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UNIVERSITÉ DE MONTRÉAL

# SUSTAINABILITY ASSESSMENT OF BIOREFINERY STRATEGIES UNDER UNCERTAINTY AND RISK USING MULTI-CRITERIA DECISION-MAKING (MCDM) APPROACH

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Cette thèse intitulée:

SUSTAINABILITY ASSESSMENT OF BIOREFINERY STRATEGIES

UNDER UNCERTAINTY AND RISK USING

MULTI-CRITERIA DECISION-MAKING (MCDM) APPROACH

présentée par : SANAEI Shabnam

en vue de l'obtention du diplôme de : Philosophiae Doctor

a été dûment acceptée par le jury d'examen constitué de :

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# DEDICATION

**To:**

*<u>My grandmother</u> who was always a big support in my life from the moment I took the first step to the last day of her life when I was very far from her and she was struggling with life. My angel was always encouraging me to celebrate life with following my passions. She was looking forward to seeing a day that I can successfully deliver my PhD, however unfortunately life did not let me to have a chance to celebrate such a great moment in my life with her. Although she is no longer in this world, her memories continue to regulate my life. She is not beside me but inside my heart. The biggest success to me would be being as nice as she was.*

*Rest in peace Maman Ashi…*

**To:**

*<u>My mom and dad, and my sister:</u> who have always dedicated their life to me and never left my side. Without them this work could not be possible. Their everlasting love, their endless kindness, their dedication and encouragement and more than anything else their patience made me able to follow my passions. They have always made all my dreams come true. The biggest success to me is being able to live in a way they do, to be as nice, unique and lovely as they are. I am very fortunate and grateful to have such a gorgeous family who mean everything to me.*

*Love you my angels beyond the words...*

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&

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# RÉSUMÉ

Le bioraffinage est potentiellement une solution novatrice en rétro-installation dans l'industrie des produits forestiers, ainsi que dans le contexte de projet d'implantation Greenfield dans le secteur agricole. L'intégration de cette gamme de technologies émergentes dans des installations existantes de production de pâte et papier supporterait l'industrie forestière dans la transformation de son modèle d'affaires grâce à la production d'un portefeuille de produits élargi. Dans le contexte du bioraffinage Greenfield, les actionnaires visent à atteindre un avantage compétitif en pénétrant le marché avec des produits verts. Les stratégies de bioraffinage ne sont pas toutes durables, et à chaque stratégie sont rattachés des risques particuliers. En prenant la perspective de l'investisseur, il est critique que les stratégies non durables soient éliminées de la liste des possibilités de bioraffinage dès les premières étapes stratégiques de conception.

Malgré la nécessité d'impliquer l'incertitude dans la prise de décision stratégique, spécifiquement dans le contexte du bioraffinage considérant des technologies émergentes, aucune source de littérature ne fait référence à une approche systématique afin d'identifier les stratégies durables considérant plusieurs sources d'incertitude et considérant l'attitude de risque des preneurs de décision. .

L'objectif global de cette thèse est d'illustrer une méthodologie de conception pour la prise de décision stratégique prenant en compte l'incertitude tout en quantifiant l'attitude de risque des preneurs de décision, ce afin d'identifier des stratégies de bioraffinage durables. La méthodologie proposée a été démontrée par deux études de cas illustrées par (a) le bioraffinage agricole du triticale dans un contexte d'implantation Greenfield, et (b) le bioraffinage forestier en rétro-installation dans une usine de pâte Kraft. Afin de minimiser les risques, une approche par phase a été considérée pour l'implantation sur le court et le long terme des stratégies de bioraffinage à l'étude.

La méthodologie présentée dans cette thèse vise à évaluer les alternatives de bioraffinage d'un point de vue économique, de compétitivité de marché, et environnemental, en utilisant les outils d'analyse de systèmes incluant les analyses technico-économiques classiques. Les résultats de ces évaluations sont incorporés dans un ensemble de critères 'intelligents' de durabilité. Contrairement aux analyses conventionnelles qui, généralement, utilisent seulement, pour la

prise de décision, des indicateurs de rentabilité sur le court terme, ce travail définit des critères multidisciplinaires représentant la rentabilité, la performance économique d'un point de vue du modèle d'affaires, les impacts environnementaux potentiels, la compétitivité de marché, ainsi que les risques technologiques et de marché – tels des indicateurs de durabilité du bioraffinage. Ces critères sont inévitablement en conflit, et doivent être agrégés en un score unique de durabilité pour chaque stratégie de bioraffinage, en menant un processus de prise de décision multicritère (MCDM – acronyme anglais), basé sur un panel multidisciplinaire impliquant des panélistes aux expertises variées afin de couvrir toutes les dimensions critiques qui seront considérées dans la prise de décision stratégique. L'approche MCDM offre certains avantages par rapport aux autres méthodes disponibles incluant : (a) la reconnaissance des préférences des preneurs de décision considérant l'importance relative des critères, (b) la recherche d'un consensus parmi les parties prenantes au projet, et (c) la concentration sur l'interprétation des critères.

Un haut niveau d'incertitude est associé avec l'information récoltée en début d'une phase de conception qui, si ignoré, compromettra la sélection des stratégies de bioraffinage. Dans n'importe quelle situation incertaine, les preneurs de décision doivent faire face au risque, et dès lors qu'il y a un risque, chaque preneur de décision démontre une attitude spécifique vis à vis du risque, étant soit opposé au risque, soit neutre au risque ou preneur de risque. Il est critique que tant l'incertitude que les risques soient considérés dans la prise de décision stratégiques. Lorsque ces concepts sont pris en considération, les paramètres MCDM incluant les facteurs de pondération et la fonction d'utilité peuvent être affectés ainsi que la décision finale.

Lorsque l'incertitude est considérée dans l'évaluation des critères, chaque critère doit être présenté aux preneurs de décision considérant un éventail de valeurs comprises entre des limites probables minimum et maximum qui peuvent affecter les facteurs de pondération des critères. Par exemple, dans le cas où l'incertitude dans les valeurs des critères est considérablement redondante entre les alternatives, les critères ne permettent plus aux preneurs de décision de différencier les alternatives. Comparé à la prise de décision dans des conditions déterministes où l'incertitude n'est pas évaluée, les preneurs de décision attribuent un facteur de pondération plus petit pour les critères concernés. D'autre part, l'attitude vis à vis du risque des preneurs de décision affecte la fonction d'utilité, représentant la préférence des preneurs de décision, et qui, par défaut, est normalement considérée comme linéaire. (neutralité quant au risque) dans l'absence de quantification de l'attitude de risque des preneurs de décision.

Dans cette thèse, une méthodologie pratique et systématique est développée et démontrée afin de prendre des décisions plus 'intelligentes' au niveau stratégique de conception en évaluant la durabilité des stratégies de bioraffinage considérant l'incertitude et les risques. Les données d'incertitude ont été quantifiées grâce à une méthode d'analyse de risque stochastique (analyse Monte Carlo) par le biais de fonctions de distribution de probabilité pour les critères de durabilité. Également, l'incertitude du panel a été considérée en terme de niveau de consensus parmi les membres du panel afin de prendre une décision finale. Cependant, l'attitude de risque des preneurs de décision a été mesurée utilisant une loterie et impliquant une théorie d'aversion au risque par laquelle la préférence des preneurs de décision est quantifiée pour la prise de décision. En raison de la quantification de l'incertitude et des risques, les preneurs de décision ont gagné une compréhension détaillée résultant en une décision plus robuste. Une des réalisations de cette thèse démontre qu'adresser l'attitude de risque des preneurs de décision tout en impliquant l'incertitude dans la prise de décision pourrait aider à mieux différencier les alternatives et conséquemment permettre aux preneurs de décision d'éliminer plus d'options à un niveau stratégique avec une plus grande confiance.

Les résultats dans cette thèse illustrent l'importance d'appliquer une approche systématique pour la prise de décision stratégique, considérant des critères de durabilité et impliquant l'incertitude et l'attitude de risque des preneurs de décision dans la prise de décision multicritère. Une fois ces concepts acquis par la haute gestion des entreprises, un consensus peut alors être atteint objectivement et systématiquement pour la prise de décision permettant ainsi une meilleure décision.

# ABSTRACT

The biorefinery is a potential game-changing solution for retrofit in the forest products industry, and in the greenfield context for the agricultural industry. Integration of this set of emerging technologies into existing pulp and paper facilities would help the forestry industry with business transformation by the manufacture of an expanded product portfolio. In a greenfield biorefinery context, stakeholders are more aiming to achieve a competitive advantage by penetrating the green products market. Not all biorefinery strategies are sustainable, and each strategy has its own particular risks. Using the investor perspective it is critical that unsustainable strategies are screened out from the list of biorefinery possibilities during the strategic early design stage.

Despite of necessity of involving uncertainty in strategic decision-making especially in the context biorefinery as an emerging technology, a systematic approach to identify sustainable strategies considering different sources of uncertainty and addressing risk attitude of decision makers, is missing in literature.

The overall objective of this thesis is to illustrate a design-based methodology for strategic decision-making under uncertainty while quantifying risk attitude of decision makers, in order to identify sustainable biorefinery strategies. The proposed methodology has been demonstrated by two case studies addressing (a) the triticale-based greenfield agriculture biorefinery, and (b) the forest biomass-based biorefinery in retrofit to a kraft pulp mill. In order to mitigate risk, a phased approach has been considered for candidate biorefinery strategies, to be implemented over the near and then longer-term.

The methodology presented in this thesis assesses biorefinery alternatives from economic, market competitiveness and environmental perspectives, using systems analysis tools including classical techno-economic assessment. The results of these assessments are incorporated into a set of “intelligent” sustainability criteria. In contrast to conventional analyses which generally use only short-term profitability metrics for decision-making, this work defines multidisciplinary criteria representing profitability and business-oriented economic performance, potential environmental footprint, market competitiveness, as well as technology and market risks - as indicators of biorefinery sustainability. These criteria are inevitably conflicting, and thus they need to be aggregated into a unique sustainability score for each biorefinery strategy, through conducting a multi-criteria decision-making (MCDM) by a multi-disciplinary panel with various

backgrounds to ensure that expertise in the critical dimensions that should be considered in strategic decision making is captured. MCDM approach offers certain advantages over the other available methods, including: (a) reflecting the preferences of decision makers regarding the relative importance of the criteria, (b) consensus building among project stakeholders and (c) a focus on criterion interpretation.

There is a high level of uncertainty associated with information at the early stage of design that if ignored, the biorefinery strategy selection may not be well-informed. In addition, in any uncertain situation, decision-makers must face risk, and whenever there is risk, each individual decision-maker has his/her own attitude toward risk, that is risk averse, risk neutral or risk prone. It is critical that both uncertainty and risk attitude of decision makers be addressed in strategic decision-making. When these concepts are taken into consideration, MCDM parameters including weighting factors and utility functions of decision criteria and consequently the final decision can be affected.

When involving uncertainty in criteria evaluation, each criterion should be presented to decision-makers as a range of values within a minimum and a maximum probable limit, which can result in changing the criteria weighting factors. For example, in the case that involving uncertainty in criterion values shows considerable overlap between the alternatives, that criterion can not help decision-makers anymore to differentiate between the alternatives. Compared to the deterministic condition where uncertainty is not evaluated, decision makers would likely attribute a lower weighting factor to this criterion. Moreover, the risk attitude of decision-makers affects the utility function, representing preference of decision makers, which is normally considered linear by default (risk neutrality) in the absence of quantifying attitude toward risk of decision makers.

In this thesis, a practical and systematic methodology is developed and demonstrated whose goal is to make more "intelligent" decisions at strategic level of design, by assessing sustainability of biorefinery strategies under both uncertainty and risk. The data uncertainty has been quantified by a stochastic risk analysis method (Monte Carlo analysis) in the form of probability distribution functions of sustainability criteria. In addition, panel uncertainty has been addressed in terms of the level of consensus among the panel members for making the final decision. Moreover, the risk attitude of decision-makers has been measured using a lottery approach and applying risk aversion theory, by which the preference of decision-makers is quantified for decision making. As a consequence of quantifying uncertainty and risk, decision-makers were provided with improved understanding resulting in more robust decisions. One of the achievements in this thesis is showing that addressing risk attitude of decision makers on top of involving uncertainty in strategic decision making could help to more differentiate between the alternatives and consequently enabled decision makers to screen out more options at the strategic level with more confidence.

The results in this thesis illustrate the importance of applying a systematic approach for making a strategic design decision, considering sustainability criteria and involving uncertainty and decision makers' risk attitude in multi-criteria decision-making. Once these concepts are understood by the senior management of companies, then consensus building can be objectively and systematically accounted for, in decision making and a better decision can be made.

# CONDENSÉ EN FRANÇAIS

Les changements climatiques et le déclin des ressources énergétiques fossiles dans le futur face à une population mondiale en forte croissance ont été les forces motrices principales dans le développement d'alternatives de production d'énergie, de produits chimiques et matériaux à partir de ressources renouvelables grâce à l'implantation de technologies de bioraffinage. Les unités de bioraffinage peuvent être implantées de manière autonome comme dans le cas plus spécifique du bioraffinage agricole, ou être intégrées dans des usines existantes comme dans le cas plus spécifique du secteur forestier. Dans le contexte du bioraffinage Greenfield d'une part, les preneurs de décision identifient une stratégie de produit prédéfinie afin d'avoir un avantage compétitif en augmentant leur part de marché par la production de produits verts. La force motrice derrière le modèle d'affaires est principalement l'accroissement des parts de marchés. D'autre part, la force motrice principale pour le bioraffinage comme stratégie de transformation pour le secteur forestier est de survivre tout en étant compétitif sur le plus long terme. L'intégration du bioraffinage grâce à l'implantation de technologies émergentes dans les usines existantes de pâte et papier doit supporter les entreprises de produits forestiers dans la transformation de leur modèle d'affaires par la production d'un portefeuille de produits étendu. Ce modèle présente quelques avantages compétitifs pour l'implantation du bioraffinage incluant des infrastructures existantes de pâte et papier, ayant sur un savoir-faire d'ingénierie, ayant accès à la biomasse, des chaines d'approvisionnement existantes, ainsi que bénéficiant d'un potentiel d'intégration de procédé dans une usine.

Dans chaque contexte, le bioraffinage se présente sous de multiples configurations possibles étant donné la variété de la biomasse, les procédés de production, les produits ciblés. Cependant toutes les stratégies de bioraffinage ne sont pas durables, et chaque stratégie présente des risques particuliers. Considérant la perspective des investisseurs, il est critique que les stratégies non-durables soient identifiées et exclues de la liste des options de bioraffinage dès les premières étapes stratégiques de conception.

Malgré la nécessité de considérer, dans la prise de décision stratégique, le risque et l'incertitude associés au bioraffinage, des lacunes dans l'ensemble des connaissances ont été identifiés dans cette thèse, basé sur une revue de la littérature :

- Une approche systématique est absente dans la littérature afin d'évaluer la durabilité des stratégies de bioraffinage considérant l'incertitude et le risque, en prenant en compte les valeurs des actionnaires des entreprises pour la prise de décision stratégique,
- Des critères pratiques et interprétables de durabilité pour le contexte spécifique du bioraffinage ne sont pas identifiés dans la littérature afin de refléter correctement les différents aspects des projets de bioraffinage tels que la compétitivité, les risques technologiques et de marché à un niveau de conception stratégique,
- Une approche pratique afin d'adresser les critères de durabilité dans une prise de décision multicritère (MCDM acronyme anglais) tout en assurant un processus de décision gérable (raffinement des critères) n'est pas proposée comme outil dans les études disponibles,
- Combiner les deux concepts (1) d'incertitude associée aux données considérées, (2) d'attitude vis à vis du risque des preneurs de décision pour la prise de décision stratégique des stratégies de bioraffinage n'est pas considéré dans la littérature,

D'après les lacunes identifiées dans l'ensemble de la connaissance, l'objectif principal de cette thèse est défini comme suit :

- Développer une approche systématique pour la prise de décision dès les premières étapes de conception afin d'évaluer les critères de durabilité considérant l'incertitude et qualifiant l'attitude vis à vis du risque des preneurs de décision, et l'illustrer grâce à deux études de cas utilisant les contextes de bioraffinage Greenfield et en rétro-installation.

La réalisation de l'objectif principal mentionné est associée aux sous-objectifs suivants :

- Développer et évaluer les critères de durabilité nécessaires et efficaces pour les systèmes de bioraffinage, et les raffiner en un groupe de critères importants afin d'assurer une prise de décision gérable.
- Quantifier l'incertitude dans la durabilité et l'attitude vis à vis du risque des preneurs de décision afin de les inclure dans la prise de décision stratégique et de comparer la décision finale utilisant le même panel considérant ou non ces deux concepts.

Afin de rencontrer ces objectifs, une approche systématique a été développée considérant les étapes ci-dessous:

- Conception du bioraffinage résultant en la définition des alternatives de conception,
- Analyse économique (technico-économique) et analyse environnementale (analyse de cycle de vie: ACV) des alternatives de conception définies,
- Définition et évaluation des critères de durabilité,
- Raffinement des critères de durabilité utilisant une série de MCDM,
- Évaluation de l'incertitude utilisant une analyse Monte Carlo. Une fonction de distribution de probabilité pour chaque critère de durabilité est générée,
- Attribution d'une importance relative pour chaque critère incertain durant un seul MCDM sur une journée,
- Mesure de l'attitude vis à vis du risque des preneurs de décision utilisant une loterie durant un MCDM d'un jour. Une fonction d'utilité est formulée pour chaque critère,
- Prise de décision :
    - Prise de décision considérant l'incertitude (analyse Monte Carlo)
    - Prise de décision considérant l'incertitude et le risque (analyse Monte Carlo)
- Analyse critique des résultats afin d'identifier l'importance de la durabilité, l'incertitude et le risque dans la prise de décision stratégique dans le contexte du bioraffinage.

La méthodologie proposée dans cette thèse a été démontrée par deux études de cas adressant (a) le bioraffinage agricole Greenfield du triticale, et (b) le bioraffinage forestier en rétro-installation dans une usine kraft.

Il illustre le pouvoir de la méthode MCDM afin de distinguer les options de produit-procédé utilisant une perspective de durabilité de plusieurs manières telles que :

- le transfert des connaissances aux preneurs de décision multidisciplinaires considérant une gamme de critères de durabilité,
- l'approche systématique permettant d'accroitre la connaissance et le respect des membres du panel pour l'interprétation des critères de durabilité,
- la comparaison et la définition du poids de chaque critère prenant en compte les résultats de chaque alternative de bioraffinage, et
- l'explication des résultats des alternatives préférées et moins préférées.

Cette thèse introduit une gamme de critères de durabilité pratiques et interprétables permettant aux preneurs de décision stratégiques ayant des perspectives différentes d'identifier et rejeter les stratégies de bioraffinage indésirable en une journée.

Les résultats de cette thèse démontrent comment l'importance relative des critères de décision et les valeurs d'utilité de chaque critère représentant la préférence des preneurs de décision seront affectées respectivement par l'incertitude dans la prise de décision et la quantification de l'attitude vis à vis du risque de preneurs de décision. Par exemple, les résultats démontrent qu'en adressant l'incertitude dans l'évaluation des critères, le critère le plus important change du Taux de Retour Interne (TRI) avec 35% d'importance dans des conditions déterministes, au Retour sur Capitaux Investis (ROCE acronyme anglais) avec 25% d'importance. De manière similaire le poids associé à tous les autres critères change. Également, la quantification de l'attitude vis à vis du risque des preneurs de décision démontre que les panélistes peuvent être des preneurs de risque dans le cas de certains critères tels que le TRI alors qu'ils sont opposés au risque pour des critères comme ceux associés à la technologie.

Une des réalisations dans cette thèse démontre qu'adresser l'attitude vis à vis du risque des preneurs de décision tout en impliquant l'incertitude dans la prise de décision stratégique pourrait aider dans la différentiation des alternatives et conséquemment permettre aux preneurs de décision d'éliminer plus d'options avec plus de confiance au niveau stratégique. Considérant ces deux concepts (incertitude et attitude vis à vis du risque) en même temps permet une meilleure représentation de la performance potentielle de chaque alternative de conception supportant une meilleure transparence dans la décision.

Les résultats de cette thèse confirment qu'impliquer l'incertitude et le risque pourrait changer la base de prise de décision et parfois changer la décision finale.

