúde de seguintes gerações (ex. toxicidade genética); de **Médio** dano, impactos que podem causar um dano severo, porém reversível ao ser humano (ex. bronquite); e de **Pequeno** dano, que são impactos que afetam momentaneamente o ser humano (ex. alergias), com severidade baixa (ex. coceiras).

Tab. IV-16. Quadro do critério Danos à saúde humana.

DANOS A SAÚDE HUMANA								
Escala de resposta	Alternativas							
	Mudanças Climáticas	Acidificação	Eutrofização	Diminuição da camada de ozônio	Toxicidade humana	Diminuição de Recursos Abióticos	SMOG	Uso e ocupação de terras
Grande								
Médio								
Pequeno								

DANOS AO ECOSSISTEMA

Entende-se como um **Grande** dano ao ecossistema, impactos que acarretam no desaparecimento de espécies da fauna e flora ou em danos irreversíveis aos biomas (ex. desertificação) ou permanecem na cadeia trófica causando efeitos negativos na saúde das espécies; de **Médio** dano, impactos que podem causar um dano severo, porém reversível aos ecossistemas (ex. mortandade de parcela das espécies de determinada região; alteração na qualidade de um determinado corpo hídrico); e de **Pequeno** dano, que são impactos que afetam momentaneamente o ecossistema (ex. ruídos), com severidade baixa (ex. afugentamento de espécies da fauna).

Tab. IV-17. Quadro do critério Danos ao ecossistema.

DANOS AO ECOSSISTEMA								
Escala de resposta	Alternativas							
	Mudanças Climáticas	Acidificação	Eutrofização	Diminuição da camada de ozônio	Toxicidade humana	Diminuição de Recursos Abióticos	SMOG	Uso e ocupação de terras
Grande								
Médio								
Pequeno								

ESGOTAMENTO DE RECURSOS

Considere como um **Grande esgotamento,** impactos que afetam as reservas abióticas de tal forma que acarretem seu esgotamento total ou que impeçam gerações futuras de consumirem tais recursos (renováveis ou não renováveis) (ex. o consumo em larga escala). Um **Médio esgotamento** é aquele que diminui consideravelmente o acesso aos recursos para as atuais e futuras gerações (mas não o esgota) (ex. uma alteração na geografia/qualidade do solo de determinada área que dificulte a extração de minérios). Por fim, um **Pequeno esgotamento** é aquele que afeta momentaneamente o acesso a determinado recurso, mas pode ser revertido (ex: a alteração na qualidade de um corpo hídrico que afeta a extração de areia).

Tab. IV-18. Quadro do critério Esgotamento de recursos.

ESGOTAMENTO DE RECURSOS								
Escala de resposta	Alternativas							
	Mudanças Climáticas	Acidificação	Eutrofização	Diminuição da camada de ozônio	Toxicidade humana	Diminuição de Recursos Abióticos	SMOG	Uso e ocupação de terras
Grande esgot.								
Médio esgot.								
Pequeno esgot.								

POSSIBILIDADE DE TRATAMENTO

Não há a possibilidade de tratamento quando um dos efeitos de um impacto não pode ser amenizados/revertidos de forma tecnológica. **Há pouca possibilidade** de tratamento quando existem técnicas somente para controlar/amenizar os efeitos de determinado impacto, mas não é possível revertê-los à condição de restabelecer as funções e qualidade ambiental do meio (ex. uso de maquinário para desassorear determinado corpo hídrico afetado pela erosão a montante). **Há possibilidade** de tratamento quando existem meios tecnológicos de amenizar e reverter as condições de qualidade ambiental do meio (ex. aeradores e tratamentos para um corpo hídrico poluído; operação de pessoas afetadas pela catarata).

Tab. IV-19. Quadro do critério Possibilidade de tratamento.

POSSIBILIDADE DE TRATAMENTO								
Escala de resposta	Alternativas							
	Mudanças Climáticas	Acidificação	Eutrofização	Diminuição da camada de ozônio	Toxicidade humana	Diminuição de Recursos Abióticos	SMOG	Uso e ocupação de terras
Não há poss.								
Há pouca poss.								
Há poss.								

COMENTÁRIOS ADICIONAIS (SE HOUVEREM):

GLOSSÁRIO DE CATEGORIAS

A. AQUECIMENTO GLOBAL (MUDANÇAS CLIMÁTICAS): grande parte das atividades humanas emite, em maior ou menor grau, substâncias que conhecemos como gases de efeito estufa (GEE). Quando são emitidos em quantidade superior à possibilidade de absorção do nosso planeta, estes gases ficam depositados em nossa atmosfera, formando uma espécie de barreira que acaba por potencializar um efeito natural de aquecimento da Terra. Esta barreira retém a radiação solar na atmosfera (diminuindo sua dissipação), e consequentemente, elevando a temperatura do planeta. Este desequilíbrio térmico causa mudanças no clima e gera impactos como o derretimento das calotas polares, desertificações, aumento de estressores ligados à saúde humana e outras alterações no regime climático.

B. ACIDIFICAÇÃO: este tipo de impacto ambiental é causado devido à emissão de algumas substâncias gasosas derivadas de nitrogênio e enxofre, que podem reagir com outras como a água e criar outras substâncias, ácidas, como por exemplo, o ácido sulfúrico. Essas substâncias retornam para a superfície terrestre através das chuvas ácidas, causando diversos danos à vegetação e ao solo, meios aquáticos (diminuição ou extinção de vida marinha) e ao meio antrópico (degradação de construções e monumentos).

C. EUTROFIZAÇÃO: fenômeno causado pelo lançamento excessivo de nutrientes (especialmente fósforo e nitrogênio) provenientes de efluentes domésticos ou atividades agrícolas em um corpo hídrico. Esta sobrecarga de matéria orgânica causa uma proliferação excessiva de algas nesse ambiente, que resulta na alteração da cadeia de processos bioquímicos do meio (como por exemplo, a redução da taxa de oxigênio dissolvido) e afeta toda a fauna e flora deste ecossistema.

D. DIMINUIÇÃO DA CAMADA DE OZÔNIO: a concentração do ozônio (O_3) é significativamente mais alta na estratosfera do que em outras partes da atmosfera, o que resulta em uma camada que protege a terra de radiação ultravioleta. As moléculas de ozônio absorvem grandes quantidades desta radiação, removendo a radiação UVC que ameaça a vida e reduz a radiação prejudicial UVB. No entanto, uma série de substâncias (algumas das quais ocorrem naturalmente na estratosfera) tem o potencial de degradar esta camada, entre elas:

compostos clorados (tais como os clorofluorcarbonetos - CFCs), compostos de bromo, metano (CH_4), óxido nitroso (N_2O) e vapor de água H_2O. A diminuição da camada de ozônio causa sérios efeitos sobre a vida na superfície da Terra, incluindo flora, fauna e seres humanos (sob a forma de câncer de pele, redução de imunidade, etc.).

E. TOXICIDADE HUMANA: algumas substâncias são nocivas aos seres humanos e ao meio ambiente, e quando lançadas por emissões atmosféricas, efluentes líquidos ou resíduos sólidos, podem acarretar em grandes danos ambientais agudos ou crônicos. Esta toxicidade abrange vários efeitos diferentes: toxicidade aguda, irritação, efeitos corrosivos, efeitos alergênicos, danos aos órgãos, danos ao material genético (genotoxicidade), efeitos cancerígenos, toxicidade para o sistema reprodutivo, neurotoxicidade, etc. As substâncias que contribuem para a toxicidade humana são numerosas. Alguns exemplos são os metais pesados (chumbo, mercúrio, etc.), óxidos nitrosos (NOx), compostos orgânicos voláteis (COVs), compostos orgânicos clorados, material particulado, óxidos de enxofre (SOx), etc.

F. DIMINUIÇÃO DE RECURSOS ABIÓTICOS: diminuição de Recursos Abióticos é uma categoria de impacto que mede a quantidade de recursos "não vivos" consumidos, como por exemplo o minério de ferro, o calcário e o petróleo. Os impactos estão associados a disponibilidade (ou diminuição na disponibilidade) destes recursos, e portanto, os efeitos desta categoria recaem na viabilidade de recursos para as gerações futuras.

G. FORMAÇÃO DE SMOG FOTOQUÍMICO: fenômeno é caracterizado pela emissão de substâncias para a atmosfera, como os compostos orgânicos voláteis – COVs e óxidos nitroso (NOx), que facilitam a criação de ozônio na camada inferior da atmosfera (troposfera), formando uma fumaça roxo-acinzentada nesta faixa. Em altas concentrações, este ozônio é perigoso para a saúde humana e quando inalada pode provocar diversos danos cardiorrespiratórios (ex: rinite, asma, bronquite, câncer de pulmão, ataque cardíaco, etc) e eventualmente causa a morte prematura. Os efeitos do smog afetam também a saúde da fauna (pelos mesmos motivos cardiorrespiratórios) e atingem a flora (necrose na superfície das folhas).

H. USO E OCUPAÇÃO DE TERRA: o uso e ocupação de terra têm sido considerados uma das principais causas da degradação da biodiversidade o que pode causar a diminuição na oferta de recursos bióticos e da diversidade genética (danos aos genes, espécies e ecossistemas). Por exemplo, a redução de área natural pela extração de terra pode gerar uma perda para determinado ecossistema, pela simples diminuição de área disponível. Efeitos indiretos podem ser associados à degradação da paisagem e alterações nas condições abióticas e de microclima (umidade, regime de vento, nutrientes disponíveis no ambiente) atingindo microflora e fauna. O uso de terra pode ainda afetar as funções de suporte de vida, como alterações na produção de biomassa (geralmente menor em áreas ocupadas por humanos), impactos estruturais (erosão, enchentes) e perda de espécies.

GLOSSÁRIO DE CRITÉRIOS

I. ABRANGÊNCIA ESPACIAL: critério referente à área sobre a qual o impacto é esperado para atuar (VOLKWEIN; GIHR; KLOPFFER, 1996). Parte-se do princípio que os problemas ambientais que afetam uma área maior (global ou regional) ou áreas geográficas mais significativas (áreas naturais protegidas, lugares populosos) são mais graves do que aqueles que afetam áreas menores (AGARSKI et al., 2016).

II. DURAÇÃO: refere-se ao fato de que os problemas ambientais com uma duração mais longa são mais graves do que aqueles que têm uma duração menor (AGARSKI et al., 2016). Parte-se do princípio que se uma ação ocorre durante um período mais longo, a probabilidade de aumentar o impacto ambiental também se torna maior (SOARES; TOFFOLETTO, DESCHÊNES, 2006).

III. REVERSIBILIDADE: este critério deve levar em consideração a possibilidade e a dificuldade de reversibilidade (artificial ou natural) da própria categoria de impacto (SOARES; TOFFOLETTO, DESCHÊNES, 2006), ou seja, a capacidade do sistema (ambiente afetado) de retornar ao seu estado anterior (SÁNCHEZ, 2006). Parte-se do princípio de que as consequências ambientais irreversíveis são um problema maior do que aqueles que podem ser remediados para restabelecer uma condição anterior após um determinado período (AGARSKI et al., 2016).

IV. PROBABILIDADE DE OCORRÊNCIA: refere-se ao grau de incerteza acerca da ocorrência do impacto. Um exemplo de classificação de extremos com relação a impactos pode ser: (i) alta, quando não há incerteza sobre a ocorrência do impacto e (ii) baixa, quando é muito pouco provável a ocorrência do impacto em questão (SÁNCHEZ, 2006).

V. DANOS À SAÚDE HUMANA: este critério aplica-se à mortalidade e às doenças humanas. Diferentemente dos critérios anteriores, este é um critério relacionado ao dano causado pelos impactos ambientais. O impacto para a saúde humana ocorre por diversos motivos quando originados por impactos ambientais.

VI. DANOS AO ECOSSISTEMA: este critério expressa o efeito sobre a biodiversidade. Aplica-se ao desaparecimento ou diminuição do saldo das espécies e dos ecossistemas (danos causados à fauna e flora). Diferentemente dos critérios anteriores, este é um critério relacionado ao dano causado pelos impactos ambientais.