De manière générale, l'avantage majeur de ce travail est associé à la prise en compte des concepts de durabilité, de l'incertitude et l'attitude vis à vis du risque dans la prise de décision de manière réaliste et pratique dans le contexte du bioraffinage d'une manière qu'ils soient interprétables pour les preneurs de décision. Lorsque ces concepts sont compris par la haute gestion des entreprises qui considère une transformation de l'entreprise, un consensus peut être atteint objectivement et pris en compte dans la prise de décision afin d'atteindre une meilleure décision.

La comparaison des deux études de cas de bioraffinage dans cette thèse démontre que même si une stratégie de produit de valeur ajoutée est généralement plus prometteuse que la stratégie de bioraffinage ciblant des commodités, cette dernière stratégie peut être intéressante dans le contexte du bioraffinage agricole Greenfield ciblant une croissance des parts de marché des producteurs existants, alors que dans le contexte du bioraffinage forestier la stratégie de produits de valeur ajoutée permet de garantir la durabilité du modèle d'affaires et de prioriser la position compétitive de l'entreprise sur le marché.

Considérant la méthodologie développée et les résultats obtenus démontrés par le biais des deux études de cas, les contributions majeures de cette thèse à la connaissance peuvent être synthétisées comme suit :

- Définition d'une nouvelle gamme de critères de durabilité pratiques et interprétables dans le contexte du bioraffinage pouvant adresser différents aspects associés à la performance du projet incluant les performances économiques et de compétitivité ainsi que les risques technologiques et de marché pour les stratégies de bioraffinage, comme par exemple :
    - 'Downside Economic Performance' (DEP) adressant le risque de marché,
    - 'Phase I Implementation Uncertainty' (PIC) adressant le risque technologique,
    - 'Resistance to Supply Market Uncertainty' (RTMU) comme critère économique d'affaires représentant la sensibilité associée aux incertitudes du marché,
- Ajustement des piliers de durabilité pour le contexte du bioraffinage, en remplaçant le pilier social avec la compétitivité afin d'adresser (1) le succès du portefeuille de produits à atteindre des parts de marché et la compétitivité associée vis à vis des producteurs existants, et (2) l'accès compétitif à la biomasse,
- Introduction d'une méthode afin de raffiner les critères de durabilité nécessaires en une gamme de critères de décision importants utilisant une série de panels MCDM, et agréger ces critères importants mais conflictuels dans un index de durabilité unique employant MCDM,

- Développement d'une conception en rétro-installation (évaluation des potentiels d'intégration entre une usine et le bioraffinage) et l'approche par phases de la conception de bioraffinage pour le contexte du bioraffinage forestier,
- Incorporation des trois concepts de durabilité, incertitude et attitude vis à vis du risque des preneurs de décision dans la prise de décision pour le bioraffinage :
    - Ceci a été réalisé en appliquant une approche systématique qui combine MCDM avec (1) l'analyse Monte Carlo afin de quantifier l'incertitude associée avec les critères de durabilité, et (2) la méthode d'analyse de risque utilisant une loterie afin de quantifier l'attitude vis à vis du risque des actionnaires,
    - Investigation de l'impact de l'incertitude et de l'attitude vis à vis du risque dans la prise de décision stratégique pour l'évaluation de la durabilité des stratégies de bioraffinage en comparant les stratégies de bioraffinage prometteuses (résultant de la décision finale) avec et sans risque ni incertitude,

Les opportunités majeures d'étendre l'approche développée dans cette thèse dans de futurs travaux sont les suivantes :

- Application de l'approche systématique développée lors de panels industriels :
    - Ce travail est une balance entre l'incorporation de nouvelles idées dans la prise de décision stratégique – évaluation de l'incertitude statistique et prise en compte de l'attitude vis à vis du risque des preneurs de décision – et leur mise en pratique. Afin d'être pratique, l'objectif est d'avoir une interface avec les membres multidisciplinaires du panel permettant d'interpréter les résultats et de communiquer de manières rigoureuses les définitions.
    - L'approche de prise de décision proposée dans cette thèse est grandement empirique et dépend sensiblement de l'expertise de l'hôte du panel. L'expérience acquise grâce à l'application de la méthodologie permet des améliorations futures quant aux aspects pratiques de la méthodologie.
- Incorporation de la question des scénarios improbables et des politiques environnementales futures dans la prise de décision :
    - Le risque et l'incertitude dans la prise de décision dès les premières étapes de conception sont fondamentaux et ce travail présente une méthodologie pratique

afin d'évaluer de manière compréhensive ces aspects dans le contexte du bioraffinage. Cependant, il y a encore d'autres sources d'incertitude qui pourraient être considérées dans un panel, spécifiquement la question des scénarios improbables et des politiques environnementales futures.

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| | |
|---|---|
| AHP | Analytical Hierarchy Process |
| ARUC | Ability to Respond to Unknown Changes |
| BDMT | Bone-Dry Metric Ton |
| CAB | Competitive Access to Biomass |
| CDF | Cumulative Distribution function |
| CE | Certainty Equivalent |
| CPC | Competitiveness on Production Costs |
| DEP | Downside Economic Performance |
| DIRR | Downside Internal Rate of Return (DIRR) |
| EBIT | Earnings before Interest and Taxes |
| EBITDA | Earnings before Interest, Taxes, Depreciation and Amortization |
| FCF | Free Cash Flow |
| FCI | Fixed Capital Investment Cost |
| GHG | Greenhouse Gas Emissions |
| HF | Hog Fuel |
| IRR | Internal Rate of Return |
| LCA | Life Cycle Analysis |
| MAUT | Multi Attribute Utility Theory |
| MCDM | Multi Criteria Decision Making |
| NG | Natural Gas |
| NPV | Net Present Value |
| NRE | Non-Renewable Energy |
| PDF | Probability Distribution Function |

| | |
|---|---|
| QR | Quality Revenue |
| RD | Revenue Diversification |
| RO | Respiratory Organics |
| ROCE | Return On Capital Employed |
| RT | Risk Tolerance |
| RTMU | Resistance to Supply Market Uncertainty |
| SC | Sustainability Score |
| SBV | Short-term Business Viability |
| SSCF | Simultaneous Saccharification and Fermentation |
| TCI | Total Capital Investment Cost |
| WCI | Working Capital Investment Cost |
| WWT | Waste Water Treatment |

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# CHAPTER 1 INTRODUCTION

## 1.1 Problem statement

Climate change and dwindling fossil energy resources in the future for the fast growing world's population have been the main driving forces to develop the idea of producing energy, chemicals and materials from renewable resources. Biomass is one of these renewable resources that can be used to produce a variety of bio-products. Similarity between the chemical elements in biomass and crude oil has provided an opportunity to produce a set of renewable products from biomass using biorefinery technologies that can directly replace or substitute existing fossil-based products in the market (Hernandez 2013). Biorefineries can be stand-alone or integrated into the existing facilities, which the former has gained more attention in the agricultural-based context while the latter is targeted in the forestry sector. In a greenfield biorefinery context on one hand, stakeholders have a pre-defined product strategy aiming to achieve a competitive advantage by increasing their market share through producing green products. Thus their main driving force is growing market share. On the other hand, the main driving force of focusing on biorefinery as a transformational strategy in the forestry sector is staying in business and be competitive in the longer term. Over the past few years, the forestry industry in North America has been facing significant challenges mainly due to the declining market demand, increasing competition with the global low-cost producers, increase in energy cost and also the aged facilities in their pulp and paper mills. These issues have forced forest products companies to look for a transformational strategy. Integration of the biorefinery as a set of emerging technologies into the existing pulp and paper facilities would help them with business transformation by the manufacture of an expanded product portfolio. They have some competitive advantages for biorefinery implementation including the existing infrastructure at their pulp and paper facilities, having the engineering know-how, having a good access to biomass, existing supply chain networks, as well as process integration potentials at a mill.

Biorefineries can have various possible configurations because of the variety of biomass, production processes and products. However not all biorefinery strategies are sustainable, and each strategy has its particular associated risks. Using the investor perspective, in this case either the forest products companies or agricultural sector companies, it is critical that unsustainable strategies can be screened out from the list of biorefinery possibilities during the strategic early design stage.

According to the classical definition, aggregation of three economic, environmental and social pillars can be called sustainability. Although social pillar conceptually is important, on a practical level it is generally more linked to the economic or environmental performance. Since technology needs to serve the market, performance of a strategy in terms of its success in the market (market competitiveness) especially in the context of emerging technologies like the biorefinery, is crucial to be assessed along with other aspects of sustainability. This shows the necessity of competitiveness analysis as a pillar of sustainability assessment in order to evaluate the success of the product portfolio to get the market share and their capability to be competitive with the existing main players in the market. A sustainable investment option must not only generate a reasonable profit, but should also be environmentally benign, and remain competitive for the longer-term.

Traditionally the performance of projects has been typically assessed using profitability criteria commonly presented by Internal Rate of Return (IRR) or Net Present Value (NPV). However, from an investor perspective, biorefinery projects should not only be profitable in the short-term, but also should have a robust business model to enable value creation in the long-term while mitigating risks. They should also guarantee business viability under the probable poor market conditions, due to the risk associated with the market price volatility of bioproducts. In addition, they need also to be capable to be implemented at the full scale in order be first to the market given the risk associated with project execution. Considering all challenges for having access to biomass, biorefinery projects should also have the potential to secure low-cost access to biomass over the long-term. Moreover they should be able to compete on market prices with the existing producers to create margins. In addition to the economic and competitiveness opportunities, they should also guarantee better environmental performance compared to the fossil-based competitive product portfolio available in the market. These facts confirm the necessity of developing a set of representative sustainability criteria by which different biorefinery strategies can be well distinguished.

Sustainability assessment of biorefinery strategies is complicated because of employing conflicting criteria, and also due to the large uncertainties associated with information for these emerging technologies at the strategic level of design, which can cause decision failures if it is ignored in project selection. As an inseparable component of any business, decision makers would face risks (Van Bossuyt, Hoyle et al. 2012). Whenever risk exists, each individual decision maker has his/her own attitude toward risk (Schuwirth, Reichert et al. 2012).

Taking this into account, in order to make a realistic and wise decision, not only sustainability and uncertainty should be taken into account, but also the level of risk aversion among the stakeholders should be addressed in any strategic design decision making.

The choice of a biorefinery strategy is not made by individuals but by multi-disciplinary stakeholders who together can be risk averse or risk prone. It is always hard to get multi-disciplinary stakeholders together, and if it can happen, sustainability along with uncertainty and attitude toward risk should be presented in a practical and interpretable format to facilitate the complexity of decision making and make it manageable for the stakeholders. However, the challenge is how a company can translate these concepts (sustainability, uncertainty and attitude toward risk) and bring them into their strategic decision making for biorefinery strategies.

This needs a systematic approach by which the sustainability of biorefinery strategies under uncertainty and risk can be assessed in strategic design decision making, and then can be applied in both greenfield and retrofit biorefinery contexts.

Developing this systematic approach is the main motivation for the research presented in this thesis.

## 1.2 Hypotheses and objectives

The ultimate goal of this thesis is to present a systematic approach by which sustainability of biorefinery strategies, in both greenfield and retrofit context, can be assessed taking into account uncertainty associated with this emerging technologies and considering risk attitude of decision makers. Based on that, the main hypothesis of this work is as follows:

- <u>Main Hypothesis:</u> multi-criteria decision making (MCDM) can enable companies to address sustainability under uncertainty and risk, in a practical way at the strategic level of biorefinery design decision making which can be illustrated in both greenfield and retrofit contexts.

This overall hypothesis has been divided into two sub-hypotheses as follows:

- Specific Hypothesis 1: There is a set of practical and interpretable evaluation criteria using which strategic decision makers having different perspectives will be able to identify and reject undesirable biorefinery strategies in a single day format.
- Specific Hypothesis 2: By considering uncertainty in sustainability assessment and by quantifying risk attitude of decision makers the basis of decision making is changed.

The problem statement and the hypotheses dictate development of a systematic approach that can address the concepts of sustainability, uncertainty and risk attitude of decision makers in strategic decision making in order to identify promising biorefinery strategies. Considering that the main objective of this thesis is as follows:

- Main Objective: To develop a systematic approach for early stage design decision making by evaluating sustainability criteria under uncertainty and quantifying the risk attitude of decision makers.

The accomplishment of the main objective has been tied to following sub-objectives:

- Specific Objective 1: To develop and evaluate a set of necessary and sufficient sustainability criteria for biorefinery systems, and to refine them to a set of important criteria to keep decision making manageable.
- Specific Objective 2: To quantify both uncertainty in sustainability and risk attitude of decision makers in order to involve them in strategic decision making and to compare the final decision using the same panel with and without considering the these two concepts.

## 1.3 Thesis organization

This thesis has been written in five chapters. In Chapter 1, the relevant literature is reviewed in order to identify the gaps in the body of knowledge. Chapter 2 presents first the methodology that has been followed in this study to meet the objectives and then presents the developed systematic approach that by which sustainability of biorefinery strategies can be assessed under uncertainty and risk. At the end of Chapter 2, the case studies to which the methodology is applied are introduced. Chapter 3 synthesizes the results obtained in the process of demonstrating the methodology. In Chapter 4, overall conclusions are given, followed by Chapter 5 which presents the contributions to knowledge and recommendations for future work.

In Appendices A to F the articles that were published in or submitted to peer-reviewed scientific journals are presented. A complementary publication (book chapter) is presented in Appendix G.

# CHAPTER 2 LITERATURE REVIEW

## 2.1 Biorefinery process design

Among the several existing definitions for biorefinery, according to National Renewable Energy Laboratory (NREL) it is defined as "*a facility that integrates conversion processes and equipments to produce fuels, power and chemicals from biomass*" (Fernando, Adhikari et al. 2006). There are variety of biomass (agricultural vs. forestry biomass, etc.), process (thermochemical vs. biochemical pathways) and product (energy, chemicals and materials) which result in several possible biomass-process-product combinations as biorefinery design alternatives. In addition, there are two main biorefinery contexts including (1) greenfield and (2) retrofit or integrated biorefinery.

A few overall approaches for biorefinery design have been proposed which mainly are product-driven and process-driven approaches (Hytonen 2011). The importance of product portfolio selection for biorefinery design was introduced by Farmer (Farmer 2006). His approach was improved then by Wising and Stuart (Wising and Stuart 2006) by combining product design with process design using process systems engineering and process integration tools. Furthermore, Janssen *et al.*(Janssen, Chambost et al. 2008) evolved it with proposing a phased approach for biorefinery implementation, taking into account the strengths and constraints of forest biorefinery industry.

Sammons et al. (Sammons, Yuan et al. 2008) proposed a general approach as a combination of several tools (process simulation, interactive process and molecular design, optimization, environmental analysis) for biorefinery process and product design.

Thus, depending on the context, biorefinery design can be product-driven or technology-driven.

In greenfield biorefinery context, stakeholders have a pre-defined product strategy aiming to achieve a competitive advantage by increasing their market share through producing green products. Considering that, greenfield biorefinery design always starts with selecting a product to be manufactured and therefore is more product driven (Uerdingen 2002). This type of biorefinery has gained more attention in the agricultural industry. For a given product, different process options would define different possible design alternatives from the available biomass, among which, the most promising design alternatives should be identified at the strategic level of design for further evaluation in next steps of design.

On the other hand, the retrofit biorefinery has gained more attention in the forestry industry. Although the North American forestry industry can survive in the short term by cost reductions, for the longer term forest products companies are increasingly considering business transformation in order to improve their financial position. One of these transformation strategies is integration of biorefinery technology into their existing pulp and paper facilities. Similar to the greenfield context, screening out non-promising biorefinery strategies from the list of possible solutions at the early stage strategic design is crucial. This can be done first by "retrofit design" ending up with the integrated forest biorefinery design alternatives definition.

There are several studies in the literature focusing on process integration in existing pulp and paper facilities from different perspectives with the objective of cost minimization. In order to minimize the operating cost, many studies have worked on energy and mass integration mostly employing pinch, advanced pinch and water pinch analysis methods and optimization techniques (Jonsson, Ruohonen et al. 2011; Atkins, Walmsley et al. 2012; Moshkelani, Marinova et al. 2013). However the mentioned cost reduction approaches have been applied mostly for the existing process units at the mill with the objective of profitability improvement by yield enhancement, resource conservation (mass and energy), waste minimization and quality enhancement. Although these methods along with revenue maximization by finding the best product configuration have been applied in the retrofit context, it has been done always for a given biorefinery technology (Mateos-Espejel, Moshkelani et al. 2011; Moshkelani, Marinova et al. 2013). Before any probable cost minimization analysis at the tactical or operational level of design, promising biorefinery technologies for being integrated into the mill should be identified at the strategic level of design. In order to do so, according to the characteristics of the mill, appropriate biorefinery strategies should be selected as the candidate design alternatives. For instance, if the recovery boiler at the mill is the bottleneck in the process, implementation of a lignin precipitation unit seems helpful because it can lead to an increase in pulp production capacity, and consequently can provide adequately high profitability. This approach is more technology-driven design but constrained to the specification of the mill which may determine the product and therefore, the candidate technology should be adjusted to convert the conventional product to the identified promising product in that technology. For instance, if the mill has a great access to a fine and dry biomass (such as saw dust) it dictates that fast pyrolysis technology can be a candidate alternative. However in the case that the mill is very far from the market, producing low-volume large-value products (added value products) would be preferred. Thus, in that case it would be better to produce added value products from the pyrolysis oil to obey this constraint.

After defining the candidate alternatives, all the potential synergies between the mill and each biorefinery candidate should be identified. However, all the potential benefits at different sectors at the mill have not been well assessed in literature. Hytönen *et al*. (Hytonen and Stuart 2009) have analyzed integration of biorefinery technologies into a kraft pulp mill from different aspects including capital cost saving, operating costs synergies and revenue diversification for bioethanol production. However their work exclude cost synergies in material handling system and incremental cost caused by the additional operating labor to handle the biorefinery plant. Moreover, the associated costs with modifications of existing equipments at the mill being adapted to be used above their current capacity to cover biorefinery utility demand has not been addressed either. Beside this, in their study targeted integrations have been assessed only from an economic perspective, while companies nowadays are more looking for the profitable options that have less environmental impacts and more social benefits (Epstein 2008).

After defining the design alternatives along with identifying all of their integration potentials with the existing facilities, these candidate strategies should be assessed in terms of their sustainability performance. Sustainability assessment of biorefinery strategies is reviewed in the following section.

## 2.2 Sustainability assessment of biorefinery strategies

Although there are different definitions for the sustainability concept, most commonly sustainable development is defined as *"… development that meets the needs of current generations without compromising the ability of future generations to meet their needs and aspirations"* from the Brundtland Report (Bruntland 1987). There are different interpretations of this definition among which it is mainly defined as an industrial system that is able to create profit while providing less environmental impacts and having more social benefits (Piluso, Huang et al. 2008). According to the classical definition, aggregation of economic, environmental and social pillars can be called sustainability. Incorporation of these pillars in evaluating projects have been also called sustainable engineering, green engineering, design for environment, and eco-efficiency (Allen and Shonnard 2012).

In the literature most of sustainability assessment studies in the context of biorefinery belong to the tactical and operational levels. They typically apply a superstructure of biorefinery options, process systems engineering (PSE) tools and mathematical optimization methods for multi objective problems (Buping, Ng et al. 2011; Sharma, Sarker et al. 2011; Gebreslassie, Waymire et al. 2013; Wang, Gebreslassie et al. 2013; Santibanez-Aguilar, Gonzalez-Campos et al. 2014). These methods have been applied in a wide range of applications including selection of most appropriate feedstock, determination of optimal production capacity, identification of optimal process stages, and figuring out the optimal supply chain design. However some surveys clearly prove that the most common decision problems that companies regularly face are pathway selection at the strategic level of design (Hodgett 2013). At that level, decision makers are not looking for the optimal solution but are interested in identifying non-promising options to screen them out from the list of investment possibilities.

Traditionally these types of problems are solved by rationalization taking into account several assumptions, however this can possibly end up with inaccurate results (Othman 2011). Therefore, it is crucial to apply a systematic approach for comparing candidate strategies at the strategic level of design.