VII. ESGOTAMENTO DE RECURSOS: este critério diz respeito ao esgotamento nas reservas naturais de matéria-prima (renovável e não renovável). Diferentemente dos critérios anteriores, este é um critério relacionado ao dano causado pelos impactos ambientais.

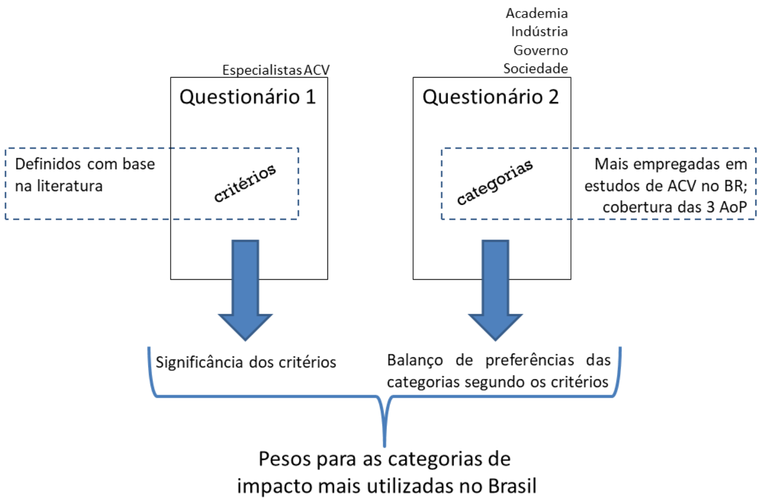
VIII. POSSIBILIDADE DE TRATAMENTO: este critério refere-se à disponibilidade tecnológica de remediar ou recuperar determinada área atingida por determinado impacto. Parte-se do princípio que um impacto, para o qual não exista tecnologia de "combate", representa uma pior condição se comparada ao impacto que pode ser tratado.

QUANTO À PESQUISA

A interpretação dos resultados de uma ACV nem sempre permite a decisão com absoluta certeza. A condição de *trade-off* é muito comum entre diferentes categorias de impacto quando analisamos diferentes cenários. Para estes casos, a ponderação (apesar de opcional) é um bom caminho no auxílio à interpretação e a tomada de decisão. A ponderação é baseada no modo como entendemos a importância (ou significância) dos impactos e para tanto partimos de julgamentos. Como diferentes pessoas julgam de formas distintas diferentes situações, entendemos que um conjunto de pesos voltados para o Brasil poderia melhorar o desenvolvimento e aplicação da ACV (pode ser mais ajustada para a condição nacional do que os pesos já existentes). Para auxiliar na "extração" deste julgamento por parte dos *stakeholders* nacionais, utilizaremos a abordagem de análise de decisão multicritério pelo emprego do AHP-PROMETHEE II.

Este é o questionário (chamando de Questionário 2) busca extrair a significância pelo balanço de preferências das categorias de impacto sob os diversos critérios elencados. O conjunto de categorias representa as mais utilizadas pela comunidade brasileira de ACV, identificadas por Zanghelini et al. (2016). Além disso, o conjunto de 8 categorias atende às recomendações de cobertura das 3 áreas de proteção (ABNT ISO, 2006a; 2006b) e recomendações do guia ILCD. Um esquema ilustrativo contendo a metodologia resumida para esta tarefa é apresentada abaixo.

Fig. IV-11. Fluxograma básico do modelo MCDA aplicado nesta tese (Q2).



Em posse da significância dos critérios extraída pelo questionário 1 e do balanço de preferências das categorias de impacto extraída deste questionário que você participou, será possível criar um conjunto de pesos para as categorias de impacto potencial mais empregadas em estudos de ACV no Brasil. Desta forma a interpretação poderá ser complementada e a tomada de decisão poderá ser mais clara.

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APÊNDICE E – MCDA Methods

There are several types of MCDA approaches (BEHZADIAN et al., 2010; BOUFATEH et al., 2011; JESWANI et al., 2010; LINKOV; MOBERG, 2012; LINKOV; SEAGER, 2011; SHIELDS; BLENGINI; SOLAR, 2011; TURCKSIN et al., 2011), each involving its own framework (HUANG; KEISLER; LINKOV, 2011; ZANGHELINI; CHERUBINI; SOARES, 2018). They can vary from simple approaches requiring very little information to sophisticated methods based on mathematical programming techniques that require extensive information on each attribute and the preferences of the decision-makers (DE MONTIS et al., 2000; GREENING; BERNOW, 2004). According to De Montis et al. (2005), the number of existing methods is already quite large and is still increasing. Thus, the choice of the 'right' method is not an easy task (DE MONTIS et al., 2005). As a reflex, Cinelli, Coles e Kirwan (2014) reported that researchers do not usually properly define the reasons for choosing a certain MCDA method instead of another. Ultimately the choice of a particular method depends on the specific problem as well as on users' demands, for instance familiarity and affinity (CINELLI; COLES; KIRWAN, 2014; DE MONTIS et al., 2005).

In scientific literature it is possible to find several different classifications for MCDA approaches. However, the most usual have shown to be a division into three main groups: (i) 'Analytic Hierarchy Process' (AHP), (ii) multi-attribute theory variants, as the 'Multi-Attribute Utility Theory' (MAUT), and (iii) outranking methods as 'Preference Ranking Organization Method of Enrichment Evaluation' (PROMETHEE) and 'ELimination and Et Choice Translating Reality' (ELECTRE).

- AHP

Considered the most popular MCDA method, the AHP was created by Saaty in the 80's (GELDERMANN; RENTZ, 2005; ROWLEY et al., 2012; VAIDYA; KUMAR, 2006). The approach is grounded in the pair-wise comparison of alternatives (LINKOV; MOBERG, 2012) which may be taken from actual measurements or from a fundamental scale which reflects the relative strength of preferences and feelings (SAATY, 1987). The scale ranges from 1/9 for least valued than, to 1 for equal, and to 9 for absolutely more important than covering the entire spectrum of the comparison (VAIDYA; KUMAR, 2006). According to Doumpos and Zapounidis (2004), as a product of pair-wise comparisons under such scale, a matrix is generated. Assuming that all comparisons are consistent, weights are estimated by a linear regression calculating the eigenvalue of the matrix (DOUMPOS; ZAPOUNIDIS, 2004; SAATY, 1990). A consistent reciprocal matrix, according to SAATY (1990), is when a level of inconsistency in the model, called the consistency index (CI), is acceptable (around 10%).

- MAUT

Method that resolve the disparate units (e.g. costs, environmental impact, etc.) into a utility or value so comparison can occur (LINKOV; MOBERG, 2012). This technique requires the decision-maker to evaluate the alternatives on each value dimension (called attribute) separately (JANSEN, 2001). Generally, the utility-function is a non-linear function to rescale a numerical value on some measure of interest onto a 0-1 scale with 0 representing the worst preference and 1 the best (SEPPALA et al., 2002). Jansen (2001) explicates that the respondent is asked how much more important each attribute is when related to the least important one. After that single-attribute value functions and attributed weights are multiplied and summed to result into a Score for each alternative. The higher is this value, the more desirable the alternative (SEPPALA et al., 2002).

- OUTRANKING

In this type of MCDA, the decision is based on the aggregation of stakeholder preferences, established when different alternatives are compared from the perspective of each set of criteria (BENOIT; RESSOUX, 2003; SEPPALA et al., 2001). It is assumed that the decision maker can express strict preference or indifference or weak preference when comparing one alternative to another for each criterion (SEPPALA et al., 2002). The idea is that an alternative "a" is superior to an alternative "b" if there are strong enough arguments in favor of "a" being at least as good as "b" (from the point of view of the decision maker) (GELDERMAN; RENTZ, 2005; GUITOUNI; MARTEL, 1998). According to such a relation it is possible to conduct pair-wise comparisons between each pair of alternatives under consideration for each of the criteria/attributes to support or refute the hypothesis that one alternative is better than the other (SEPPALA et al., 2002). Based on those axioms, each outranking method (e.g. PROMETHEE, ELECTRE, POMETHEE II) have an aggregation algorithm that results in raking, choice or sorting for the decision making. For instance, PROMETHEE works with preference index (phi) and balance of preferences (phi net) according to six possibilities of preference function (for each criterion).

This classification may be found in several references, including Benoit and Rousseaux (2003), Udo de Haes et al. (2002), Gelderman et al (2000), Huang; Keisler and Linkov (2011), Linkov et al (2004), Linkov and Moberg (2012). According to Huang, Keisler and Linkov (2011) and Herva and Roca (2013) they have been the most widely MCDA tools in sustainability-related research. For instance, an extended research in scientific databases considering papers that applied LCA and MCDA have demonstrated that authors have chosen majorly three MCDA methods to aid interpretation of results: Weighted Sum Approach (WSA), AHP and Outranking methods and their variations (ZANGHELINI; CHERUBINI; SOARES, 2018). Complimentarily, but with less frequency, others MCDA approaches were also applied such as MAUT, 'Multi-Attribute Value Theory'(MAVT), 'Simple Multi-Attribute Rated Technique' (SMART), 'Novel Approach to Imprecise Assessment and Decision Environments' (NAIADE), 'Technique for Order of Preference by Similarity to Ideal Solution' (TOPSIS), 'Measuring Attractiveness by a Categorical Based Evaluation Technique' (MACBETH) and SWING.

Tab. IV-20 lists the most important MCDA methods regarding their application and alignment in sustainable decision making based on Huang; Keisler and Linkov (2011), De Montis et al. (2000), . Cinelli, Coles e Kirwan (2014), Boufateh et al. (2011), Geldermann and Rentz, (2005) and Prado-Lopez et al. (2014). Thus, AHP, MAUT, PROMETHEE, ELECTRE, 'Dominance-based rough set approach'(DRSA), TOPSIS, 'Stochastic multi-attribute analysis' (SMAA), SMART, Regime and NAIADE were considered for a further comparison according to some aspects, such as compensatory and easy to understand, and supported the choice of AHP-PROMETHEE II as the MCDA applied in this research. Some of those criteria were based on De Montis et al. (2000), Munda (2005) and Cinelli, Coles e Kirwan (2014) guidelines to aid MCDA choice. Others were included to provide a wider vision of their application on LCA panels. The rationale behind each criterion positioned in the first column in Tab. IV-20 (i.e. Criteria) is described below:

- PRINCIPLE: describes the functionality of each method. For instance, PROMETHEE is based on a paired comparison of alternatives to elicit preferences in relations of preference, indifference or even incomparability, whereas de approach requires external weighting for aggregation of results (BEHZADIAN et al., 2010; CINELLI; COLES; KIRWAN, 2014; HERVA; ROCA, 2013; PRADO-LOPEZ et al., 2013);

- CLASSIFICATION: classification of each method according to its principles. Basically, those methods are classified or as outranking or as utility-based. Outranking methods are based on the aggregation of preferences (coefficient of importance) from stakeholders, established when compared alternatives against each criterion (BENOIT;

RESSOUX, 2003; SEPPÄLLÄ et al., 2001). Utility-based methods convert different units and values into a utility or value, so comparison can occur (LINKOV and MOBERG, 2012);

- INPUT DATA: Capability of including information which is qualitative and quantitative in nature (CINELLI; COLES; KIRWAN, 2014; DE MONTIS et al., 2000). Better methods allow the use of both kinds in a way that its application may encompass greater possibilities of decision making;

- CRITERIA TYPOLOGY: it is significance of the weights used to assign importance levels to the criteria (CINELLI; COLES; KIRWAN, 2014). MCDA methods are divided into two main typologies: trade-offs and coefficient of preference;

- COMPLEXITY: simplicity of its structure based on users (i.e. decision makers) perspective (CINELLI; COLES; KIRWAN, 2014);

- THRESHOLD: represent turning-points values that can be used to model complex preference structures and uncertain information (CINELLI; COLES; KIRWAN, 2014). For Gelderman et al. (2000) especially the principles of weak preference and incomparability are valuable in environmental decision support, because they better represent the real situation;