In some studies sustainability has been addressed by detailed analysis based on conceptual process design in which all processes are first simulated and then they are assessed in terms of economic and environmental performance (Posada, Rincon et al. 2012; Posada, Patel et al. 2013). For instance, a method has been presented by Hung *et al*. (Huang, Lin et al. 2009) as a design modeling for integrated forest biorefinery options in which two simulation softwares (Aspen Plus for biorefinery process and WinGems for pulp production process) are linked. Besides all advantages of these types of conceptual design, it should be noted that they are not easily applicable at the strategic level of design due to being time-intensive and data demanding.

There are some exceptional cases in literature that the results of assessing sustainability pillars in their context are consistent and so decision making has not been very challenging. For instance Pourhashem *et al*. (Pourhashem, Adler et al. 2013) have assessed three lignin-based biorefinery strategies separately in terms of economic and environmental performance. In their study one option was showing the best performance in both economic and environmental aspects and so decision making about the most sustainable strategy was straightforward. In addition, Gheewala *et al*. (Gheewala, Bonnet et al. 2011) have also analyzed the degree of sustainability associated with different scenarios of bioethanol production from sugar cane using five criteria, including three economic criteria and one criterion for each of the social and environmental pillars. In that study, choosing the most promising scenario was also not challenging given that one scenario always showed the best performance on each sustainability dimension.

Gnansounou (Gnansounou 2011) performed a sustainability assessment of two wheat-based bioethanol production strategies using twenty economic, environmental, and social criteria. The various criteria were qualitatively evaluated, leading to a lower level of accuracy compared to employing quantitative criteria which can be completely objective and verifiable.

Sacramento-Rivero (Sacramento-Rivero 2012) developed a methodology for sustainability assessment of biorefinery strategies using a framework considering fourteen indicators within five themes: feedstock, process, product, environment, and corporate. This methodology generates a radar plot which can quantify the current distance of a biorefinery project from the ideal sustainability performance for each indicator depending on how far the criterion value is from zero (representing the highest sustainability level). Although this study introduces an interesting set of normalized sustainability criteria, their integration into a unique sustainability score has not been addressed.

Normally identifying sustainable strategies for a company is not a straightforward task mainly due to employing sustainability criteria which in nature are conflicting. It implies a multi-objective problem in decision making (Othman 2011). Thus employing a systematic decision making approach at the early stage design seems crucial by which conflicting sustainability criteria can be aggregated into one index. This approach would enable stakeholders and decision makers to compare the performance of different biorefinery strategies for their investment. Multi Criteria Decision Making (MCDM) methods can help decision makers to aggregate conflicting criteria into an index as sustainability performance by quantifying a relative importance for each sustainability criterion. The MCDM method and its application to identify sustainable strategies is reviewed in section 2.3.

## 2.3 Multi criteria decision making (MCDM)

### 2.3.1 Introduction

According to the definition presented by Eisenhardt and Zbaracki (Eisenhardt and Zbaracki 1992) strategic decisions are *"infrequent decisions made by the top leaders of an organisation that critically affect organizational health and survival"*. The two main challenges in any strategic decision making are the presence of high uncertainty and complexity of considering different conflicting aspects of the project (Zopounidis and Pardalos 2010). Considering these challenges, it is probable that managers would face difficulty in making decision without the support of decision making tool. These critical types of decisions (strategic decisions) need to be systematically addressed with a decision making process. At this level of design, investors are looking for screening out non-promising strategies to limit the number of possibilities to further analyze at the next steps of design, while at the tactical and operational level of design the main objective would be finding a unique optimal solution.

A successful decision making approach would end up with a right decision. However the question is that how decision makers can evaluate if the process has been successful or not? A right decision should not put emphasis on the final result only, but also on the decision making process itself. Multi criteria decision making (MCDM) is a systematic tool which facilitates obtaining the right decision if it can be well executed.

MCDM is performed by following several steps within two phases including a pre-panel and a panel phase. These steps are as following (Munda 1995):

- Pre-panel phase:
  - Reviewing of the decision context;
  - Defining of the objectives of decision making;
  - Alternatives definition;
  - Introduction of criteria.
- Panel phase:
  - Criteria evaluation and interpretation;
  - Identification of preferences of the panel;
  - Quantifying the relative importance of the decision criteria;

- Calculating the final scores representing the performance of the design alternatives;
- Ranking the alternatives, interpretation of results and making a final decision

Advantages and disadvantages of MCDM methods have been reviewed in several studies among which Oman (Omann 2004) has presented a deep analysis. The main advantages of MCDM methods can be summarized as following:

- They make the decision problem well structured for stakeholders;
- They can carry out several conflicting heterogeneous criteria when human's mind is incapable to draw conclusion from them;
- They provide much more information about the criteria than just a number, through interpreting them;
- They have an interactive approach;
- They reflect the preferences of decision makers
- They can well address data uncertainty and attitude toward risk in a rational ;
- They provide the discussion and negotiation among the decision makers (stakeholders) ending up with building consensus among them for the final decision.

However MCDM methods have also some weaknesses as follows (Omann 2004):

- They might contain too much information for stakeholders, this is why sometimes stakeholders are not motivated enough to participate;
- The result of an MCDM depends on the panel and is not necessarily reproducible;
- Depending on the expertise of the MCDM conductor, there would be a risk of applying the method improperly.

Recently three survey workshops were held across Canada with the objective of introducing MCDM tool to stakeholders from Canada's forestry sector, and to understand how forestry companies evaluate and select biorefinery projects. The results show that about 33% of these companies do not have clearly defined decision making process related to biorefinery selection as their transformational strategy. Moreover, about 75% of the forest product companies evaluate biorefinery on a somewhat ad-hoc basis, one strategy at a time (Chambost, Mariano et al. 2014).

In these workshops, participants were asked about the drivers that possibly can motivate them to use a systematic decision making approach in their company. The results show that the majority of them believe that two main drivers would be (1) the capability of this tool to decide about the projects that need to be assessed not only from a profitability aspect but also from sustainability perspective and (2) the capability of MCDM to incorporate the two concepts of sustainability and risk into strategic decision making.

In addition, since most companies usually involve from 5 to 20 stakeholders in the decision-making, the panel approach for getting consensus among the stakeholders was of their interest (Chambost, Mariano et al. 2014).

However besides all drivers, some barriers were also recognized as challenges in terms of implementation of an MCDM process. Among these barriers, two main issues include complexity of the MCDM process and difficulty of dedicating a full day for stakeholders to this activity.

MCDM methods are assessed using several criteria, to investigate their compatibility for sustainable development (Table 2-1) (Omann 2004). The conclusion that can be drawn is that MCDM methods are appropriate tools for sustainability decision making (Munda, Nijkamp et al. 1994).

**Table 2-1. Overview of the compatibility of MCDM methods for sustainability decision making (Omann 2004)**

| Requirement | Fulfilment | Comment |
|---|---|---|
| **Systems characteristics** | | |
| Addressing of all dimensions and objectives | + | - |
| Addressing of different levels | + | - |
| Incommensurability and incomparability | ~ + | Depends on the method |
| Addressing of trade-offs | + | Not all MCDA methods allow for incomparability |
| Mechanisms to address uncertainty | ~ | Not all MCDA methods can address uncertainty |
| Consideration of hierarchies | ~ | Depends on the method used |
| Addressing of self-organisation and evolutionary character | ~ + | - |
| Addressing of non-linearity | ~ | Depends on the method used |
| Coping with different forms of data | + | - |
| **Principles of sustainable development** | | |
| Supporting strong sustainability | ~ | Depends on whether the method is compensatory |
| Supporting justice | ~ + | Can hardly be addressed by decision aid |
| Support of democracy | ~ + | Depends on the persons in charge |
| Respecting and integrating multiple perspectives | ~ + | Largely depends on persons in charge |
| **Decision procedure** | | |
| Focus on process and result | + | - |
| Allowing and supporting learning | ~ + | Depends on the approach |
| Allowing non-agreement | ~ + | Depends on the approach |
| Transparency of the process | + | - |
| Degree of acceptance of result | ~ + | Depends on degree of participation |
| Understanding of process and result | ~ | Depends on the method used and analysts |
| Bridging the gap between research and policy | + | - |
| Interdisciplinary research group | + | Indirectly required by MCDA |
| Understanding of language | ~ | Depends on persons in charge |
| Flexibility of approach | ~ + | Depends on how the facilitators apply MCDA |

## 2.3.2 MCDM classification

There are several publications in which different classifications of MCDMs have been presented (Omann 2004). Although reviewing all the available classifications would not add additional value to this study, understanding the basis of their classification and introducing the widely applied MCDM methods can shed light on the decision making path in this project.

There are different perspectives for MCDM classifications. For instance, in some references, they are divided into the two groups of discrete and continuous methods. In another categorization, two types of MCDM methods are identified, the methods which treat quantitative criteria versus the methods that are able to handle both qualitative and quantitative criteria. In another perspective, all MCDM methods that end up with one solution put in one category against the MCDM methods which can rank the alternatives.

There are several frameworks introduced in literature for selecting an appropriate MCDM method considering the context of the decision making problem. In some cases MCDM has been suggested to be used in order to identify the most appropriate MCDM approach for a specific decision making context. However it does not seem an applicable approach because of the chicken and egg debate around it. Hwang and Yoon (Hwang and Yoon 1981) introduced a typology tree representing several questions that would lead an MCDM conductor to select an appropriate decision making method. Another technique has been presented by Montis *et al.* (Montis, Toro et al. 2000) in which a list of qualification criteria is introduced, to compare the available MCDM methods. Guitoni and Martel (Guitouni and Martel 1998) also proposed a framework to choose one decision making method among the available techniques. In that study, an overview of 29 commonly used methods can be found.

Besides all values of these efforts, the choice of MCDM method would be less important than well performing (Pomerol 2000). Among all available MCDM methods, two widely used methods are Analytical Hierarchy Process (AHP) and Multi Attribute Utility Theory (MAUT).

In AHP method introduced by Saaty (Saaty 1980), first the problem is decomposed into hierarchy levels, then pair-wise semi-qualitative comparison between the criteria is conducted, and at the end results are synthesized. On the other hand, Multi Attribute Utility Theory (MAUT), presented by Keeney & Raiffa (Keeney and Raiffa 1976), quantifies the decision maker's preferences through expected utility theory. This method is performed by following five main steps:

- Problem structuring in which the goal of decision making and the design alternatives are defined
- Criteria definition and evaluating the performance of the design alternatives using those criteria

- o Decision makers' preference evaluation (utility functions formulation) representing risk attitude of decisions makers
- o Quantifying relative importance of the decision criteria (criteria weighting factors) using trade-off activity
- o Ranking the alternatives and interpreting the results

The AHP method is a well-established and simple decision making approach for multi-criteria decision problems. However, it has some major drawbacks which cause MAUT being preferred. For instance, AHP's validity has always been a subject of debate because of semi-qualitative comparison between the criteria instead of measuring their relative importance quantitatively. In addition, rank reversal is arguably the main drawback of AHP method. Furthermore, decision makers' preference and the criteria importance can not considered separately in AHP method. In contrast, the MAUT method uses utility functions for representing decision makers' preferences and quantifies criteria weights independently by a trade-off activity. Thus, although MAUT is a more complex method, it is a more rigorous and reliable decision making approach.

Although both of these common methods have been applied for different decision making problems in the forestry industry context, they have not been widely used in the biorefinery context.

### 2.3.3 MCDM application for sustainability assessment

The application of MCDM to identify sustainable strategies has been analyzed by Wang *et al*. (Wang, Jing et al. 2009) and Lai *et al*.(Lai E. 2008) in the context of the energy and urban water systems respectively. However their general approach can be applied in any other context, including the biorefinery. There are currently numerous applications of MCDM approaches in general and for the forestry sector in particular which has been reviewed by Balteiro and Romero (Diaz-Balteiro and Romero 2008).

MCDM methods have not only application at the strategic level of design but also they can be employed in hybrid methods for the other design levels in which it has been relatively easy to optimize a weighted objective function, but it was always difficult to understand the relative importance of the objectives. For instance in some studies MCDM was accompanied with multi objective optimization methods through which they first compute a set of promising strategies via a Pareto multi-objective optimization, and then apply MCDM to identify the preferred options applying relative importance of the objectives (Perera, Attalage et al. 2013).

In the literature there are just few studies which have employed MCDM to identify sustainable biorefinery strategies at the strategic level of design. The drawback of most of these available studies is that in order to calculate an integrated score for each alternative, they have attributed an arbitrary relative importance (weighting factor) to each criterion. These weights were set without considering the context of the results, instead of being quantified using a logical and systematic approach. Although some criteria can be very important in concept, in the context of the results they may not help decision makers to differentiate between the candidate alternatives. In such cases, their relative importance should be less than expected. As one of the mentioned studies, Posada *et al*. (Posada, Patel et al. 2013) used MCDM to identify promising bioethanol-based products among twelve candidates. They defined a set of sustainability criteria, with arbitrary weights, addressing economic, environmental, safety and health performance and then normalized them using the impacts of the comparative petrochemical-based pathways. The variability of their subjective weighting factors was examined by Monte Carlo analysis through changing the weights within a specified range considering an upper and a lower limit. However these boundaries themselves were defined subjectively. The issue of arbitrary attributed weights without considering the context of the results can be seen in the other contexts as well. For instance in the context of chemical design for methyl methacrylate (MMA) production, Sugiyama *et al*. (Sugiyama, Fischer et al. 2008) have applied MCDM using a set of sustainability criteria including economic, environment, health and safety. However through an arbitrarily manner equal weighting factors were attributed to monetary and non-monetary criteria. As a continuation of their work, Patel *et al*. (Patel, Meesters et al. 2012; Patel, Meesters et al. 2013) added some criteria into their list and employed them to assess laboratory experiments. They defined five main groups of decision criteria each including some sub-criteria. However they also assumed equal weighting factors for the criteria which is not necessarily consistent with reality. Another example of assigning the arbitrary weightings belongs to Schaidle *et al*. (Schaidle, Moline et al. 2011). They have compared three biorefinery options producing fuels in the existing infrastructure considering a set of economic, environmental and social criteria. Their criteria were weighted arbitrarily through four scenarios. In the base case, they were weighted equally, and in other scenarios each time one criterion was given twice the importance of the other two. Their results clearly show that applying different weighting factors can change the final decision dramatically. It proves the necessity of quantifying the relative importance of decision criteria in the context of the results through a systematic approach by conducting a multidisciplinary panel of decision makers.

In the context of biorefinery, tere are only a few studies in the literature that conduct a panel to evaluate the relative importance of the criteria. The European network called Biosynergy (Agostini 2010) employed MCDM method for considering different pillars of sustainability to assess biorefinery strategies. Similarly Othman (Othman 2011) has used MCDM to aggregate a set of quantitative and qualitative sustainability criteria (economic, environmental and social criteria) to compare some process design alternatives for biodiesel production. However, attributed scores to the decision criteria with which their relative importance is measured, was not obtained from conducting a multidisciplinary panel. Papalexandrou *et al*. (Papalexandrou, Pilavachi et al. 2008) also used MCDM to assess different biofuel production options using the production cost, biofuel yield, green-house gas emissions and total cycle energy consumption as decision criteria.

Besides all the values of these studies, it should be noted that their employed MCDM method is Analytical Hierarchy Process (AHP) which performs a semi-qualitative comparison between the criteria and does not trade-off the values quantitatively. In addition, it needs to deal with a large number of pair-wise comparisons between the criteria that is challenging specifically when decision are made using a large number of criteria. It also has been shown that sometimes this method can not reflect the preferences of the decision makers correctly (Dyer and Forman 1989).

One of the studies in which the decision makers' preference were well reflected in measuring weighting factors of the decision criteria is what was done by Cohen *et al*. (Cohen, Jansson et al. 2010). They used Multi Attribute Utility Theory (MAUT) method employing a set of conflicting criteria for identifying promising standalone biorefinery technologies to produce lignocellulosic bioethanol. In order to quantify weighting factors of each criterion, they conducted a multidisciplinary panel. In addition to some drawbacks of their study including measuring environmental criterion qualitatively, the major limitation of their work is that their criteria were evaluated using the available information in the literature while different sources in literature do not necessarily have the same basis for their assessment. This would be an obstacle in comparing the available reported information in different works. This issue has been addressed by Hytönen and Stuart (Hytonen and Stuart 2011) through quantifying uncertainty caused by extracting data from publications with different economic analysis bases. They used MCDM in the retrofit biorefinery context in order to first quantify the relative importance of the decision criteria and then accordingly to identify promising bioethanol production pathways. However the main gap in their work is employing a set of decision criteria that all address economic performance while numbers of other criteria should be added to the list of criteria addressing different aspects of the project. However this would increase the number of criteria using which MCDM would not be easily manageable.

This issue has been addressed in this thesis by not only using MCDM to quantify the criteria weights, but also to refine a set of necessary sustainability criteria into a set of important criteria for being employed to make a decision. This objective will be met by employing a systematic approach with a cascade of MCDMs for sustainability assessment of biorefinery strategies in which MCDM is employed first to refine the decision criteria and then to aggregate the identified important sustainability criteria.

Given the uncertainty associated with emerging technologies like the biorefinery, especially at the strategic level of design with the scarce data, involving uncertainty in sustainability decision making seems crucial. However it has not been well addressed in literature. This issue is reviewed in the following section.

## 2.4 Uncertainty analysis

There is a high level of uncertainty associated with information at the strategic level of design, which can cause decision failure if it is ignored in project selection. Hoffman *et al* (Hoffmann, McRae et al. 2004) introduced three main reasons that justify why companies should pay more attention to project selection properly at the strategic level of decision making. The first reason is that financial resources are limited and among numerous potential emerging technologies, these resources should only be allocated to promising long-term strategies. In addition, despite traditional project selection procedures which were mainly based on fulfilling the economic objectives, nowadays decision makers should include environmental and competitiveness objectives which make the process more complex due to the conflict that they often have with the conventional objectives. The last reason is that most of information at the strategic level of design are uncertain and if this uncertainty is not addressed in decision making, the results may mislead decision makers and they may end with wrong decisions (Shakhsi-Niaei, Torabi et al. 2011).

There are several studies in the literature addressing uncertainty in decision making at tactical and operational level of design in order to find the optimal solution. Among these studies, we can refer to what has been done by Gebreslassie *et al*. (Gebreslassie, Waymire et al.) and Pistikopoulos *et al*. (Pistikopoulos 1995). Most of these studies working on uncertainty analysis are about supply chain optimization summarized by Gloria *et al*. (Giarola, Bezzo et al. 2013). Good Reviews of uncertainty analysis in optimization can be found by what has been done by Sahinidis and Verderame *et al*. (Sahinidis 2004; Verderame, Elia et al. 2010) In the context of the integrated forest biorefinery design, uncertainty analysis in optimal retrofit of an existing pulp and paper mill to an integrated biorefinery was reviewed by Svensson (Svensson 2008). Besides all values of these studies, it should be noted that multi objective optimization methods under uncertainty are computationally intensive which makes them difficult to be applied at a strategic level of design which commonly deal with many uncertain parameters.

Despite the necessity of involving uncertainty in strategic decision making, especially in the context emerging technologies such as biorefinery, nowadays decisions are mainly made using deterministic values (Dorini, Kapelan et al. 2011) and little attention has been paid to decision making under uncertainty (Shakhsi-Niaei, Torabi et al. 2011). In order to address this issue, a set of sustainability decision criteria covering economic, environmental and competitiveness aspects of a biorefinery project should be evaluated under uncertainty and then be employed by an appropriate systematic decision making approach. Some researchers (Medaglia, Graves et al. 2007), have tried to consider uncertainty in the project selection in a comprehensive way, however their proposed method does not seem practical because of its time intensity thst causes more complexity in the process (Shakhsi-Niaei, Torabi et al. 2011). In contrast to these complex methods, more applicable techniques such as MCDM, seem more appropriate for this purpose (Keeney and Raiffa 1976).

There are different sources of uncertainty associated with biorefinery project selection using MCDM including:

- Uncertainty in parameters used in evaluation models which is called data uncertainty

- Uncertainty in evaluation model itself which is called model uncertainty
- Uncertainty in decision making due to probable inconsistency of panelists in scoring process and also due to the lack of complete consensus among them on the attributed relative importance to decision criteria, this is called panel uncertainty presented by the level of consensus among the panel.

There are several mathematical and computational methods for uncertainty analysis among which statistical methods, fuzzy mathematics and artificial intelligence can be mentioned (Liu and Huang 2012). Among these methods, statistical methods in general and Monte Carlo analysis in particular, are the most commonly used method.