- COMPENSATION DEGREE: it is the possibility of offsetting a disadvantage on some criteria by a sufficiently large advantage on another criterion (MUNDA, 2005; ROWLEY et al., 2012). Gelderman and Rentz (2005) illustrate the compensation degree by stating that "the compensation could represent a situation in environmental assessment where low emissions into the water counterbalanced higher emissions into the air". The level of compensation among sustainability spheres determines the distinction between approaches based on strong and weak sustainability concepts (CINELLI; COLES; KIRWAN, 2014). Thus, compensatory methods represent weak sustainability;

- UNCERTAINTY AND SENSIBILITY: capability of handling uncertain, imprecise or missing information (CINELLI; COLES; KIRWAN, 2014; DE MONTIS et al., 2000);

- STAKEHOLDER'S PARTICIPATION: it is the possibility of involvement of more than one person as decision maker (DE MONTIS et al., 2000), condition preferable when performing environmental decision making;

- PANEL RELATION: aspect related to the complexity for panelists to answer or complete the panel including the level of information that is needed. The subjects to be weighted should be easy to explain to a panel (GOEDKOOP; SPRIENSMA, 1999);

- FRIENDLY TO USE: aspect based in the statement "desirable property for mathematical aggregation procedures in the framework of sustainability decisions is simplicity" (MUNDA, 2005).

- EASY TO UNDERSTAND: this notion is estimated by the LCA practitioner and includes the level of knowledge and the time required to apply the method as well as the easiness with which a physical sense can be attributed to the constants that need to be fixed arbitrarily a priori (BENOIT; RESSOUX, 2003).

- ALLOWS LCA: possibility of relation with LCA methodology. Aspect strongly linked to compensation degree (i.e. sustainability vocation);

- REPRODUCIBILITY: degree of facility / possibility in reproducing the method and decision making;

- KIND OF RESULTS: type of final results for decision making (e.g. ranking of alternatives, unique choice…);

- SOFTWARE SUPPORT: Availability of tools to implement the method, manage the information and show the results in a clear and multi-perspective manner (CINELLI; COLES; KIRWAN, 2014);

- MAIN REFERENCE: as described, it is the main publication (reference) related to each method. For instance, the AHP was created by Saaty and published in 1980. Thus, the main reference of such method is (1) Saaty (1980).

Considering these 17 aspects, the MCDA methods were confronted with the support of publications of practitioners, MCDA method developers, comparisons and guidelines for ground the choice of the MCDA approach (Tab. IV-20).

Tab. IV-20. Comparison between MCDA methods that are applicable to environmental decision making.

Criteria	AHP/ANP	MAUT/MAVT	PROMETHEE	ELECTRE	DRSA	TOPSIS	SMAA	SMART	Regime	NAIADE
Principle	Hierarchical structure based on criteria set (value tree). Pair-wise comparison of alternatives and WSA aggregation (1-2-5-8)	Synthesis of information for a single parameter in function utility for each alternative. Elicitation of preference for each utility and aggregation (8)	Pair-wise comparison of alternatives to elicit preferences in relations of pref., indif., incomparab. Aggregation requires external weighting (8-16-28-29)	Aggregation of preferences from one alternative to another, elicited in pair-wise comparison. Preferences in four relations: indif., pref., poor pref., incomparab. (16-28)	Based on dominance relations, with decision rules such as "if {} then {}". Pref. is described in pair-wise comparison by the decision maker	Based on the balance of distances between the ideal positive and the ideal negative solutions. Internal normalization of panelists' responses. Aggregation requires external weighting.	Combines outranking normalization (paired comparison to identify preferences) with Monte Carlo analysis in the weighting (16)	Simple multi-attribute weighting method, based on proportion estimation (21) with the support of panelists (11)	based on paired comparison of alternatives, where the comparison of each specific set of alternatives is not influenced by the presence of effects and other alternatives	Outranking method based on the semantic distance of the paired comparison (4). It does not require (explicit) weighting (4-5-6)
Classification	Utility-based (9)	Utility-based (9)	Outranking (5-8-9)	Outranking (6-8-9)	-	Utility-based (10)	Other (9) Outranking (16)	Utility-based (9-10)	Outranking (9-25)	Other (9) Outranking (4)
Input data**	quali/quantitative (1-5-6)	quali/quantitative (6)	quali/quantitative	Majorlyquantitative (6)	quali/quantitative	quantitative	quali/quantitative	quali/quantitative (21)	quali /quantitative (6-23-24)	quali/quantitative (3-4-6)
Criteria tipology**	trade-offs (8)	trade-offs (8)	Coef. ofimportance (8)	Coef. of importance/trade-offs (8)	Null (8)	Coef. ofimportance(6)	Coef. ofimportance(20)	Trade-offs	Coef. ofimportance(6)	Coef. ofimportance
Complexity	Low	Medium	Medium (7)	High (8)	Low	Medium	High	Medium	Medium (25)	High (3)
Threshold**	No (8)	No (8)	Indiference, incomparab. andpreference (5-8)	Indif., pref., poor pref., incomparab. (5-8)	As result from decision rule	No	Indiferenceandpreference(16)	No	-	Indiferenceandpreference
Compensation degree**	Total (5-9)	Total (9)	Partial (8-9)	Null (29) / Partial (8-9)	Null	Total	Partial (16-20) / Total (9)	Total (9)	Partial (24)	Partial(3)
Uncertainty and sensibility	Possible/Partial (9)	Possible (9)	Possible (9-30)	Possible (9)	Possible	Possible	Possible (9-20)	Possible (9)	Possible (9)	Possible (9)
Stakeholders' participation	Required (5-6) Null(4)	Required (6)	Required (27)	Supported (4-6)	Supported (8)	Required	Required (16)	Required (21)	Required(4-6)	Required/Experts (4-6)
Panel relation	Difficult	Difficult	Easy (7-8-9)	Difficult (8)	Easy	Easy	Easy (16)	Difficult / Easy (11)	Easy	Difficult(3-4)
Friendly to use	Yes (8)	Yes	Medium (9)	No(9)	Yes	Yes	-	Yes (11-21)	Medium(24)	No (3-4)
Easy to understand	No	No	Yes (7-8-9-15)	No (8-9)	Yes	Yes	-	Yes (11)	Medium (25)	No (3-4)
Allows LCA	Yes	Yes	Yes	Yes	Yes	Yes	Yes (16)	Yes (11)	Yes	Yes
Reproducibility	Difficult	Difficult	With scenario analysis (7)	Difficult / Possible	Difficult	Simple	-	Simple (11)	-	Possible
Kind of results	Classification and Choice(1-6)	Classification and Choice	Classification, sorting and Choice	Classification, sorting and Choice	Classification, sorting and Choice(8)	Classification and Choice	Classification (20)	Classification (21)	Classification (24-25)	Classification, conflict analysis and Choice (5)
Software support	Good (5)	Bad	Good (8)	Razonable(5)	Bad	Bad	-	-	Good (24)	Good (3-4-5)
Main reference	(1)	(12)	(13-14)	(17)	(18)	(19)	(22)	(23)	(26)	(27)

References: (1) Saaty (1990); (2) Vaidya and Kumar (2006); (3) De Mello et al. (2012); (4) Gerber et al. (2012); (5) De Montis et al. (2000); (6) De Montis et al. (2005); (7) Figueira, Greco and Ehrogott (2005); (8) Cinelli, Coles and Kirwan (2014); (9) Polatidis et al. (2006); (10) Boufateh et al (2011); (11) Myllyviita et al. (2012); (12) Keeney and Raffia (1976); (13) Brans, Vincke e Mareschal (1986); (14) Brans and Vincke (1985); (15) Al-Shemmeri, Al-Kloub and Pearman (1997); (16) Prado-Lopez et al. (2013); (17) Roy (1968); (18) Greco et al. (2005); (19) Hwang and Yoon (1981); (20) Rogers and Seager (2009); (21)Mustajoki et al. (2005); (22) Lahdelma et al. (1998); (23) Edwards (1977); (23) Munda (2005); (24) Russi and Tabara (2004); (25) Wager (2005); (26) Hinloopen and Nijkamp (1983); (27) Munda (1995); (28) Herva and Roca (2013); (29) Behzadian et al. (2010); (30) Turcksin et al (2011).** Criteria from De Montis et al (2000), Munda (2005) and Cinelli, Coles and Kirwan (2014).

The distinction between the compensatory and non-compensatory methods is a matter of the decision rule used by Herva and Roca (2013) and was the first aspect to be considered in our choice for the MCDA method in this research. This is based on several authors that indicate that for a strong sustainability decision, compensatory methods should be avoided (see DE MONTIS et al. 2000; HERVA; ROCA, 2013; MUNDA, 2005; TURCKSIN et al. 2011). According to Herva and Roca (2013), MAUT, AHP and WSA are examples of compensatory methods, while outranking methods such as PROMETHEE and NAIADE are partial-compensatory. Complimentarily, Munda (2005) established that clear examples of non-compensatory methods are the ELECTRE methods. In the same way, Cinelli, Coles and Kirwan (2014) state that "MAUT and AHP can only use a weak sustainability perspective with criteria trade-offs as the norm, whereas ELECTRE, PROMETHEE and DRSA enforce a strong one, by limiting or abolishing the compensation among/within sustainability spheres". For Prado-Lopez (2013) alternate methods of internal normalization performing outranking such as PROMETHEE and ELECTRE, specifically ELECTRE III and PROMETHEE I, II, are advantageous for environmental problems. Therefore, from Tab. IV-20 and under 'compensation degree' criteria, AHP/ANP, MAUT/MAVT, TOPSIS, SMAA and SMART were unconsidered.

The second aspect taken in consideration was the simplicity of the method, a desirable condition indicated by Munda (2005) and key factor for the success of a panel sent to stakeholders (CINELLI; COLES; KIRWAN, 2014). For that 'easy to understand', 'friendly to use' and 'complexity' were evaluated. Regarding simplicity, according to Cinelli, Coles and Kirwan (2014) the ELECTRE class of methods is quite the opposite. Authors considered this approach as the most sophisticated among MCDA methods, arguing that it requires several parameters to be identified, some of which do not have a clear and practical meaning, and the exploitation procedures is perceived as somehow obscure by many authors. Similarly, De Mello et al. (2012), Gerber et al. (2012) and Wager (2005) have reported difficulties in performing decision making with the aid of NAIADE and Regime, respectively. However, this is not the case of PROMETHEE. PROMETHEE shows a good balance between theory and implementation, whose structure is based on the outranking approach but is easier than ELECTRE (CINELLI; COLES; KIRWAN, 2014). For Polatidis et al. (2006), PROMETHEE methods exhibit an advantage since the parameters needed have some concrete meaning for the decision maker. Therefore, PROMETHEE was strengthened whereas ELECTRE received a low score under simplicity criteria (Tab. IV-20). On top of that, PROMETHEE have the possibility of being supported by a software tool, that according to Cinelli, Coles e Kirwan (2014), is simple to understand and very powerful in terms of results representations, adding a lot to the decision making process.

Amongst the PROMETHEE family, the choice for PROMETHEE II is based on the necessity of complete ranking of alternative in our proposal, following protocols to aid in the choice of proposed MCDA methods proposed by Benoit and Rousseaux (2003) and Rowley et al. (2012). However, Behzadian et al. (2010), Turcksin et al. (2011) and Macharis et al. (2004) indicate that PROMETHEE do not properly attribute weigh to the criteria. Bogdanovic, Nikolic and Ilic (2012) affirms that criteria weights, obtained by AHP, have a higher level of coherence, correlation, consistency and accuracy than weights determined on the basis of intuition or a domain specialist's knowledge, which is mostly used in the PROMETHEE method. One of the principle reasons to use AHP is the advantage to have a pair-wise comparison simplifying the judging of the relative importance among each criterion (PASTARE et al., 2014). Because of this condition the combination of AHP and PROMETHEE II was complimentary.