Some studies focused on involving one type of uncertainty mentioned above in decision making. For instance, Liu and Huang (Liu and Huang 2012) presented a methodology to measure the sustainability of biodiesel manufacturing systems using uncertain data and employing an MCDM method. They used an interval-parameter (IP) method for uncertainty analysis. Although they mentioned that the applied relative importance of the decision criteria were given by the organization, a systematic approach for quantifying these weights is missing in their study. Cheali *et al*. (Cheali, Gernaey et al. 2014) considered data uncertainty (uncertainty in biomass and product price) in a superstructure assessment of biorefinery technologies in both biochemical and thermochemical pathways. They did not consider sustainability criteria, but only compared the economic performance of biorefinery options. Madani and Lund (Madani and Lund 2013) used the Monte Carlo method as uncertainty analysis tool through which they converted an uncertain problem to several deterministic problems. They addressed uncertainty in input data used to evaluate the decision criteria which were then aggregated into a sustainability index employing a MCDM method.

Dealing with conflicting decision criteria requires decision makers' judgments about the relative importance of them. Some people believe that these judgments may cause uncertainty in the results. There are some studies focusing on analyzing the uncertainty in the relative importance attributed to decision criteria in decision making. Chou and Ongkowijoyo (Chou and Ongkowijoyo 2014) compared sustainability performance of different renewable energy systems for policy making using an MCDM approach. They addressed uncertainty in the applied relative weighting factors of decision criteria, to investigate the dependency of the final decision on these weighting factors. Their study proposes a risk-based MCDM that uses graphical matrix modeling along with Monte Carlo simulation. In order to address uncertainty in the attributed relative importance of the criteria, they applied a triangle distribution function for the scores given by each decision maker to each criterion. These triangular distribution functions are developed using three numbers representing the pessimistic, most likely, and optimistic values that a panel member can give to the pair-wise criteria comparison.

However we believe that attributing a distribution function to the scores for pair-wise comparisons, does not decrease subjectivity associated with the applied criteria weighting factors. The reason is that the numbers for pessimistic, most likely and optimistic values are also given by the panel members and by changing the panel these numbers may possibly change. In addition, requesting panelists to give three numbers to each criterion comparison, would considerably increase the time needed to perform the panel which makes decision making process less and less practical to be applied by companies.

In any MCDM decision making process, if the panel is changed there is a possibility that the criteria weights and consequently ranking of the alternatives would be changed. However changing the results by changing the panelists (stakeholders) - project selection for different companies- should not be seen as an uncertainty of the results but it is just as a result of following different objectives in different companies according to their mission and vision. For instance, when one company is leading more toward developing sustainable products and penetrating the green market, for the decision makers in that company, environmental criteria would be more important than for others companies. In contrast, for a company with limited financial resources for investing in new projects, capital investment cost is a very important criterion by which they can well differentiate the alternatives to identify the project they can go with. The only thing that can bring uncertainty in the results is overemphasis or underemphasis of one aspect of sustainability as a result of missing a multidisciplinary panel. However as soon as decision making is performed by a multi-disciplinary panel in a company, the results would not be uncertain in the context of that company.

Another type of uncertainty is model uncertainty. In sustainability assessments, this type of uncertainty is mainly associated with life cycle analysis (LCA) models because the uncertainty associated with it, as a method which deals not only with the main studied process but also with many upstream and downstream processes, is more than uncertainty involved in other models including techno-economic model. There are studies that have worked on addressing uncertainty in LCA models, however this type of uncertainty is beyond the scope of this study, and the uncertainty in the applied models has been assumed the same for all the studied candidates in this study.

There are some studies in literature addressing different sources of uncertainty -from data to panel uncertainty- in decision making. For instance, Flores-Alsina *et al.* (Flores-Alsina, Rodriguez-Roda et al. 2008) have assessed sustainability under uncertainty for waste water treatment systems employing an MCDM method. They developed probability distribution functions for sustainability criteria by applying uncertain parameters and employing Monte Carlo analysis, to investigate the effect of involving data uncertainty in decision making. They categorized uncertain parameters in three groups of low uncertain parameters with just 5% variation compared to the deterministic value, moderate and highly uncertain parameters with 25% and 50% variation respectively. In addition to data uncertainty, they also addressed uncertainty in the applied relative importance of the decision criteria in MCDM. Besides all values of their systematic approach, there are some limitations mainly about the way criteria weights have been treated. In deterministic conditions, they arbitrarily assumed the same weighting factors for decision criteria instead of quantifying them with decision makers (stakeholders). In addition, in order to address uncertainty in the applied weighting factors, they arbitrarily defined some scenarios representing different combinations of criteria weights. Although they investigated the effect of uncertainty in data and criteria weight on the final decision separately, the two sources of uncertainty have not been applied simultaneously in decision making. Doroni *et al.* (Dorini, Kapelan et al. 2011) compared bio-based with coal-based electricity generation in terms of sustainability performance by quantifying uncertainty using Monte Carlo analysis and aggregating uncertain decision criteria using MCDM method. They showed how much involving each type of uncertainty can affect the final decision by presenting the results for three cases including (1) assuming no uncertainty, (2) involving uncertainty in data and (3) involving uncertainty in data and decision-makers' preferences. In order to address uncertainty in criteria weights, instead of attributing a deterministic value to each pair-wise comparison between the criteria, a probability distribution function was considered for it. For instance, in their analysis with six decision makers (panelists), instead of making an average value for the given numbers by panelists to each criterion, they have assumed 1/6 probability to each number representing the opinion of each panelist. Finally, in each iteration of Monte Carlo method, in addition to extracting a random value from uncertain parameters, a random value has been also generated from the developed distribution functions of the criteria' weights using which at each iteration sustainability score has been calculated. Patel *et al*. (Patel, Meesters et al. 2012) assessed sustainability performance of but-1,3-diene production via a bio-based process compared to the conventional process, using a MCDM approach under uncertainty. They have defined a set of quantitative and qualitative sustainability criteria evaluated under uncertainty using Monte Carlo analysis method. In addition to data uncertainty, they also addressed uncertainty in the attributed relative importance to each decision criterion by generating random weighting sets within the ranges they defined for variation of each criterion weight. However the main limitation of this work is that the attributed weighting factors are arbitrary in both deterministic and uncertain conditions, instead of reflecting decision makers' opinion by quantifying weights in the panel. Shakhsi-Niaei *et al*. (Shakhsi-Niaei, Torabi et al. 2011) presented a framework for project selection under uncertainty which addresses two phases of project selection, first screening out non-promising options (strategic level) and then selecting the final promising project. In the first phase they used Monte Carlo analysis linked with MCDM whereas second phase in which Monte Carlo analysis is linked with integer programming module considering budget and other logical constrains to find the optimal solution. Their method has been applied in project selection for Iran Telecommunication Research Center (ITRC).

There are a number of studies in the literature that already demonstrated how to address uncertainty in sustainability assessment and decision making. However a method for identifying sustainable biorefinery strategies at the strategic level of design considering different sources of uncertainty is relatively missing in literature.

In addition, investing in biorefinery is dealing with risk, and whenever there is risk, decision makers would have their own attitude toward risk. Considering that, uncertainty and risk should be both addressed at the strategic level of design to increase the reliability of the decision making process. In this regard, risk analysis is reviewed in the following section.

## 2.5 Risk assessment

In strategic decision problems, decision makers face risk as potential outcome of uncertain events (Van Bossuyt, Hoyle et al. 2012). For instance, in the context of the forest products industry, decision makers must accept risk and take it into account in decision making. If they had not accepted risk, they would never open the door to biorefinery. Whenever risk exists, each individual decision maker has his or her own attitude toward risk (Schuwirth, Reichert et al. 2012). The decision for a biorefinery strategy is not made by individuals but with multi-disciplinary stakeholders who together can be risk averse or risk prone. In order to make a realistic and wise decision, the level of risk aversion among the stakeholders should be quantified and taken into account for strategic design decision making.

Normally dealing with design risk within an organization would be done qualitatively through an informal procedure. It means that a quantitative approach by which stakeholders can practically make an informed decision taking into account their risk attitude, is almost missing in reality (Van Bossuyt, Hoyle et al. 2012). There are several existing methods of risk assessment reviewed by Van-Bossuyt *et al.* (Van Bossuyt, Hoyle et al. 2012). Some of these methods are Fault Tree Analysis (FTA) (Ericson 1999), Failure Modes and Effects Analysis (FMEA) (Franklin, Shebl et al. 2012), Risk in Early Design (RED) (Lough, Stone et al. 2009), Functional Failure Identification Propagation (FFIP) (Kurtoglu and Tumer 2008), Function Failure Design Method (FFDM) (Stone, Tumer et al. 2005). However the main limitation of these methods is that they can not be practically used in an enterprise in order to address risk attitude of decision makers (Van Bossuyt, Hoyle et al. 2012) because these existing models generally use an expected value approach. For example in FTA and FMEA that commonly have an industrial application, risk is addressed as an expected value, meaning that if decision makers should make a decision between a risky option with 1% chance of occurring 10000 $ loss and another risky option with 0.1% chance of occurring 100000 $ loss, these options would be considered identical according to the expected value. However this approach is ignoring the preference of the decision makers in an organization and does not take into account the willingness to take risk that is always changing from one context into another (Van Bossuyt, Hoyle et al. 2012). For instance, innovative technology providers and entrepreneurs normally seek risks, whereas leadership personnel at corporate level who are more conservative to take risk (Van Bossuyt, Hoyle et al. 2012).

There are three types of attitude toward risk including “risk averse” person who does not like to take risk and seeks certainty in outcomes, “risk neutral” person who is ready to take essential risks in short-term to achieve his/her desired outcomes in longer term, and “risk prone” person who is ready to take large risks and more uncertainty in outcomes is acceptable for him/her (Van Bossuyt, Hoyle et al. 2012). Individuals can have different attitude toward risk in different domains. A person can be risk-prone for financial decisions, but risk averse in social situations (Van Bossuyt, Hoyle et al. 2012).

Quintero-Bermudez *et al*. (Quintero-Bermudez, Janssen et al.) compared different panels for the same decision making objective. Their results show that there is a high level of consensus in the results of academic and industrial panels. Knowing that industrial and academic panels are completely different in terms of their risk attitude, it can be concluded that this difference may not be captured in their study because of not quantifying risk attitude of decision makers. This confirms the necessity of addressing risk attitude of panel members in decision making.

There are mainly four steps in conventional risk assessment methods which include (Standard 2009):

- Risk identification
- Risk analysis
- Risk evaluation
- Risk treatment

The importance of considering uncertainty and risk in decision making has been discussed by Hazelrigg (Hazelrigg 1998). When these two concepts are involved in decision making, MAUT method is preferred to pair-wise comparisons decision making methods (Catrinu and Nordgård 2010). In these preferred methods utility is a measure of satisfaction of a result (Keeney and Raiffa 1976), often expressed as a quadratic, logarithmic or exponential function in which the shape of utility function denotes the risk attitude of decision makers (Van Bossuyt, Hoyle et al. 2012). In the literature inclusion of multi attribute problems under uncertainty and risk for a complex decision making problems is rare (Thevenot, Steva et al. 2006). Thevenot *et al*.

(Thevenot, Steva et al. 2006) showed how uncertainty and risk attitude of decision makers can be both integrated into design decision making.

Currently most of methods for developing utility function of the decision criteria require making lotteries to decision makers. In a lottery activity, decision makers are offered a choice between receiving a certain outcome and a lottery in which there is 50% chance of receiving an amount that is more than the certain offer and a 50% chance of receiving an amount that is less than the certain offer. If the decision maker is risk averse, he/she prefers to choose the certain offer, whereas the risk prone decision maker who prefers to try his/her chance to have the possibility of getting more than certain offer. These lottery games demonstrate decision makers' preference patterns (Becker and Sarin 1987).

In the context of the biorefinery, a systematic method for sustainability assessment which can address not only different sources of uncertainty, but also the risk attitude of decision makers, is missing in the literature.

The objective of this thesis is to develop a systematic approach to practically and realistically address different sources of uncertainty and the risk attitude of decision makers in strategic sustainability decision making. This has been done employing a set of sustainability criteria in MCDM approach and quantifying uncertainty by Monte Carlo analysis and measuring attitude toward risk of decision makers using panel-based lottery activity using risk aversion theory.

## 2.6 Gaps in the body of knowledge

Based on the literature review the following gaps in the body of knowledge were identified:

- A systematic approach for sustainability assessment of biorefinery strategies under uncertainty and addressing risk attitude of decision makers, by implicating the values of multidisciplinary company stakeholders , for strategic decision making is missing in literature:
    - This identified gap confirms the necessity of developing a systematic approach to identify sustainable biorefinery strategies at the strategic level of design, by evaluating a set of important sustainability criteria under uncertainty and quantifying risk attitude of decision maker.

- A set of practical and interpretable sustainability criteria for biorefinery context that can well reflect different aspects of the biorefinery projects such as competitiveness, technology and market risks at the strategic level of design is missing in literature:
    - This identified gap shows the necessity of defining new decision criteria for the biorefinery context.
- A practical approach for addressing a complete set of sustainability criteria in MCDM while keeping decision making process manageable is missing in literature:
    - This identified gap confirms the necessity of applying a method for converting a set of necessary sustainability criteria into a set of important criteria.
- Combining both concepts of (1) uncertainty associated with the implicated data, (2) risk attitude of decision makers in strategic biorefinery decision making is missing in literature.
    - This identified gap confirms the necessity of a method which can well address the concepts of sustainability, uncertainty and risk simultaneously in the strategic decision making for biorefinery context.

# CHAPTER 3 OVERALL METHODOLOGICAL APPROACH

In order to address the identified gaps in the body of knowledge, a systematic approach for sustainability assessment of biorefinery strategies and strategic decision making under uncertainty and risk, has been developed in this study. This chapter starts with explaining the methodology that was followed to develop that systematic approach (section 3.1) following by introduction of the systematic approach itself (section 3.2), and at the end, the case studies are introduced.

## 3.1 Methodology overview

The conventional decision making approaches in industry, relatively miss to systematically address the three concepts of sustainability, uncertainty and risk in strategic decision making. This thesis investigates the best way to first address sustainability, and then involves uncertainty and risk attitude of decision makers in strategic decision making. The main steps that have been followed to meet this objective is shown in Figure 3-1 along with introducing the case studies and the publications as a result of demonstrating each step.

As can be seen in this figure, this project was done by following three main steps:

(1) Sustainability assessment of biorefinery strategies and strategic decision making under deterministic conditions, demonstrating how to involve sustainability concept in strategic decision making.

(2) Sustainability assessment of biorefinery strategies under uncertainty and risk, demonstrating how to involve the concepts of uncertainty and risk attitude of decision makers in sustainability decision making at the strategic design level.

(3) Critically analyze the results to investigate the importance of involving sustainability, uncertainty and risk in strategic decision making in the biorefinery context.

In Figure 3-1, each of these three main steps (shown as gray boxes), are broken-down into several intermediate steps (shown as white boxes), that are explained in the following sections.

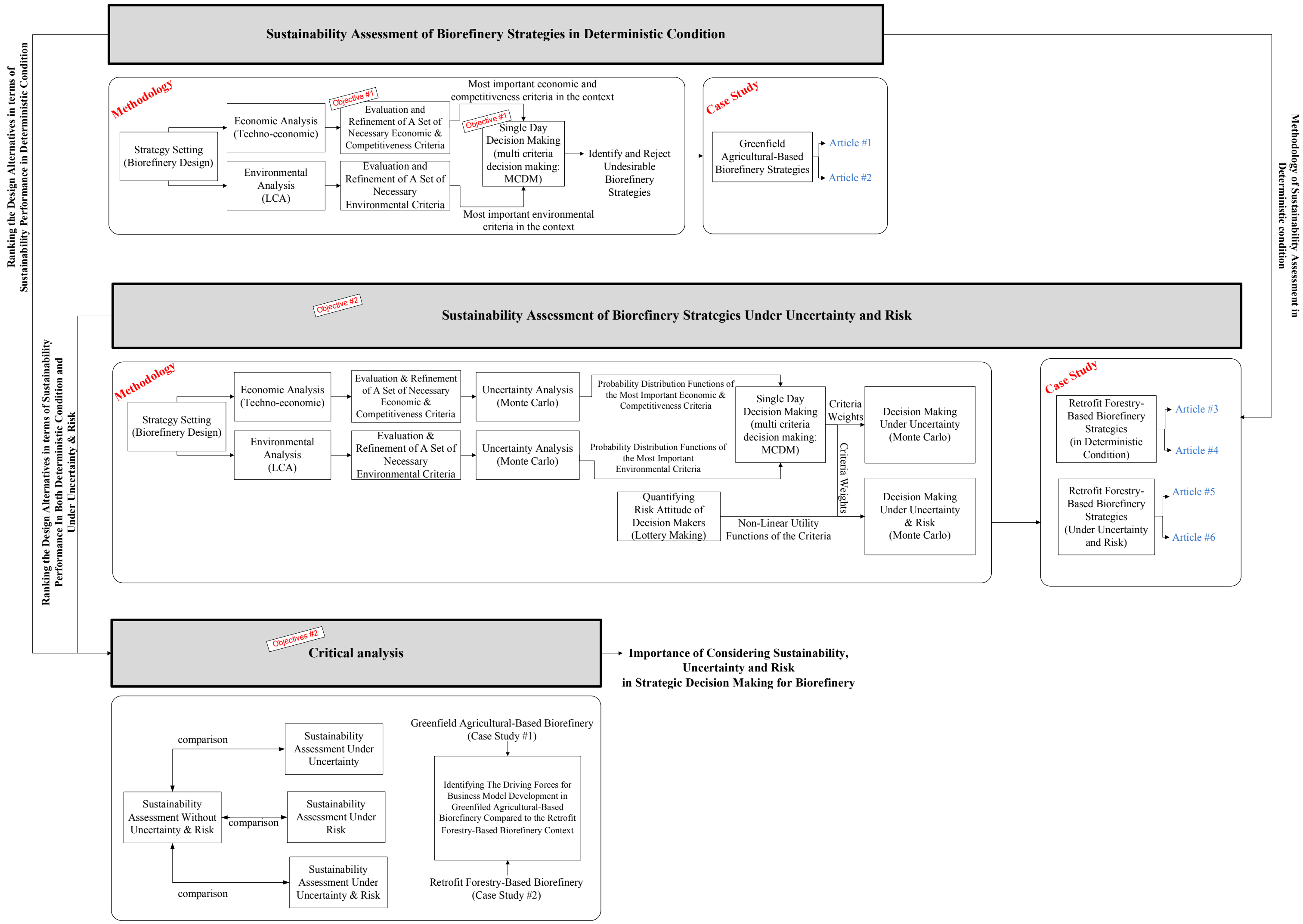



**Figure 3-1 Overview of the methodology**

### 3.1.1 Sustainability assessment under deterministic conditions

This section is designed to address the first sub-objective of this thesis which is to improve the conventional strategic decision making approaches by taking the sustainability concept into account. It starts with strategy setting (biorefinery design) to define design alternatives. Then the defined alternatives are assessed by a set of necessary sustainability criteria developed for biorefinery systems. Those criteria should then be refined into a set of important criteria to keep decision making manageable. This refinement is carried out using MCDM method.

Considering that, sustainability assessment of biorefinery strategies under deterministic conditions can be summarized with the following main steps:

- Strategy setting (biorefinery design) resulting in design alternatives definition,
- Economic analysis (techno-economic) and environmental assessment (life cycle assessment: LCA) of the defined design alternatives,
- Evaluation and refinement of a set of necessary sustainability criteria
- Conducting a single-day decision making panel (MCDM), to attribute relative importance to the criteria and rank the design alternatives in order to screen out undesirable biorefinery alternatives.

Through biorefinery design, normally the following listed activities are followed resulting in definition of product-process combinations (design alternatives):

- Product selection in product-driven design and technology selection in process-driven design
- Market analysis and investigation of biomass availability to target an appropriate production capacity for the product portfolio

After defining the design alternatives, mass and energy balances of the candidate product-process combinations are performed. Using the result of the mass and energy balances and also gathering the required market data, the economic performance of the defined design alternatives is assessed through the following steps:

- Capital investment cost (Capex), production cost (Opex) and revenue estimation
- Economic analysis by conventional techno-economic model
- Validating the economic results with technology providers

In parallel, environmental performance of the design alternatives should be assessed by LCA using the results of the mass and energy balances.

As the next step, a set of practical and interpretable sustainability criteria need to be evaluated using the results of economic and environmental analyses. In order to meet this objective, three sets of necessary criteria including (1) economic, (2) competitiveness and (3) environmental criteria are defined and evaluated. However aggregating these three dimensions for sustainability assessment, normally involves a large set of criteria, potentially increasing the level of inconsistency and making a panel impractical. Therefore, a refined set of pertinent criteria needs to be identified. This has been done by conducting different MCDM panels, one at the time employing the criteria of each sustainability pillar separately. In each MCDM, a relative importance is attributed to each decision criterion. Therefore, the two main objectives of conducting each of these MCDMs are:

- To identify the most promising design alternatives independently in the perspective of each sustainability pillar
- To identify a set of important criteria for each sustainability pillar

As a result of this refinement process, for each sustainability pillar, a set of necessary criteria are refined into a set of important criteria. These refined sets of criteria will be aggregated then in another single day MCDM panel to assess sustainability of the design alternatives.

Following these main steps would result in ranking the design alternatives in term of their sustainability performance under deterministic conditions, using which non-promising alternatives can be identified and screened out from the list of alternatives to be further analyzed.

This part of the methodology has been demonstrated using a greenfield agricultural-based case study and resulted in three publications including two journal articles: Article 1 (appendix A) & Article 2 (appendix B) and a book chapter (appendix G) which are introduced later in Chapter 4.

The developed methodology in this section is then applied in a retrofit forestry-based biorefinery case study explained in the next section.

### 3.1.2 Sustainability assessment under uncertainty and risk

This part of the methodology is designed to address the second sub-objective of this thesis which is about improving strategic sustainability decision making by quantifying both uncertainty associated with the employed data and the risk attitude of decision makers. This has been done through the following steps:

- Applying the developed approach in the previous section comprising of the following main steps:
    - Strategy setting (biorefinery design) resulting in design alternatives definition
    - Economic analysis (techno-economic) and environmental assessment (life cycle analysis: LCA) of the defined design alternatives,
    - Sustainability criteria definition, evaluation and refinement using MCDM
- Uncertainty assessment using Monte Carlo analysis. This step results in generating a probability distribution function for each of the identified important sustainability criteria (refined criteria in previous step).
- Attribute a relative importance to each criterion considering uncertainty, in a single day panel activity
- Measuring risk by quantifying risk attitude of decision makers via lottery making in a single day MCDM format
- Decision making
    - Decision making under uncertainty (Monte Carlo analysis)
    - Decision making under uncertainty and risk (Mote Carlo analysis)

What makes this part of methodology different from the previous section is involving uncertainty and risk in strategic decision making which are briefly explained as follows.

The uncertainty in the evaluated sustainability criteria come from data uncertainty, model uncertainty and panel uncertainty among which this study addresses data and panel uncertainties. The nature of data uncertainty in economic analysis belongs to the uncertainty in the market data, while in environmental assessment, data uncertainty is due to associated uncertainty with mass and energy balance information. In order to quantify data uncertainty, two Monte Carlo analyses are conducted separately, one for the economic and competitiveness criteria, and one for the environmental criteria. The result of these analyses is probability distribution function (PDF) of the decision criteria. These PDFs are then employed in a single day MCDM panel in order to quantify the relative importance (weight) of the criteria under uncertainty. These criteria weights are then used in decision making to calculate the sustainability score by which the alternatives are ranked.

The attitude of decision makers toward risk determines their preference for the decision criteria which is presented as criteria utility functions. Thus quantifying risk attitude of decision makers results in formulating the utility functions, in which the curvature of utility functions is determined by the level of risk aversion among decision makers. The risk attitude of decision makers is measured using a lottery-based risk assessment method. The result of this method is used to formulate the utility function of each criterion which is then employed in decision making to calculate the sustainability score by which the alternatives can be ranked.

After uncertainty analysis and risk assessment, decision makers would have probability distribution function of each criterion, its relative importance and its utility function. In last step, this information is used to calculate a sustainability score for each alternative and rank them accordingly, once under uncertainty only and once under uncertainty and risk. This has been done by Monte Carlo analysis, which employs criteria PDFs, and in each iteration generates a random value from each, converts it into utility value applying the developed utility function, and at the end calculates the sustainability score applying the obtained criteria weights. The result would be sustainability score of the alternatives in terms of probability distribution functions.

This part of the methodology has been demonstrated using a retrofit forestry-based case study and has resulted in four journal articles including Articles 3 to 6 (appendices C to F), which are introduced later in Chapter 4.

### 3.1.3 Critical analysis

In order to investigate the importance of considering uncertainty and risk in decision making (to address the second sub-objective), a critical analysis has been done as the last step of the methodology.

In this part of the methodology, the result of decision making under deterministic conditions is compared once with the final decision when uncertainty is involved in decision making, once with the final decision when risk is taken into account, and once more with the final decision when both uncertainty and risk are involved in decision making. These comparisons would respectively show the importance of considering uncertainty, risk attitude of decision makers and both of them in strategic decision making for biorefinery context.

Based on all the explained steps, a general methodology could be developed representing a systematic approach that can be applied for sustainability assessment and strategic decision making under uncertainty and risk in any biorefinery context. This systematic approach is presented in more detail in the following section.

## 3.2 Systematic approach for sustainability assessment under uncertainty and risk

The developed systematic approach in this section (Figure 3-2), is designed to address the main objective of this study. In Figure 3-2 the main steps are shown in gray boxes and are then broken down into the sub-steps shown in the white boxes below each main step.

These main steps are explained in detail through the following sections:

- Strategy setting (biorefinery design)
- Economic analysis and environmental assessment
- Sustainability criteria definition, evaluation and refinement
- Decision making in deterministic conditions
- Uncertainty analysis
- Risk assessment
- Decision making under uncertainty and risk.

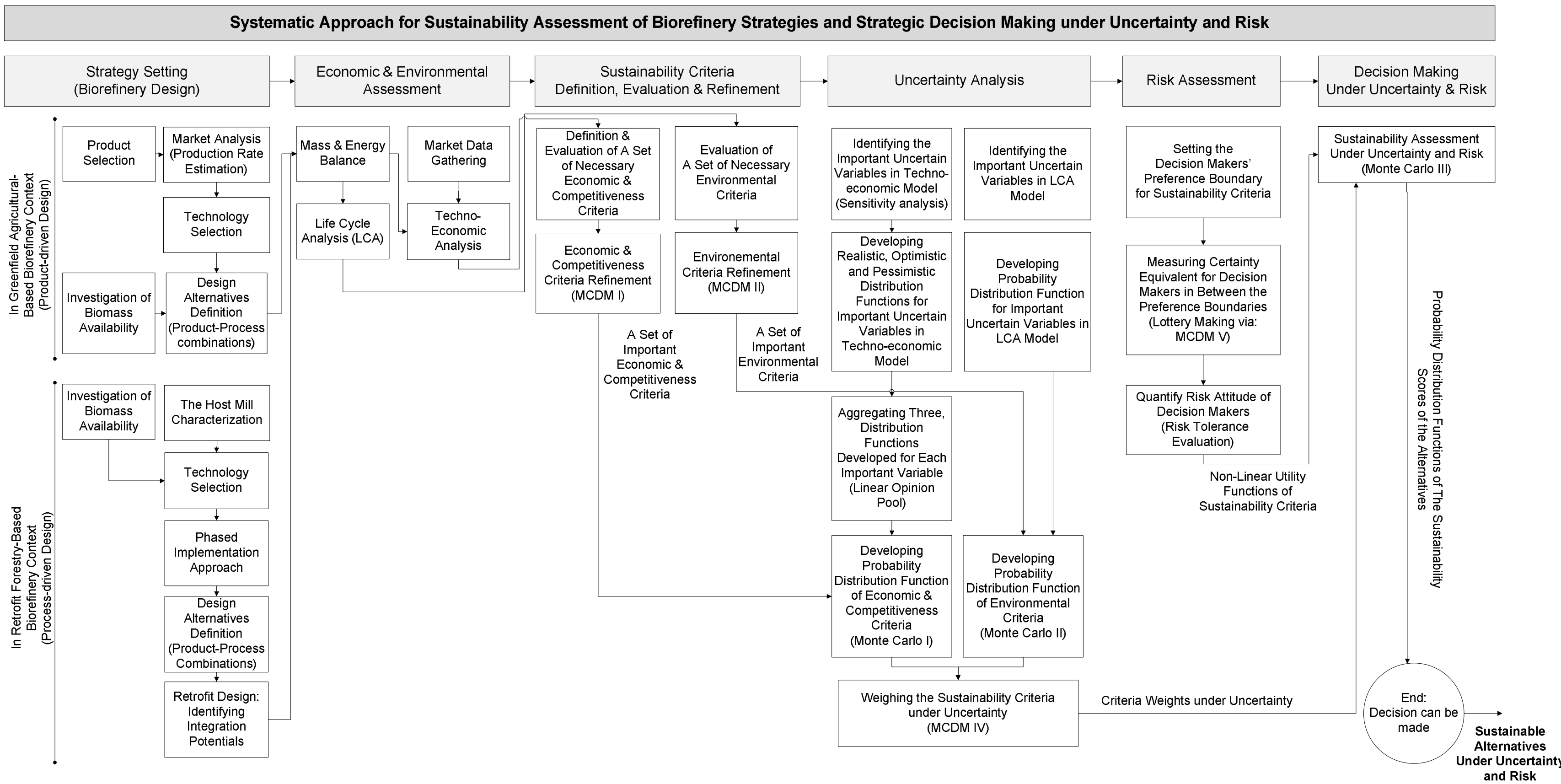



**Figure 3-2 Systematic approach for sustainability assessment of biorefinery strategies and strategic decision making under uncertainty and risk**

### 3.2.1 Strategy setting (biorefinery design)

The first step in any sustainability assessment for biorefinery technologies is strategy setting or biorefinery design through which the design alternatives can be defined to be assessed later in terms of their sustainability performance. Depending on the context (greenfield or retrofit biorefinery), the methodology for biorefinery design would be different. As mentioned before in greenfield agricultural-based biorefinery, stakeholders have a pre-defined product strategy and their objective is to achieve a competitive advantage by penetrating to the green market, and consequently increase their market share. However in retrofit forestry-based biorefinery as a pre-defined infrastructure context, the objective of stakeholders is staying competitive in the market by diversifying product portfolio thanks to the biorefinery. Taking this fact into account, the methodology of strategy setting in these contexts is explained through the following sections.

#### 3.2.1.1 Design alternatives definition in greenfield vs. retrofit biorefinery

The first step of strategy setting in greenfield agricultural-based biorefinery context is product (commodity or added value product) selection. In order to identify production rate of the selected product, market analysis is done by which the demand for the defined product and its feasible production capacity is investigated. Then the technologies (process options) by which the defined product can be produced at the targeted capacity are identified (technology selection). Considering this information, and taking into account the biomass availability, product-process combinations are defined as design alternatives to be further analyzed later in terms of sustainability performance.

On the other side, forest products companies have some competitive advantages including the established infrastructure, a good access to biomass, engineering know-how, and established supply chain for biomass and product (Mansoornejad, Chambost et al. 2010). These companies would like to identify the most promising biorefinery strategies for being integrated into their existing facilities by which they can diversify their product portfolio using the available biomass around the mill. Thus the availability of biomass and characteristics of the host mill dictate biorefinery technologies that can be selected to be further analyzed. For instance, when the minimum feasible capacity of a biorefinery technology is about 1000 bdmt/day biomass, if the maximum available biomass at the mill would be less than this amount, this technology should not be selected as a candidate technology for that specific mill. In addition, for example if the mill is very far from the market (characteristic of the mill), the technologies that produce large volume of commodity products are not appropriate to be considered as the candidate options in the context of that specific mill due to the difficulty of transferring large volume products to the far away market.

Thus considering characteristics of the mill and availability of biomass (type and capacity), some process technologies are selected as the design alternatives. On these candidate technologies, phased approach and also retrofit design are applied which each is explained through the following sections.

#### 3.2.1.2 Phased approach

After targeting some biorefinery technologies, in order to mitigate technology and market risks associated with their implementation, a phased approach is applied to each design alternative. Three suggested biorefinery implementation phases introduced by Chambost *et al*. (Chambost, McNutt et al. 2008) include Phase I for lowering operating cost, Phase II for increasing revenue and Phase III to improve margin (Figure 3-3).

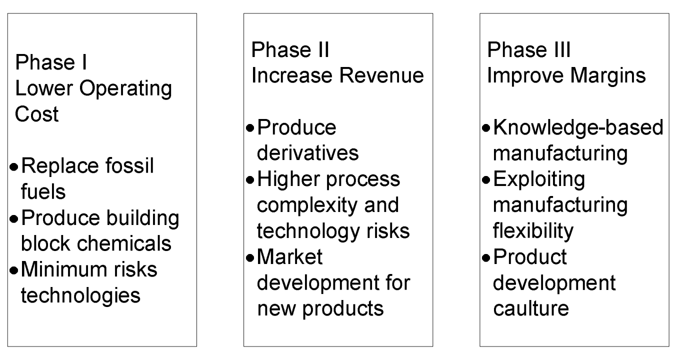



**Figure 3-3 Strategic implementation of the biorefinery by a forest products company (Chambost, McNutt et al. 2008)**

In this study for each biorefinery technology, Phase I represents minimum market risk for the core business transformation, whereas Phase II which involves the technology that when implemented, typically results in manufacturing of value-added products ending with higher revenue but along with a higher risk. These phases are designed based on (1) targeting different end products from one specific product stream and (2) implementing all associated processes to convert that stream into the targeted value-added products.

In this study it is assumed that Phase I would be constructed within two years and will be in production for about five years in order to set the ground for Phase II implementation. In the sixth year of production while Phase I is still running, Phase II will start to be constructed in a year and then from seventh year of production, biorefinery would get ready to be completely switched to Phase II strategy.

### 3.2.1.3 Retrofit design

In order to quantify the potential synergies between the biorefinery process and pulp production line at the mill, and to maximize the benefits of transformation strategy, unique characteristics of the mill and all integration potentials should be identified first. This is done through a retrofit design. The integration potentials can be categorized in three groups including the integration potentials in process, biomass and product sectors.

***Integration Potentials in Process Sector***

The first integration potential at process sector can be using leftovers, *e.g* rejected oversize chips, at the mill in biorefinery process. Other potential integrations can be process units that have a capability to be integrated into the biorefinery process which mainly include (1) boilers and turbines at the energy island (energy integration), (2) waste water treatment (WWT) facilities, (3) landfill area for solid wastes disposal (4) unused existing equipments, and (5) Warehouse and buildings.

In order to evaluate energy integration potentials, the existing energy island at the mill needs to be characterized and the energy sinks and sources should be identified by energy balance of the mill. This will show whether the studied mill is energy demanding or it has any type of excess steam or electricity that can be used in the biorefinery plant. The next step would be identification of the types and working capacities of the boilers and turbines currently available at the energy island. This would help analyzer to identify how much of needed energy in biorefinery process can be supplied by the existing facilities at the energy island and consequently how much incremental fuel would be needed to produce total estimated energy consumed by biorefinery process. In a case that existing nominal capacities of the boilers and turbines would be adequate to supply energy demand of the both biorefinery and pulp process, just the cost of excess fuel that is fed to the boilers will be addressed in economic analysis. Whereas cases in which new boilers are required to support high energy demand of biorefinery process, for which the cost of additional fuels and also cost of new boilers should be addressed in techno-economic model.

Another process-oriented integration potential is treating liquid wastes of biorefinery process using the existing WWT facilities at the mill. In order to evaluate this potential, two specifications of the WWT unit need to be investigated including current Biochemical Oxygen Demand (BOD) content and hydraulic loading of the wastes. Subtraction of the current BOD content and hydraulic loading at the mill, from the maximum capacity of them that can be handled by WWT, would result in identifying how much of liquid wastes in biorefinery process can be treated by the existing WWT at the mill. If all wastes can be treated by the existing WWT, the associated cost of excess power consumption due to using more aerators because of need to additional oxygen as a result of higher BOD load, would be the only incremental cost that should be addressed in economic analysis. Otherwise cost of a new WWT system should be applied in economic analysis. Moreover, the composition of liquid wastes of biorefinery process should be determined in order to estimate possible additional costs associated with treating them. As an example, when liquid wastes contain any type of acids, the cost of acid neutralization should be addressed in economic analysis as well. Besides all liquid wastes, biorefinery process may have some solid wastes. Sometimes landfill area at the mill would have enough capacity to handle these solid wastes, otherwise they should be sent to the landfill of any facilities close to the mill or should be transferred to the city landfill. In each of these cases, the associated cost for landfilling should be seen as incremental cost in economic analysis.

Commonly there are many unused equipments at the mill that can possibly be used in biorefinery process for which the cost of bringing them back to the process should be well reflected in economic analysis.

***Integration Potentials in Biomass Sector***

The first question that should be answered for any type of biorefinery integration is that what type of biomass, at what extent and at which price can be potentially supplied by the forest lands around the mill (in specific radius) to be fed into the biorefinery process. In order to estimate the available biomass, potential future demand of the other mills in the studied area should be taken into account. In estimation of the delivered biomass price, biomass purchased cost, load and transportation cost and also stumpage cost should be considered to develop a cost model for the supplied biomass.

Another potential integration on biomass side is about cost synergies in material handling systems. In the case of using different biomass species for biorefinery process compared to pulp production line, a new material handling system should be considered due to the risk of biomass contamination. However even in that case, still there would be some synergies between the two material handling systems, such as using the existing scales and dumpers that result in considerable cost saving. Identification of these synergies would help the analyzer to estimate the incremental cost of the additional facilities.

***Integration Potentials in Product Sector***

One of important potential synergies between the mill and biorefinery process is on product side which would be mainly product portfolio diversification and supply chain synergy. The potential benefits of margin creation and revenue stabilization associated with diversifying product portfolio should be addressed by adding the revenue from biorefinery products to the list of existing products at the mill. It would be better if the economic analysis can cover all the associated costs from the received biomass at the mill gate to delivered products to the customers. However this would need detailed evaluation of supply chain opportunities which are usually assessed not in strategic level of deign but later in tactical and practical level. Supply chain design of integrated forest biorefinery has been well addressed in literature through several studies (Mansoornejad, Chambost et al. 2010; Dansereau, El-Halwagi et al. 2012; Mansoornejad, Pistikopoulos et al. 2013), however it is beyond the scope of this study. Considering this fact, the economic analysis in this study covers all the costs associated with business transformation from the delivered biomass at the mill gate to the final products excluding transporting them to the targeted markets.

The selected biorefinery technologies considering the identified integration potentials associated with each, are assessed in terms of sustainability through following sections.

### 3.2.2 Economic and environmental assessment

#### 3.2.2.1 Techno-economic analysis

Techno-economic evaluation is a conventional methodology (Peters and Timmerhaus 2003) in which the technical performance of a system is analyzed and its results are used to assess the economic performance. The main steps comprising techno-economic analysis are (I) capital investment cost estimation, (II) production cost estimation, (III) revenue estimation, and (IV) economic evaluation comprise the conventional techno-economic methodology.

In this thesis, the investment cost has been estimated using large-block analysis (Janssen 2007) in which (a) cost of the main process blocks is provided by technology developers, and (b) cost of the supplementary process blocks are estimated using open sources in a way that they can be compared on a relative basis. Annual revenue is estimated using the sale price of each product determined by market analysis. Finally, the economic analysis is performed using the estimated costs and revenue.

#### 3.2.2.2 LCA-based environmental analysis

In order to get insight about the concept of LCA-based environmental analysis, LCA method and its application in biorefinery context has been reviewed and presented as a book chapter in Appendix G. The main steps in LCA-based environmental analysis are shown in Figure 3-4.

The environmental analysis of the biorefinery design alternatives in this study, have been presented in more detail by Batsy et al. (Batsy, Lesage et al. 2013).