The AHP-PROMETHEE approach was first proposed by Macharis et al. (2004) and has already been apply by several authors with positive results on environmental decision-making (BAYNAL; SARI, 2016; BOGDANOVIC; NIKOLIC; ILIC, 2012; SIBEVEI et al., 2016; TURCKSIN et al., 2011). The rationale behind the choice of this hybrid method is therefore, to utilize the simplicity and straightforward pair-wise comparison of AHP to weight conflicting (and more complex) criteria and then, compare alternatives with PROMETHEE II to guarantee a lower compensatory degree over environmental impact categories and still, simplicity for stakeholders willing to answer the panel.

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APÊNDICE F – Criteria Choice

According to Johnsen and Lokke (2012) criteria can be understood as reasons or arguments for choosing a particular starting point for weighting, and can provide an objective (or, intersubjective) basis for what otherwise may seem like subjective judgment. Every environmental impact study is based in some way on judgment criteria. Sánchez (2008) argues that, even though it is not possible to eliminate all subjectivity of this type of evaluation, the criteria should be clearly stated. One of the reasons for this condition is that the definitions for one criterion can deviate from author to author (VOLKWEIN; GIHR; KLOPFFER, 1996) which reflects in a wide range of existing criteria. Literature presents several suggestions of criteria to be considered when judging the meaning or significance of an environmental impact, derived from many bases (legal, economic, scientific, popular, etc.) (SÁNCHEZ et al., 2006).

The publication by Johnsen and Lokke (2012) compiles all the criteria used in existing weighting models under the LCA. The authors define them in two main groups: 1) General Criteria and 2) Concrete Criteria. General criteria are considered more abstract and decontextualized in relation to the environment. Those were classified into five subgroups: scope, practicality (for users), practicality (for scientists), ethics and scientificity (e.g. flexibility to include new problems, temporal and spatial representativeness, low technical skills, follows the standards, dealing with uncertainties) (FINNVEDEN, 1999; UDO DE HAES et al., 2002; HUPPES; VAN OERS, 2011; JOHNSEN; LOKKE, 2012). On the other hand, concrete criteria are somewhat more "down-to-earth" and have a stronger connection with, in theory, empirically available and more concrete information about the environment (JOHNSEN; LOKKE, 2012). For example, Soares, Toffoletto and Deschênes (2006) defined criteria including scale (significance in the region of occurrence of impact), duration, reversibility and distance to a target (in the environmental goal case). Another example, in 1990 and again in 2000, the USEPA Science Advisory Board weighting model considered the following criteria: the severity of the impact, the degree of exposure and the penalty for being wrong (in the case of pecuniary impact generator). Therefore, we opted for the definition of a set of concrete criteria for the MCDA approach proposal in this research.

Rowley et al. (2012) and Volkwein, Gihr and Klopffer (1996) indicate that the number of valuation criteria must be big enough to allow a comprehensive or nearly comprehensive valuation, and must be small enough to ease a final aggregation of the criteria. In our opinion, a comprehensive valuation must carry a good covering of criteria generally defined to assess environmental impacts in several areas (including Environmental Impact Assessment, environmental laws, LCA, and so on) defined as "Exhaustivity" or completeness (CHEVALIER; ROUSSEAUX, 1999; ROY, 1985; ROWLEY et al., 2012), and also holds for cohesion and non-redundancy. With that in mind, the definition of the criteria used in this MCDA proposal was based on the most usual (recurrent) criteria in literature (presented in Tab. IV-21) respecting three main aspects: (1) the level of environmental consequence (SOARES; TOFFOLETTO, DESCHÊNES, 2006) or dynamics of the harm (UDO DE HAES, 1994) that quantifies environmental impact; (2) the environmental consequence (SOARES; TOFFOLETTO, DESCHÊNES, 2006) or consequences of the harm (UDO DE HAES, 1994) that unlike previous criteria, it is related to the type of damage/problem caused by environmental impacts, and; (3) the possibility of recovering from the harm, criterion derived from the concept of reduce the level of consequences and the type of damage, present in Udo De Haes, (1994) as "administrative, technical, economic effort to reduce harm.

CONAMA (1986) in Tab. IV-21 is a Brazilian resolution that provides basic criteria and general guidelines for environmental impact assessment. With status of a national law, and therefore a basis for Brazilian environmental protection agencies, it demands for the identification of the condition of the impact as positive/negative and Direct/indirect, and indications of duration, frequency, reversibly, cumulative properties and social distribution of risks. Two criteria related to measurement of consequences of impact present in CONAMA (1986) are unanimity between the references in Tab. IV-21 'duration' and 'reversibility'. The former is present in all references from but Udo de Haes (1994) and it refers to the fact that environmental problems with a longer duration are more severe (the probability of increasing the environmental impact becomes greater) than those with a shorter duration (AGARSKI et al., 2016; SOARES; TOFFOLETTO, DESCHÊNES, 2006). The latter is indicated in Ericksson (1994), Udo d Haes (1994), Glasson et al. (1999), Soares, Toffoletto and Deschênes (2006) and Johnsen and Lokke (2012), and is related to the possibility and difficulty of reversing (artificially or naturally) the impact category (SOARES; TOFFOLETTO, DESCHÊNES, 2006).

'Scale' is another criterion that is recurrent in almost every reference, but oddly it is not present in CONAMA (1986). According to Volkwein, Gihr and Klopffer (1996) this criterion referring to the area on which the impact is expected to act. For instance, it is assumed by Agarski et al., (2016) that environmental problems affecting a larger area (global or regional) or more significant geographic areas (protected natural areas, crowded places) are more severe than those affecting smaller areas.