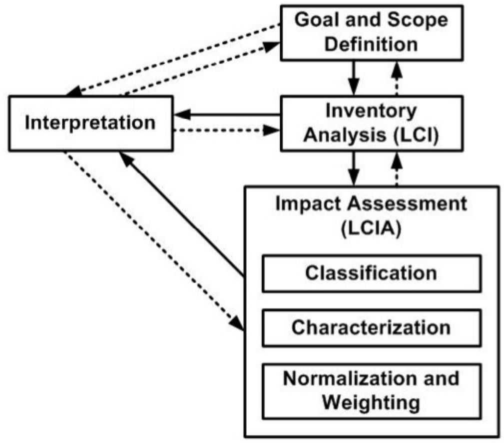



**Figure 3-4 Life Cycle Analysis (LCA) methodology(Gaudreault, Samson et al. 2007)**

## 3.2.3 Sustainability criteria definition

According to the classical definition, sustainability is the aggregation of economic, environmental and social pillars. However as explained earlier, in this study sustainability has defined as the aggregation of economic, environmental and competitiveness performance evaluated by a set of "intelligent" criteria.

***Economic and Competitiveness Criteria***

Economic and competitiveness performance of the design alternatives are assessed by a set of "smart" criteria. In this study first a set of economic and competitiveness criteria were defined and applied in the first case study (greenfield agricultural-based biorefinery). However based on the received comments from the decision making panel, the identified important economic and competitiveness criteria were modified and then employed in the second case study (retrofit forestry-based biorefinery case study. It results in assessing the candidate biorefinery strategies in terms of their economic and competitiveness performance using ten criteria.

***Environmental Criteria***

Beside ten defined economic and competitiveness criteria in this study, eight environmental criteria have been evaluated by Batsy et al. (Batsy, Lesage et al. 2013). By adding these environmental criteria into the list, they would consist of eighteen sustainability criteria that employing all of them can make decision making impractical. The only remedy would be screening out less important criteria in the context of this study that can not help decision makers to well distinguish between the alternatives. This is done through criteria refinement procedure suggested to be perused by a cascade of MCDM panels.

### 3.2.4 Sustainability criteria refinement using MCDM

Aggregating the three sustainability dimensions for decision making potentially involves a large set of decision making criteria, increasing drastically the level of inconsistency and making a decision making impractical. Therefore, a refined set of pertinent criteria is identified based on the separate MCDM panels one employing the economic and competitiveness criteria, and one using the environmental criteria. By conducting the first MCDM, relative importance of the economic and competitiveness criteria are evaluated and by performing the second one the relative importance of environmental criteria are quantified. Thus, by screening out less important criteria, a set of necessary sustainability criteria can be refined into a set of important criteria which can keep decision making manageable.

Among the available MCDM methods, multi-attribute utility theory (MAUT) (Keeney and Raiffa 1976) has been chosen in this study. In this method, the metrics that quantify the decision criteria are called attributes, for instance if profitability of a design alternative would be a decision criterion, internal rate of return (IRR) can be considered as the attribute (Janssen 2007). In the MAUT method, there are two key parameters used to rank the design alternatives which are (1) utility function $(u_i(x_i))$ and (2) relative importance of each decision criterion $(w_i)$. Using these two parameters, the overall utility value $(U(x))$ of each design alternative, is calculated according to the following equation:

$$U(x) = \sum_{i=1}^{N} w_i \cdot u_i(x_i) \tag{3-1}$$

Where U(x) is the overall utility value or the final score, N is the number of criteria, $w_i$ is weighting factor of criterion i such that $0 \le w_i \le 1$ and $\sum_{i=1}^{N} w_i = 1$, and $u_i(x_i)$ is the utility function of criterion i.

***Utility Function***

The utility value is the normalized form of attribute value, between zero to one determined by utility function, representing the preference of decision makers for that criterion. In order to develop a utility function for each criterion, two values are required which include the lower and the upper bound values (Janssen 2007). The lower bound represents the minimum acceptable value for that criterion- or the worst attribute value $(x_{i_{LowerBound}})$- at which the utility value would be minimum $(u_{x_{i_{LowerBound}}}=0)$. Whereas the upper bound which represents the best criterion value $(x_{i_{UpperBound}})$ at which the utility value is maximum $(u_{x_{i_{UpperBound}}}=1)$. A function between these two boundaries would be called utility function which is commonly assumed to be linear by default (risk neutrality). If the criterion value for an alternative is equal to or below the lower bound, its utility value would be zero and if the criterion value is equal to or higher than the upper bound its utility value would be one (Janssen 2007).

For criteria that higher values are better (e.g IRR), the criterion value that for any value below it the panel would not have any preference among the alternatives, should be set as the lower bound- and similarly the criterion value that for any value above it the panel would not have any preference among the alternatives is set as the upper bound.

***Weighting Factors***

As mentioned before, in MAUT method, the trade-off activity is executed for weighing the decision criteria. As its first step, after interpreting the decision criteria, all the panelists are asked to select the most important criterion and to determine a target value for it. The target value is the minimum acceptable value for the most importance criterion satisfying investors to invest in a biorefinery strategy.

The trade-off method is based on indifference judgment between the criteria evaluated for different alternatives (Janssen 2007). In order to evaluate the relative importance of the criteria, each criterion is compared with the most important criterion one at the time. In this method each decision maker determines a criterion value that makes him/her indifferent between two situations A and B. In these designed situations the value of the most important criterion (k) and a criterion that is compared with it (m) is different but the values of the other criteria are assumed to be the same. The indifference in this comparison means that the overall utility value (U) of these situations (A and B) should be the same (equation 3-2):

$$U_A = U_B \tag{3-2}$$

In each comparison the panelists are asked to determine if in situation A they would have the target value for criterion k and the minimum value for criterion m, this is indifferent for them with which value of criterion k in situation B when criterion m would be at its maximum value. Indifferent judgment between situations A and B for each criterion, and considering that the weights should always add up to one, result in the following matrix. It represent eight equations with eight unknowns (weighting factors of the defined criteria) that by solving it, the weighting factors of the decision criteria can be obtained (Janssen 2007).

$$\begin{bmatrix} 1-u_k(x^B_{k,m=1}) & -1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 1-u_k(x^B_{k,m=N}) & 0 & \cdots & -1 \\ 1 & 1 & \cdots & 1 \end{bmatrix} \begin{bmatrix} w_1 \\ \vdots \\ \vdots \\ w_N \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} \quad \forall m \neq k \tag{3-3}$$

Conducting MCDM employing the criteria for each sustainability pillar at the time, results in obtaining the relative importance of the criteria in each pillar, using which consequently a set of important sustainability criteria is identified.

### 3.2.5 Uncertainty analysis

After identifying a set of most important economic, competitiveness and environmental criteria, they should be evaluated under uncertainty. In general, uncertainty analysis has three main steps comprising classification of sources of uncertainty, identification of important set of uncertain variables and quantifying the identified uncertainties (Kim and Augenbroe 2013).

As mentioned before, generally there are three main sources of uncertainty in sustainability assessment consisting of (1) data uncertainty representing uncertainty in the input data in economic and environmental analysis models, (2) model uncertainty representing uncertainty in the evaluation models such as techno-economic and LCA models, and (3) panel uncertainty in terms of the level of consensus among the panel members for making the final decision. Model uncertainty does mainly come from LCA model which deals not only with the studied core process but also with several background processes related to up-stream sections such as raw materials production, utilities production and etc. Evaluating this type of uncertainty is normally done in projects focusing on this topic only which is beyond the scope of this study. Thus uncertainty caused by the applied models has been assumed the same for all the studied candidates in this thesis and were excluded in uncertainty analysis.

The main objective of this part of the methodology is developing probability distribution function (PDF) of the decision criteria as a result of analyzing data uncertainty, evaluating the criteria weights accordingly and measuring the panel uncertainty.

Data uncertainty analysis can be followed through three main sub-steps including:

- Identification of important uncertain variables by sensitivity analysis
- Developing distribution function for the important uncertain variables
- Developing probability distribution function for the decision criteria as a result of uncertainty associated with input variable

### 3.2.5.1 Identification of important uncertain variables

The economic and competitiveness criteria are function of several input variables such as biomass price, product sale price, estimated capital investment cost and etc., as input data in techno-economic model. On another hand environmental criteria are functions of mass and energy balance information which is the input data to the LCA model. Without doubt uncertainty in all input variables does not have the same level of influence on the results. Considering this fact, the first step in uncertainty analysis should be identifying important independent input variables that by changing them, decision criteria are changed considerably.

In order to do so, first of all a maximum and a minimum possible value for each input variable should be identified in order to investigate how much changing that variable within the specified range can affect the results. In the absence of information specialty in the context of emerging technologies like biorefinery, a methodology is needed by which all the possible forecasted events for each input variable can be predicted. This goal can be achieved by a survey through available information in open sources and also interviews with stakeholders. Due to the insight of stakeholders in the context, they are the best to predict market models for the input variables.

However their predictions would be somehow subjective based on their personal perspectives. Considering that, decision making would face a huge dilemma how to consider them all but not to overemphasis on extreme perspectives. This issue has been addressed in this work by taking into account three possible perspectives for forecasting each input variable which are pessimistic, optimistic and realistic perspectives.

In each perspective, a minimum, most likely and maximum possible value has been attributed to each variable. Using this level of information, triangular type of distribution function is the best to represent each perspective. Based on the obtained three triangular distribution functions for each variable, the uncertainty range is achieved. Therefore a sensitivity analysis can be performed in order to investigate how much profitability of the project is sensitive to changing each variable. For the purpose of this study, if IRR would decrease or increase more than 2%, that variable is considered important uncertain variable.

In LCA model also, a minimum and a maximum possible value should be attributed to each mass and energy balance input data according to the level of uncertainty associated with them depending on the source they have been extracted from. For instance for mill’s real data, low level of uncertainty (e.g, $\pm 5\%$ variation) needs to be considered, whereas the data extracted from literature or provided by technology provider which are highly or moderately uncertain.

#### 3.2.5.2 Developing probability distribution function for the identified important uncertain variables

According to what was explained earlier, for each variable in techno-economic model three triangular PDFs are developed respectively representing pessimistic, realistic and optimistic perspective. These PDFs need to be aggregated into one distribution function to provide a unique representation of the experts’ opinion with different perspectives for each variable. There are different methods for aggregation of PDFs that normally are categorized into two main groups including mathematical methods and behavioral approaches. Although each of these methods has their own advantages and disadvantages, mathematical methods seem more applicable because they are easy to apply and are defendable (Clemen and Winkler 2007). The mathematical methods itself can be categorized in three main techniques including oxiom, linear opinion pool and bayesian methods (Clemen and Winkler 2007) among which linear opinion pool named by

Stone (Stone 1961), as the simplest and easily understandable method, has been selected in this thesis. The linear opinion pool obeys the following equation:

$$p(\theta) = \sum_{i=1}^{n} w_i p_i(\theta) \tag{3-4}$$

Where n is the number of experts (perspectives here), $p_i$ is probability distribution of variable $\theta$ based on the opinion of expert i (perspective i), $p(\theta)$ is the aggregated probability distribution, and $w_i$ is the weight of expert i (perspective i), in a way that their summation adds up to one.

It should be noted that review of different aggregation methods in the other studies shows that generally simpler mathematical aggregation methods perform as good as the complex methods (Clemen and Winkler 2007) that validates applying linear opinion pool in this study.

#### 3.2.5.3 Developing probability distribution function for decision criteria and weighing them

This study tries to recognize uncertainty, to quantify it and finally to present it graphically to be communicable, making decision makers able to well interpret the results. Data uncertainty in this study has been quantified by Monte Carlo analysis method which generally uses probability distribution function of input parameters ($x_i$) to develop probability distribution function of output parameters ($y_i$) as a function of $x_i$ (Figure 3-5).

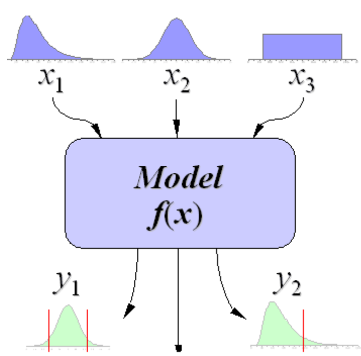



**Figure 3-5 Monte Carlo Method**

This method converts a stochastic problem into a number of deterministic problems through generating random samples from distribution function of the input variables. Although it may not be the best method in the perspective of processing time, by using it decision makers can focus on the formulation of uncertainty while keeping the mechanism simple. The main advantage of this method is its easily understood procedure by decision makers as non-mathematicians. At the same time, this method has its own disadvantages for instance it is computational intensive and its solutions depend on the number of repeated iterations.

The developed PDFs for the identified important variables are employed in Monte Carlo analysis using which the decision criteria would be evaluated in PDF format.

In order to have the economic/competitiveness and also environmental criteria in PDF format, there would be crucial to conduct two independent Monte Carlo analysis, one employing uncertain market variables in techno-economic model and one employing uncertain variables in LCA model.

However presenting all these PDFs of the decision criteria would bring complexity for decision makers, thus just three numbers will be extracted from each PDF representing the modal value (most probable value), minimum possible value (10% percentile) and maximum possible value (90% percentile) and be presented to the panel (MCDM IV). In this panel a trade-off activity is performed to attribute a relative importance to each criterion, this time considering the evaluated uncertainty associated with each criterion.

### 3.2.6 Risk assessment

The main objective of this part of the methodology is formulating utility function for each criterion using the risk attitude of decision makers. This has been done following three main steps including:

- Preference boundary setting
- Measuring certainty equivalent of decision makers in preference boundary by lottery making
- Quantifying risk tolerance of decision makers representing their attitude toward risk.

#### 3.2.6.1 Preference boundary setting

Both boundary setting and lottery making activity (steps (1) and (2)) can be done by conducting a single-day MCDM panel activity (MCDM V) with the same panel members in previous MCDMs. In this panel activity, each decision maker determines a lower and an upper bound for each criterion. The lower bound shows a value below which decision maker does not have any preference among the alternatives. Similarly the upper bound represents a value above which there is no preference for decision makers among the alternatives. For instance, taking internal rate of return (IRR) as an example, if a decision maker determines 12% as the lower bound it means that no value among the values below 12% for IRR is preferable for him/her. Moreover if a decision maker sets 30% as the upper bound, it means that for him/her, all IRR values above 30% is all good and he/she does not have any preference for example between 35% and 45% and they both are good at the same extent in his/her perspective.

In order to set these boundaries through MCDM V, each panel member has been asked to determine two numbers respectively as a lower and an upper bound for each criterion. At the end, for each criterion, the average value of the given numbers for lower bound by decision makers, is reported as the average lower bound of that criterion and the same approach is followed similarly for the upper bound.

Through this activity, a preference domain for each criterion is established.

### 3.2.6.2 Lottery making

Depending on the risk attitude of decision makers, they would have a preference between the values in a range of the lower and the upper bounds. In order to quantify this risk attitude, the panel would be put in a situation to compare a lottery option with a certain condition to measure their willingness to take risk. In order to show how this lottery making works, a simple example is illustrated. In this example a decision maker is asked to compare two following options:

- Option A: accepting a gamble in which he/she will have 50% chance to win 100 $ and 50% chance to get 0 $,
- Option B: accepting a written check with a specific amount but with 100% certainty to get it.

The average payoff of the gamble is known as expected value (E) which in this example is 50$. Using the amount that can convince decision maker not to go with the gamble, his risk attitude is measured. If that amount on the check would be less than expected value in option A, it means that he prefers not to take a risk but to receive a guaranteed amount even if it is less than the expected amount (e.g, CE=20$ on Figure 3-6), he may have got in the gamble but of course with risk of losing. This means that he/she is risk averse for that specific criterion. If with a written check with the amount of 50 $ (the same as the expected value) decision maker agrees not to try the gamble it means that he/she is risk neutral. In contrast, if any value below or equal to 50$ on the check can not satisfy him/her to give up the gamble, and he/she would accept not to go with the gamble only if the amount of guaranteed check would be more than 50$ (e.g, CE=80$ on Figure 3-6), it means that he/she prefers to take risk but try his/her chance to win more than a guaranteed value even if it is uncertain to be happened. These decision makers are risk prone. This is the basis of risk aversion theory representing different attitude toward risk (Figure 3-6).

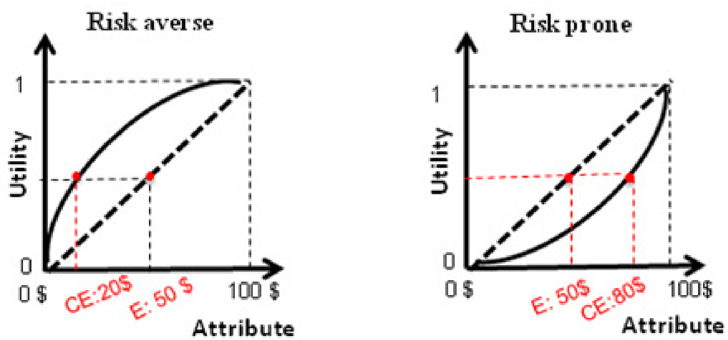



**Figure 3-6 Risk aversion theory (E: expected value, CE: certainty equivalent value)**

In the context of this study this situation has been simulated, however instead of money with the decision criteria, and instead of 100$ and 0$ using the lower and upper bound value of each criterion.

The number that decision makers give to these lotteries is called certainty equivalent (CE) as a value for which there is no difference for decision maker to achieve the CE or a lottery between the boundaries. Risk Tolerance (RT) value represents the attitude of decision maker toward risk (level of risk aversion) in the form of curvature of the utility function, which is calculated using CE value. Considering evaluated RT value, utility function of the decision criterion can be developed. Among different types of available utility functions, the exponential function is the most common and applicable one presented by equation 3-5 (Thevenot, Steva et al. 2006):

$$U_i(x_i) = A - B\exp\left(-\frac{x_i}{RT_i}\right) \tag{3-5}$$

Where A, B and RT is obtained through equations 3-6 to 3-8 (Thevenot, Steva et al. 2006):

$$A = \frac{\exp\left(-\frac{\mathrm{Min}(x_i)}{RT_i}\right)}{\left[\exp\left(-\frac{\mathrm{Min}\,(x_i)}{RT_i}\right) - \exp\left(-\frac{\mathrm{Max}(x_i)}{RT_i}\right)\right]} \tag{3-6}$$

$$B = \frac{1}{\left[\exp\left(-\frac{\mathrm{Min}(x_i)}{RT_i}\right) - \exp\left(-\frac{\mathrm{Max}(x_i)}{RT_i}\right)\right]} \tag{3-7}$$

$$RT_i = \frac{-CE_i}{\mathrm{Ln}\left(\frac{A - 0.5U_i(\mathrm{Max}(x_i)) - 0.5U_i(\mathrm{Min}\,(x_i))}{B}\right)} \tag{3-8}$$

Where $x_i$ is the criterion value, $\mathrm{Max}(x_i)$ is the upper bound value at which utility value is equal to one, $\mathrm{Min}\,(x_i)$ is the lower bound value at which utility value is equal to zero and $CE_i$ is the average of certainty equivalent numbers given by the panel members in lottery making activity.

### 3.2.7 Decision making under uncertainty and risk

#### 3.2.7.1 Decision making

As the last step both weighting factors of the economic/competitiveness and environmental criteria and the developed utility functions of them, as the result of MCDM IV and MCDM V respectively, are used to rank the alternatives. Since, decision criteria under uncertainty are in PDF form, ranking the alternatives need to perform a Monte Carlo analysis. In each iteration of Monte Carlo, a random value is generated from the PDF of each decision criterion and depending on its location and according to the preference boundary it is converted into utility value using the developed utility function for each criterion as a result of MCDM V. At the end, applying the weighting factor of the criteria obtained in MCDM IV, the overall sustainability score of each alternative is calculated in each iteration. By repeating the same procedure minimum for 1000 iterations, the sustainability scores of the alternatives will be obtained in PDF format. In order to make this result more interpretable for the panel, from each PDF, three numbers are extracted including the most probable value (modal value), minimum possible sustainability score (10% percentile), and maximum possible sustainability score (90% percentile). These numbers would enable decision makers to identify the promising biorefinery strategies under uncertainty and risk.

#### 3.2.7.2 Panel Uncertainty

Panel uncertainty is evaluated in terms of the level of consensus among the panel members for the evaluated weighting factors and also utility functions. The standard deviation of the scores that panel gave to each criterion in trade-off activity in MCDM IV, and the CE values they gave to the lotteries in MCDM V, can represent the level of consensus among the panel, respectively on the relative importance of the criteria and their utility function that will be considered along with the results to make the final decision.

### 3.2.8 Case studies introduction

There are two major categories of biorefinery,i.e. the greenfield biorefinery which is normally more applicable in an agricultural-based context, and the retrofit biorefinery which has gained more attention in the forestry sector. Considering that, the presented methodology in this thesis has been demonstrated in two case studies: a triticale-based biorefinery as a greenfield agricultural-based biorefinery context, and a retrofit forestry-based biorefinery for being integrated into a kraft pulp mill in Canada.

#### 3.2.8.1 Greenfield agricultural-based biorefinery case study

In recent years interest in implementation of new generations of biorefineries using a variety of biomass residues and non-food crops has increased. As a consequence of this interest, the agricultural sector in Canada has looked closely at integrating biorefinery activities into its current processes as a strategy to potentially enhance the future competitiveness of the sector. One of the biomass crops that can be used as a biorefinery feedstock is triticale (*X Triticosecale Wittmack*). This crop has attracted much interest, especially in Alberta, Canada, because it has characteristics similar to wheat while it does not interfere with the food chain. This energy crop is a hybrid of wheat and rye and brings together the advantages of both crops: the high yield potential and grain quality of wheat, and the environmental tolerance of rye. The unique advantages of triticale include its ability to grow on marginal land, higher yields compared to wheat, and non-competition with food-based crops. It positions triticale as a promising energy crop for the biorefinery industry. The Canadian Triticale Biorefinery Initiative (CTBI) Network is a research and development program which has focused on developing triticale as an industrial biorefining crop for Canada. Their achievements have shown that a variety of possible triticale-based product-process combinations exist. However, not all these options are necessarily sustainable, and no study to date has sought to identify the most promising triticale-based biorefinery strategies.

In order to identify promising investment opportunities, it is critically important to look at a broad and diverse range of possible strategies, diversified from commodity to more value-added products. The case study examined in this work considers three product platforms ranging from commodity to more value-added products: bioethanol, polylactic acid (PLA) and thermoplastic starch polymer (TPS/PLA blend), all using both triticale grain and straw through implementing a greenfield biorefinery plant near Red Deer in Alberta.

The proposed methodology for sustainability assessment under deterministic conditions has been demonstrated using this case study.

#### 3.2.8.2 Retrofit forestry-based biorefinery case study

The developed methodology in this study has been also illustrated by second case study with the objective of identifying the promising design alternatives of integrated forest biorefinery as a game-changing solution to the current financial challenges in the forestry sector.

The case study is designed for at a kraft pulp mill with a pulp production capacity of about 1000 tonnes/day from about 2000 tonnes of softwood chips per day. In order to identify biorefinery technologies which can fit well with the studied mill, first of all the unique characteristics of the mill were identified:

- Considering that the studied mill is energy self-sufficient, and there is a saturated power grid in the province that this mill is located in, it would be difficult to accrue large energy-related benefits from the biorefinery such as green electricity production via a combined heat and power (CHP) unit.
- Changing production bottleneck in the studied mill from one process unit into another, not due to recovery boiler capacity, shows this fact that lowering costs of the core business by increasing pulp production capacity does not seem doable.
- Considering that nearby market opportunities are limited in the context of the studied mill and also that access to markets further away is costly when the local market can not be identified, it would be better to target low volume/high value products (value-

added products) in the biorefinery strategy compared to large volume/low value products (commodity products).

- Access to large volumes of hardwood chips potentially provides a competitive advantage over mills having access only to forest residuals. This fact shows that targeting biochemical processes to produce value-added lignin-based products seems more promising in the context of the studied mill.

Considering these characteristics, four biorefinery technologies are selected to be assessed:

- Lignin precipitation (Alt.1)
- Organosolv treatment (Alt.2)
- Fast pyrolysis (Alt.3)
- Concentrated acid hydrolysis (Alt.4)

The "retrofit design" for evaluating integration potentials between the mill and the design alternatives, and the "phased approach of implementation" to mitigate technology and market risk, have been applied for the candidate strategies.

The proposed methodology for sustainability assessment under uncertainty and risk has been demonstrated using this case study.

# CHAPTER 4 PUBLICATION SUMMARY AND SYNTHESIS

## 4.1 Presentation of publications

The following articles that are published in, or submitted to peer-reviewed scientific journals can be found in Appendices A to F of this thesis:

- Article 1: Sanaei, S., Stuart, P. (2013). Systematic Assessment of Triticale-Based Biorefinery Strategies: Techno-Economic Analysis to Identify Investment Opportunities. Accepted in *Biofuel. Bioprod. Biorefin.*
- Article 2: Sanaei, S., Chambost, V., Stuart, P. (2014). Systematic Assessment of Triticale-Based Biorefinery Strategies: Sustainability Assessment Using Multi-Criteria Decision Making (MCDM). Accepted in *Biofuel. Bioprod. Biorefin.*
- Article 3: Sanaei, S., Stuart, P. (2014). Systematic Retrofit Design Methodology for Evaluation of Integrated Forest Biorefinery Strategies. Submitted to *Bioresource Technology.*
- Article 4: Sanaei, S., Stuart, P. (2014). Sustainability Assessment and Strategic Decision Making of Integrated Forest Biorefinery Strategies. Submitted to *Bioresource Technology.*
- Article 5: Sanaei, S., Stuart, P. (2014). Strategic Decision Making under Uncertainty to Identify Sustainable Biorefinery Strategies: Part I: Uncertainty Analysis. Submitted to *AIChE Journal.*
- Article 6: Sanaei, S., Stuart, P. (2014). Strategic Decision Making under Uncertainty to Identify Sustainable Biorefinery Strategies: Part II: Risk Attitude. Submitted to *AIChE Journal.*

A complementary publication (chapter book) mentioned below can also be found in Appendix G:

- Book Chapter: Sanaei, S., Janssen, M., Stuart, P., LCA-Based Environmental Evaluation of Biorefinery Projects in Stuart, R., P., El-Halwagi, M. (2012) Integrated Biorefineries: Design, analysis and Optimization, Taylor and Francis.

In addition, a list of conference presentations about what has been done in this thesis, can be found as follows:

- Sanaei, S., Stuart, P. (2011) Techno-economic analysis of Triticale-based Biorefinery Strategies. *8th Annual World Congress on Industrial Biotechnology and Bioprocessing (BioWorld Congress)*. Toronto, Canada.
- Sanaei, S., Chambost, V., Stuart, P. (2012). Application of MCDM Approach to Assess Sustainability of Triticale-based Biorefinery Strategies, *8th International Conference on Renewable Resources & Biorefineries (RRB8)*. Toulouse, France.
- Sanaei, S., Stuart, P. (2012). Identification of Promising Integrated Forest Biorefinery Strategies at Early-Stage Design: Techno-economic Analysis. *TAPPI International Bioenergy and Bioproducts (IBBC) Conference*. Savannah, USA.
- Sanaei, S., Stuart, P. (2013). Biorefinery Strategy Decision-Making under Uncertainty. *TAPPI International Bioenergy and Bioproducts (IBBC) Conference.* Green Bay, USA.
- Sanaei, S., Stuart, P. (2013). Retrofit design and strategic decision making to identify sustainable integrated forest biorefinery strategies. *Canadian Chemical Engineering (CSChE) Conference*. Fredericton, Canada.

## 4.2 Links between publications

Figure 4-1 shows how the articles in this thesis link. The first two articles present the techno-economic analysis and sustainability assessment of biorefinery strategies under deterministic conditions for a greenfield agricultural-based biorefinery case study.

The economic analysis and the proposed MCDM cascade methodology for criteria refinement are presented in “Article 1”. The refined set of economic criteria obtained in this article are then aggregated with the other sustainability criteria (refined set of environmental and competitiveness criteria) using MCDM method in “Article 2”.

In order to get an insight about LCA-based environmental analysis to better conduct the MCDM panel employing environmental criteria in Article 2, LCA-based environmental analysis of biorefinery projects was reviewed and summarized in the book chapter. The results of “Article 1” and “Article 2” were presented in *BioWorld Congress* and *8th International Conference on Renewable Resources & Biorefineries (RRB8)* respectively.

The methodology developed in these articles along with the identified set of important decision criteria that were modified first according to the received comments by the panel, were used for the second case study in this thesis presented in Article 4 (Appendix D). Another input to this article, is what was done as retrofit design in “Article 3” resulting in definition of the design alternatives and identifying all integration potentials between the biorefinery and the mill.

The results of “Article 3” and “Article 4” were presented at the *TAPPI International Bioenergy and Bioproducts (IBBC)* and *Canadian Chemical Engineering (CSChE)* Conferences.

The “Article 5” and “Article 6” respectively present a systematic approach to assess sustainability under uncertainty and quantifying risk attitude of decision makers, demonstrated by a retrofit forestry-based biorefinery case study. A part of it was presented at the *TAPPI International Bioenergy and Bioproducts (IBBC)* Conference.

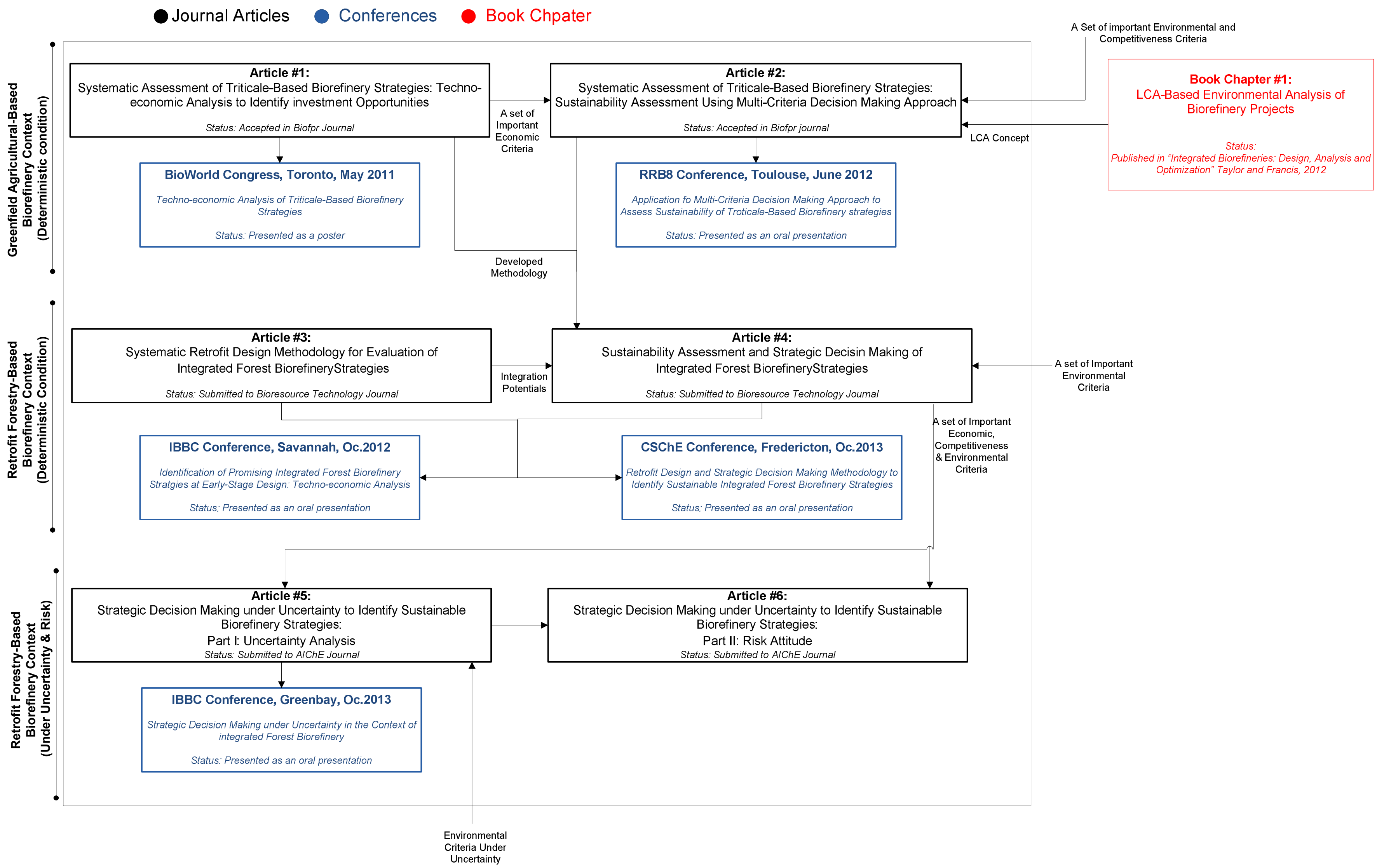



**Figure 4-1 Linkage between the publications**

## 4.3 Synthesis

As categorized in Figure 4-1, the articles represent two main themes:

- (A) Sustainability assessment of biorefinery strategies under deterministic condition in:
  - Greenfield agricultural-based context (Articles 1 & 2)
  - Retrofit forestry-based context (Articles 3&4)
- (B) Sustainability assessment of biorefinery strategies under uncertainty and risk in:
  - Retrofit forestry-based context (Articles 5&6)

Part (A) focuses on:

- Defining a set of practical and interpretable sustainability criteria including some new decision criteria evaluated using techno-economic analysis results
- Refining a set of necessary criteria into a set of important criteria
- Aggregating conflicting sustainability criteria into a unique score

These steps are applied on two case studies and address the first sub-objective in this thesis.

Part (B) focuses on:

- Involving uncertainty in sustainability decision making
- Quantifying risk attitude of decision makers
- Investigating the importance of addressing uncertainty and risk in strategic decision making

These steps are applied to a retrofit forestry-based case study and address the second sub-objective of this thesis.

A summary of results in these articles are presented in the following sections through the mentioned themes.

### 4.3.1 Sustainability assessment of greenfield agricultural-based biorefinery strategies under deterministic conditions

The implementation of a greenfield triticale-based biorefinery was considered in this thesis as the first case study to demonstrate the developed methodology for sustainability assessment under deterministic condition.

#### 4.3.1.1 Biorefinery design

The triticale-based biorefinery scenarios were defined in three product platforms, in which both triticale grain and straw are used as feedstocks. These three product platforms were (1) bioethanol, (2) polylactic acid (PLA), and (3) a blend of thermoplastic starch (TPS) and PLA. The product-process scenarios in each platform include (1) a base case (Figure 4-2) representing the minimum technology-risk option while maximizing the production capacity of the main product, and (2) several alternatives (Table 4-1) to the base case that involve higher technology risks, but can potentially lead to improved returns. The minimum risk base case for each product platform was defined using two rules: (1) the use of existing commercial/conventional technologies on the grain line, and (2) use of the most proven processes on the straw line to decrease the uncertainty in production of second-generation bioproducts. In the base cases of the bioethanol, PLA, and TPS/PLA blend platforms, the grain processing lines were defined based respectively on the Husky (Husky 2013),  NatureWorks (Gruber, Kolstad et al. 1993), and Entek (Entek 2013) technologies.

Through consideration of different process alternatives, the product portfolio of each option yielded several interesting business opportunities summarized in Table 4-1.For instance in PLA platform they are: (1) “Alt 1. Cogen” that produces electricity and steam by burning straw in a CHP unit; (2) “Alt 2. Wet Milling” replaces the dry milling unit in base case scenario with a wet milling unit, leading to the production of proteins; (3) “Alt 3. Ultra-filtration” implements a more efficient separation process, leading to acetic acid production and elimination of gypsum; (4) “Alt 4. SSCF” intensifies the process by the combination of saccharification and fermentation process steps into a single one; and (5) “Alt 5. Pearling” produces of bran and stillage by the addition of a pearling unit to the grain line.

For mass and energy balances of these product-process options, a target volume of about 151.5 MM L/y for ethanol, 100,000 t/y for PLA, and 75,000 t/y for the TPS/PLA blend has been assumed. This target was set based on market analysis and considering the production capacity of existing producers.

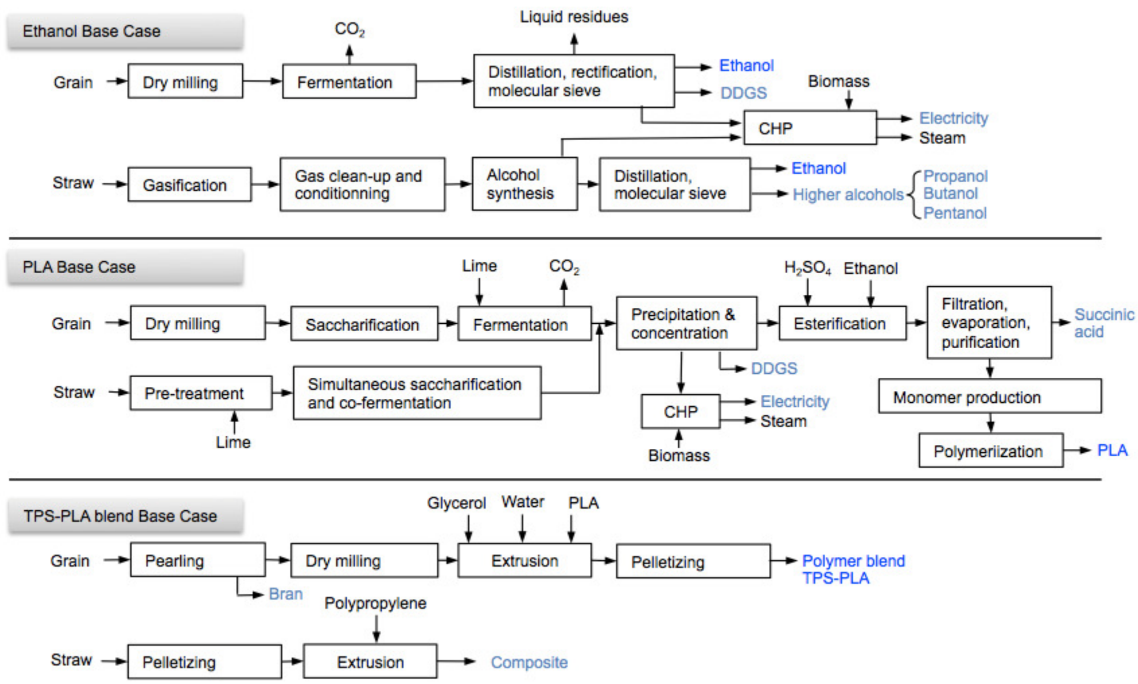



**Figure 4-2 Block flow diagram of base-case scenarios for the three biorefinery platforms**

**Table 4-1 Summary of process alternatives considered for the 3 biorefinery platforms**

| Alt. | Modifications to the Base-Case Process | | | Justification/Characteristics |
|---|---|---|---|---|
| | Ethanol | PLA | TPS/PLA Blend | |
| **1** | Use straw in combined heat and power (CHP) unit. | | | To investigate the effect of minimizing market risk in the straw line by producing electricity instead of bioproducts. |
| **2** | Replace the dry milling unit in the grain line with a wet milling unit. | | | To investigate the role of producing an extra value-added co-product (protein). This also results in purer starch in the main flow. |
| **3** | Replace gasification in the straw line with a process consisting of a pressurized low-polarity water (PLPW)[21] pre-treatment, resulting in Xylitol production as a by-product from the extracted C5 sugars. | Replace conventional separation in both grain and straw lines with ultra-filtration and electro-dialysis. | Add mechanical pulping for pre-treating straw. | -On the ethanol platform: to investigate the effect of replacing a thermochemical with a biochemical pathway in the straw line.<br>-On the PLA platform: to investigate the effect of implementing a more efficient separation unit, leading to less energy consumption and to the production of acetic acid as a co-product.<br>-On the TPS platform: to investigate the effect of extracting cellulose for use in the production of biocomposites. |
| **4** | Replace the conventional separation and purification process in the grain line with pervaporation-fermentation followed by a molecular sieve. | Simultaneous saccharification and fermentation in the grain line. | - | -On the ethanol platform: to investigate the effect of enabling an integrated continuous process, which results in energy savings.<br>-On the PLA platform: to investigate the effect of process integration, resulting in energy savings. |
| **5** | Add a pearling unit before milling in the grain line. | | - | To investigate the effect of increased purity in the main flow and reduction in the size of the other units. |

### 4.3.1.2 Techno-economic analysis

As the first pillar of sustainability, economic performance of the design alternatives is assessed by techno-economic assessment. The main assumptions in techno-economic model and its results for the base cases and alternatives can be found in Appendix A.