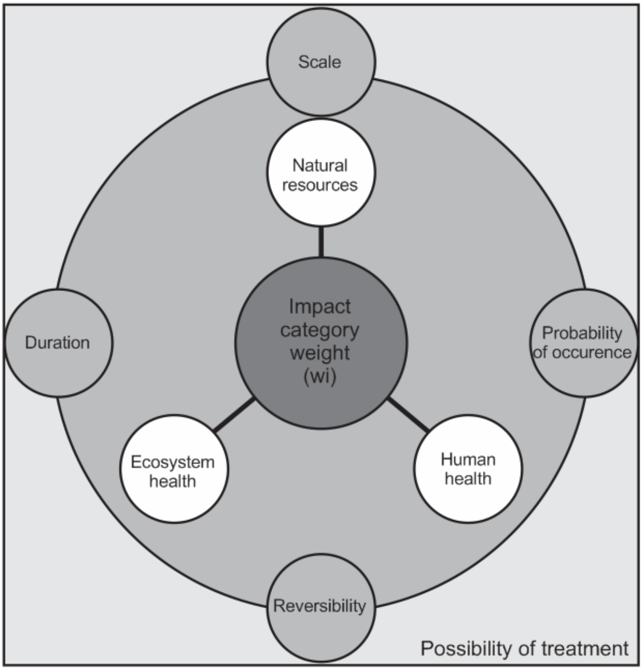
The last criterion regarding level of environmental consequences is ‘probability of occurrence’. This aspect is present in Ericksson (1994), Glasson, Therivel and Chadwick (1999) and Johnsen and Lokke (2012), and indirectly in Soares, Toffoletto and Deschênes (2006) as uncertainty of occurrence of the impact. The rationale behind this criterion is to include an element of probability of occurrence of a impact when environmental aspects exists. An example of a classification of extremes with respect to impacts may be: (i) high, when there is certain about the occurrence of the impact and (ii) low, when the impact is very unlikely to occur (SÁNCHEZ, 2006).

Environmental consequences in LCA can be represented by human health, natural ecosystem health, and natural resources (ISO, 2006; SOARES; TOFFOLETTO, DESCHÊNES, 2006). These triad is only presented by Soares, Toffoletto and Deschênes (2006) and Johnsen and Lokke (2012) and partially in Lindeijer (1994). Damage to human Health occurs for several reasons when caused by environmental impacts where the more severe the repercussions on health, the more significant the impact category (SOARES; TOFFOLETTO, DESCHÊNES, 2006). Damage to Ecosystems expresses the effect of the impacts on biodiversity. According to Soares, Toffoletto and Deschênes (2006), the more severe the repercussions on biodiversity, the more significant the impact category. Resource Depletion refers to the depletion of natural reserves of raw material (renewable and non-renewable). In this case, Soares, Toffoletto and Deschênes (2006) affirms that the more severe the repercussions on its availability, the more significant the impact category.

Finally, the last criterion is classified separately from environmental level of consequences and environmental consequences, as it comes from the technological possibility of reducing a damage reflex of an environmental impact. This criterion refers to the technological availability to remedy or recover a certain area affected by a certain impact. It is assumed that an impact, for which there is no "combat" technology, represents a worse condition compared to the impact that can be addressed. There isn’t a criterion like this in Tab. IV-21. The closest is ‘Possibility of control’, stated in Udo de Haes (1994), Block (1999) and Johnsen and Lokke (2012). Others have similar basis, but with different meanings. For instance, WtP is how much someone is willing to pay for a recovering of certain damage, criterion that essentially also ‘combats’ the impact.

The defined set of criteria is therefore: Scale, Duration, Reversibility, Probability of occurrence (in terms of quantification of environmental effects); Human health, Damage to ecosystems and Resource consumption (for environmental consequences); and lastly, Possibility of treatment (as a combat criterion). Adapting Soares, Toffoletto and Deschênes, (2006) framework on the relation of criteria in impact category weighting, our set is presented in Fig. IV-12.

Fig. IV-12. Framework of criteria in this MCDA model (adapted from SOARES, TOFFOLETTO and DESCHÊNES, 2006).



Tab. IV-21. Criteria used in environmental impact measurement from different perspectives.

Criteria	CONAMA (1986)	Erickson (1994)	Lindeijer (1994)	Udo de Haes (1994)	Glasson, Therivel and Chadwick (1999)	Block (1999)	ISO 14004 (2004)	Soares, Toffoletto and Deschênes (2006)	Johnsen and Lokke (2013)
Positive/Negative impact	X	-		-	-	-	X	-	-
Direct/Indirect impact	X	-	-	-	-	-	-	-	-
Probability of ocurrence	-	X	-	-	X	-	-	-	X
Scale	-	X	X	X	X[1]	X[2]	X	X[3]	X
Severity	-	-	-	-	-	X	X	-	-
Duration	X	X	X	-	X[1]	X	X	X	X
Frequency/Recurrence	X	-	-	-	-	X	X	-	-
Reversibility	X	X	--	X	X	-	-	X	X
Cumulative and sinergic propreties	X	-	X	-	-	-	-	-	-
Relevance to legal determinations	-	X	-	-	-	X	X	X[4]DtT	X[4]DtT
Social distribution of risks	X	X	-	-	-	-	-	-	-
Importance of the affected local	-	-	X	X	X	-	-	-	-
Level of concern from stakeholders	-	-	-	-	X	X	X	X[4]DtT	X[4,5] DtT/PoP
Political repercussion	-	-	-	-	X	-	-	-	-
Need to report on impact	-	-	-	-	-	X	-	-	-
Possibility of control	-	-	-	X	-	X	-	-	X[6]
Damage uncertainty	-	-	-	-	-	-	-	X	X
Damage to ecossystems	-	-	X	-	-	-	-	X	X
Damage to human health	-	-	X	-	-	-	-	X	X
Resource consumption	-	-	-	-	-	-	-	X	X
Replacement of the damaged item	-	-	-	-	-	-	-	-	X
Willingness to pay	-	-	X	-	-	-	-	-	X
Nature of efects	-	-	-	-	-	-	-	-	X
Time required to reduce the harm	-	-	X	X	-	-	-	-	-

1 Define one unique criteria as "spatial and temporal extension".

2 Indicate severity (linked to magnitude) and spatial coverage as independent indicators.

3 Determine spatial criteria in terms of significancy of the damaged area (e.g. an important biome)

4 The distance-to-target (DtT) criterion was considered both with respect to the legal limits of generation of impacts and with the expectations of stakeholders.

5 Indicate a criterion related to population preference (PoP), classified together with distance-to-target.

6 Indicate a criterion related to the possibility of administering solutions, classified as possibility of control.

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