### 4.3.1.3 Economic criteria definition and evaluation

The results of economic analysis were used to calculate a set of economic criteria. The economic performance of projects is often assessed using a profitability-oriented criterion commonly presented by Internal Rate of Return (IRR). However, from an investor's perspective, biorefinery projects should lead to value creation over the longer term while mitigating risks and ensuring competitiveness, and should guarantee business viability under the probable worst market conditions. Therefore, not only profitability oriented criteria, but also business oriented criteria were considered to assess the economic viability of each investment opportunity. In this thesis a unique set of economic criteria has been defined (Table 4-2) addressing profitability driven as well as business driven issues to provide a better characterization of the economic potential of each alternative.

Profitability oriented criteria included (1) internal rate of return (IRR) to assess the profitability of the project, (2) downside internal rate of return (DIRR) to evaluate the project robustness under the worst market conditions assuming highest biomass and lowest product prices, and (3) return on capital employed (ROCE) to assess the efficiency of the investment. With regard to the need to measure the impacts of external parameters on margin creation (making profit), three additional criteria were defined including (1) resistance to supply market uncertainty (RTMU) to assess project sensitivity to raw material and energy cost fluctuations, (2) ability to respond to unknown changes (ARUC) to measure the potential of risk mitigation by generating free cash flow, and (3) revenue diversification (RD) to evaluate the benefits of margin creation and revenue stabilization associated with a diversified product portfolio.

**Table 4-2 A set of economic criteria used for decision making.**

| Economic Criteria (EC) | | Interpretation* | Metric[12] |
|---|---|---|---|
| Profitability Oriented Criteria | IRR (Internal Rate of Return) | Measures the profit/risk ratio under normal market conditions. This ratio should normally be greater than 20%, the minimum target for **profitability over the short-term**, before considering probable future technology improvements. | $\mathrm{NPV} = \sum_{t=0}^{22} \frac{\mathrm{CF_t}}{(1+\mathrm{IRR})^t} = 0$ |
| | DIRR (Downside Internal Rate of Return) | Measures the viability of the business model or the **robustness** of the biorefinery process, defined as maintaining reasonable profitability (nominally, above 11%) under poor future market conditions (maximum biomass price and minimum product price). | $\mathrm{NPV} = \sum_{t=0}^{22} \frac{\mathrm{CF_t}}{(1+\mathrm{DIRR})^t} = 0$ |
| | ROCE (Return on Capital Employed) | Measures the **cash flow that the project generates from its invested capital.** | $\mathrm{ROCE} = \frac{\mathrm{EBIT}}{\text{Capital Employed}}$ |
| Business Strategy Oriented Criteria | RD (Revenue Diversification) | Measures the ability to improve margins due to product diversity and to **stabilize project revenue** by mitigating the risk of low profit from a single product because of price volatility. More diverse revenue has enhanced benefit if the process has **flexibility** between products in the product portfolio. | $\sum_{i=1}^{\text{Number of byproducts}} \frac{\text{Revenue from byproduct}}{\text{Total revenue}}$ |
| | ARUC (Ability to Respond to Unknown Changes) | Measures the ability of a biorefinery alternative to **stay in operation under unknown changes** in the future business environment, by maintaining more free cash flow (FCF) for a longer period of time. | $\sum_{i=\text{first year of construction}}^{i=\text{10th year of production}} \mathrm{FCF_i}$ |
| | RTMU (Resistance to Supply Market Uncertainty) | Measures the **sensitivity** of the project **to the market value of the raw materials and energy**. | $\frac{\mathrm{EBIT}}{\text{Cost of (raw materials + Energy)}}$ |

*The interpretation presented for each criterion was obtained as a result of the MCDM panel.

NPV: Net Present Value
CF: Cash Flow
EBIT: Earning before Interest and Tax
FCF: Free Cash Flow

Comparing the IRR of the base cases for the 3 platforms shows that producing value-added products, including PLA and a TPS/PLA blend, is more profitable (IRR more than 20%) than the production of a commodity product such as ethanol (IRR of approximately 9%).

As shown in Figure 4-3, none of the ethanol production scenarios are adequately profitable (IRR is lower than 20%), except for Alternative 3 that involves the production of a value-added co-product (xylitol) from the $C_5$ stream, which has been extracted using an advanced fractionation technology (PLPW). These results underline the importance of considering value-added co-products as part of a commodity-driven product portfolio to achieve economic profitability. For this platform, any increase in investment cost without an increase in revenue through the production of value-added co-products can lead to negative profitability (e.g., Alternative 1: cogeneration). For the PLA platform, all scenarios are profitable enough except Alternative 1 as cogeneration (IRR=17%), a capital-intensive option with no revenue from value-added co-products. For the TPS/PLA blend platform, all scenarios are profitable enough except Alternative 3 as mechanical pulping (IRR=8%). This scenario may be economically viable only in the context of an integrated biorefinery in which existing mechanical pulping equipment at the mill can be used for the biorefinery process.

The DIRR criterion shows that among all platforms, the PLA platform offers the best business viability under poor market conditions. However, ethanol (except for Alternative 3) and TPS/PLA blend platforms are not robust under the same conditions. In the case of ethanol production, it is mainly because of their dependency on biomass price. However in the case of TPA/PLA blend production, it is because of the high impact of product market price under the worst market conditions (with a large gap between average sale prices assumed under normal market conditions and the lowest price under poor market conditions). The values associated with the ROCE criterion show that value-added product platforms obtain more value from their assets than do commodity platform.

By comparing the values of the Revenue Diversification (RD) criterion for the ethanol and PLA platforms (Figure 4-4), it can be concluded that co-products play a major role in revenue creation for commodity platforms. A comparison of the PLA and TPS/PLA blend platforms in Figure 4-5 shows that specialty co-products (e.g., biocomposites) can better stabilize revenue, mainly because of their higher market value and lower market volatility compared to commodity co-products. In the same category of criteria, the values of the Ability to Respond to Unknown Changes (ARUC) criterion show that the value-added product platforms are better equipped to mitigate risks over the long term by generating more free cash flow than the commodity platform. In addition, comparing the Resistance to Supply Market Uncertainty (RTMU) criterion for the three platforms shows that high sensitivity to supply-market uncertainties has a significant impact on the economic viability of the ethanol (to a lesser extent in Alternative 3) and TPS/PLA blend platforms. This is due mainly to the high dependency of production costs on biomass price in the case of ethanol production and the high dependency of production costs on PLA price in the case of TPS/PLA blend production. Although the ethanol platform is sensitive to the supply market, the results of Alternative 3 underline that for the scenarios considered, producing value-added co-products mitigates the impact of the supply market.

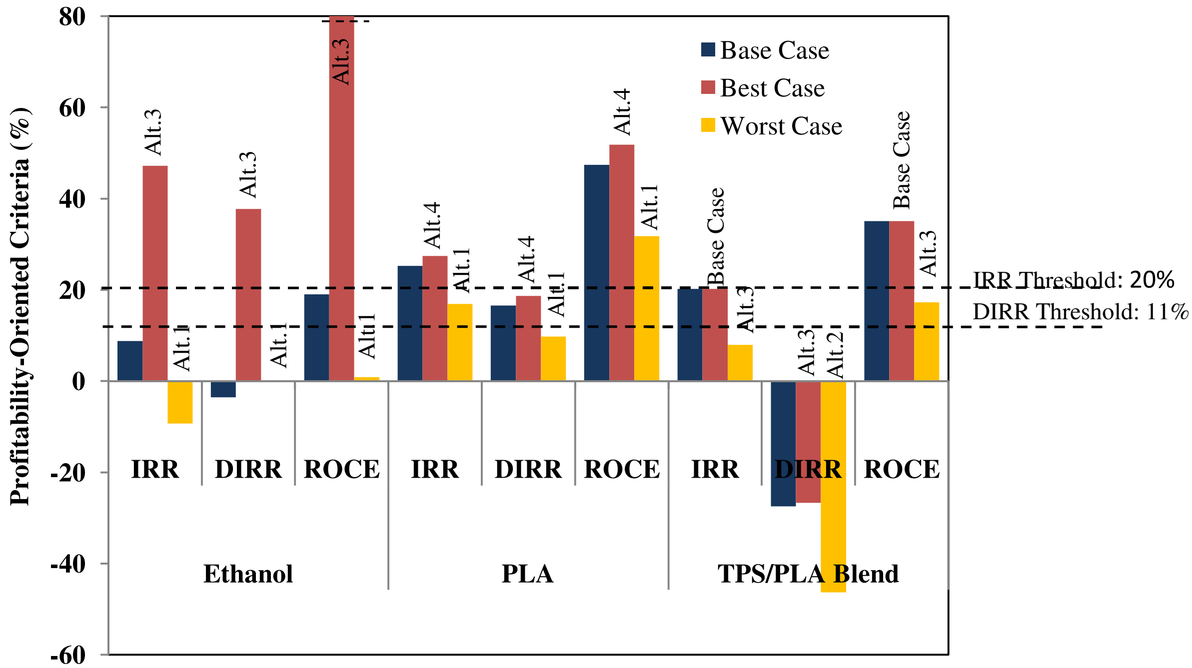



**Figure 4-3 Profitability-oriented criteria**

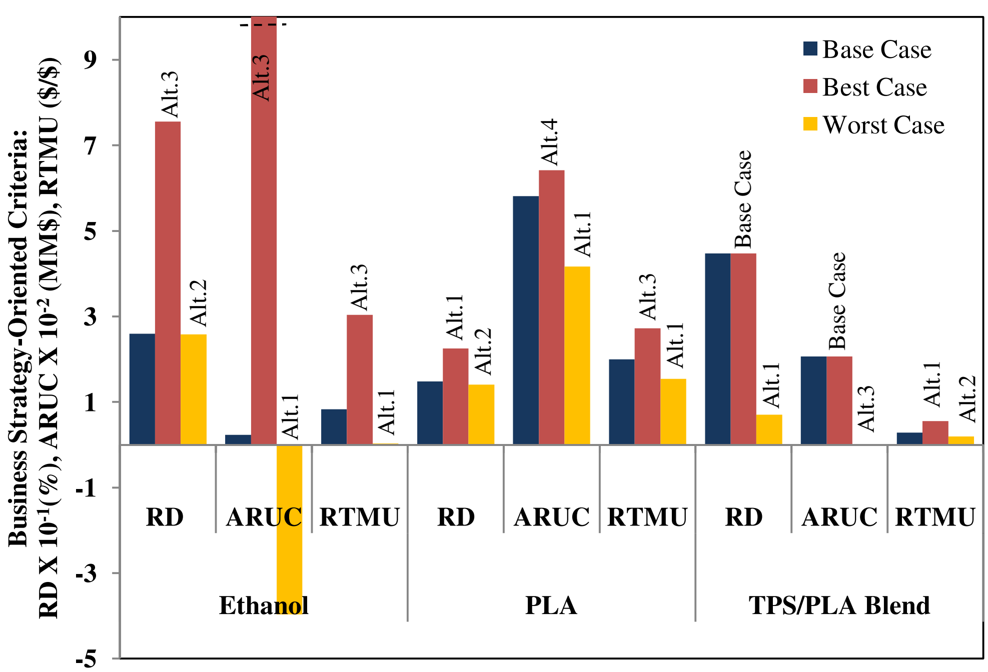



**Figure 4-4 Business strategy-oriented criteria**

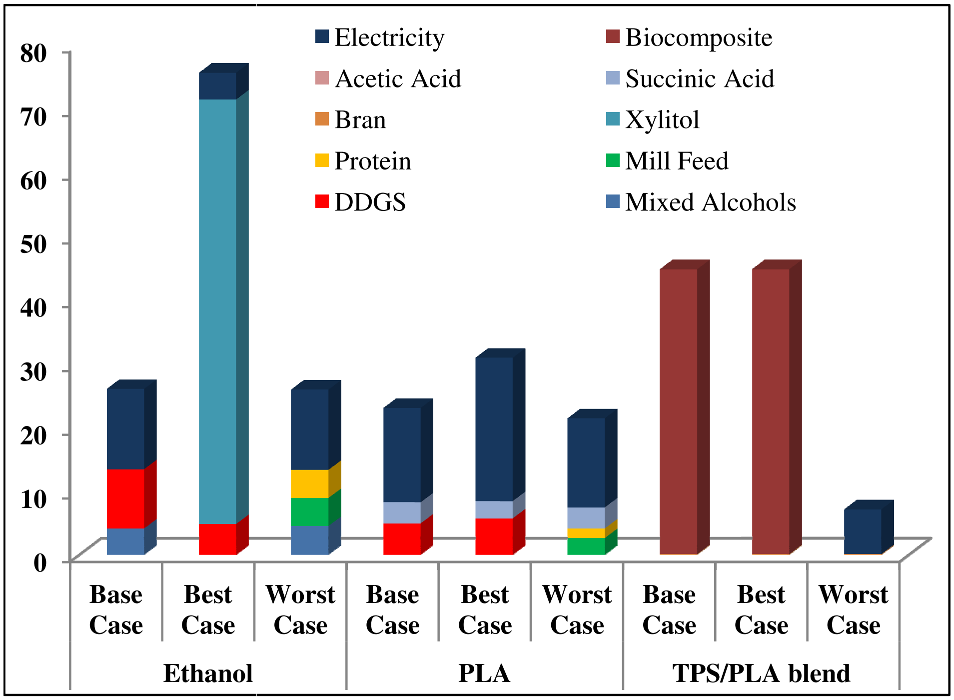



**Figure 4-5 Revenue diversification**

Although the base case in three platforms were compared, as mentioned before generally in greenfield biorefinery context, stakeholders have a pre-defined product strategy because their objective is mainly to achieve a competitive advantage through penetrating in green market. Thus for a specific type of product (e.g, PLA) they would like to compare the process design alternatives in order to identify the promising strategies to produce their target product. However, identifying the most and least promising alternatives, especially within a platform, is not straightforward. For instance, in the PLA platform, Alternative 4 (SSCF) shows the best performance on profitability-oriented criteria; however, the results associated with business strategy-oriented criteria are not necessarily in agreement with them. Therefore, calculating a unique score employing conflicting criteria for each alternative by using the MCDM tool is crucial for assessing different alternatives.

### 4.3.1.4 Criteria refinement

The number of economic criteria for being aggregated to an economic score is acceptable. However for the purpose of sustainability assessment these criteria will need to be aggregated with the environmental and competitiveness criteria which increases the number of decision criteria. Employing a large number of criteria can increase drastically the level of inconsistency and making a single panel impractical. Therefore, a refined set of pertinent criteria need to be identified based on the separate MCDM panels (MCDM cascade), one at the time employing one category of criteria (e.g, economic, competitiveness criteria and environmental criteria). This approach can convert a necessary set of economic criteria into a set of important economic criteria through first MCDM, and similarly for the competitiveness and environmental criteria through two other separate MCDMs.

In this thesis, criteria refinement and decision making was demonstrated using the PLA platform for the stakeholders who are looking for producing bio-based PLA. However the presented methodology can be applied to the other platforms likewise.

The multi-disciplinary panel in this study consisted of five panelists from industry and academia. They had various backgrounds including biorefinery expertise, energy, economics, market, and environmental sciences, ensuring that all the critical points which should be considered in strategic decision making would be captured.

As a first step in the decision making activity, panelists interpreted the meaning of each defined criterion, as presented in Table 4-2. In order to evaluate the relative importance of the economic criteria, in weighting activity the first stage was to select the most important economic criterion and to choose a target value based on the preferences of the panelists. As it could be expected, the IRR criterion representing project profitability was selected as the most important criterion, with a target value of 27%. In the next stage, the importance of each criterion was compared with that of the most important criterion using the trade-off method and the weights of the economic criteria were calculated (Figure 4-6).

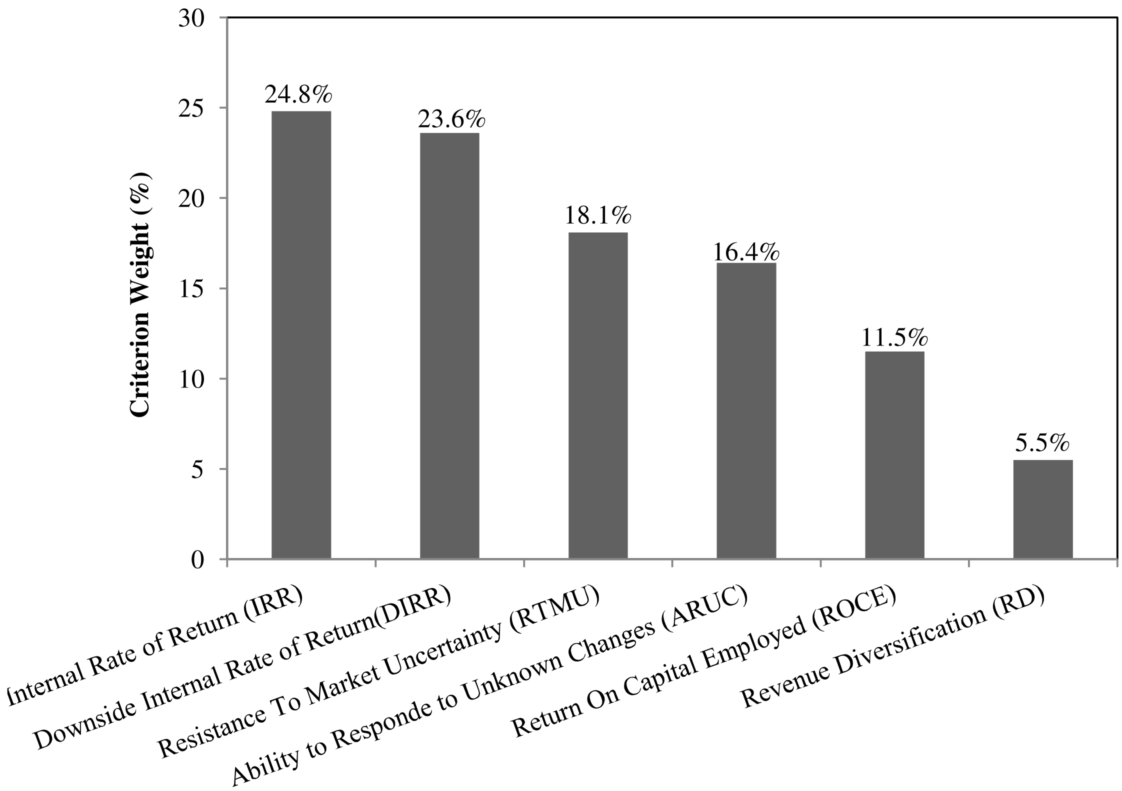



**Figure 4-6 Criteria weights resulting from MCDM**

As shown in Figure 4-6, similar weights were given to IRR and DIRR (24.8% and 23.6% respectively) and these two criteria were selected as the most important economic criteria. The standard deviation of the scores represents the level of consensus among the panel members about the relative importance of that criterion. For instance, the low standard deviation associated with DIRR implies a high degree of consensus on selecting this criterion along with IRR as the most important economic criteria. Among the business strategy-oriented criteria, the RTMU criterion was assessed as important for decision making. The two least important economic criteria were RD and ROCE, with 5.5% and 11.5% importance respectively. The low importance of the RD criterion was associated with a lack of interpretable distinction between competitiveness criteria (Diffo, Chambost et al. 201X) and the economic concept of RD.

Based on the weighting activity, three criteria, IRR, DIRR, and RTMU, were considered the important criteria to be used in the sustainability assessment of the PLA platform in the following section.

#### 4.3.1.5 Ranking the design alternatives in terms of economic performance

Another achievement of performing the conducted MCDM was ranking the alternatives in terms of economic performance using a economic score which was obtained by multiplying the weighting factor and the calculated utility value associated with each criterion.

The results presented in Figure 4-7 show that the least economically promising alternative in the PLA platform is Alternative 1 (cogeneration). In addition, the overall economic scores show that the base case, Alternative 2 (wet milling), and Alternative 5 (pearling) have almost the same economic performance. However, the levels of risk are dissimilar and may play a major role in decision making. Among these options, the base case with minimum level of risk due to its use of existing commercial technologies was favoured.

The two alternatives which show significantly better economic performance are Alternatives 4 (SSCF) and Alternative 3 (ultra filtration) due to their extremely high values of RTMU justified by low raw material (sulphuric acid) consumption in Alternative 4, and low energy demand in Alternative 3.

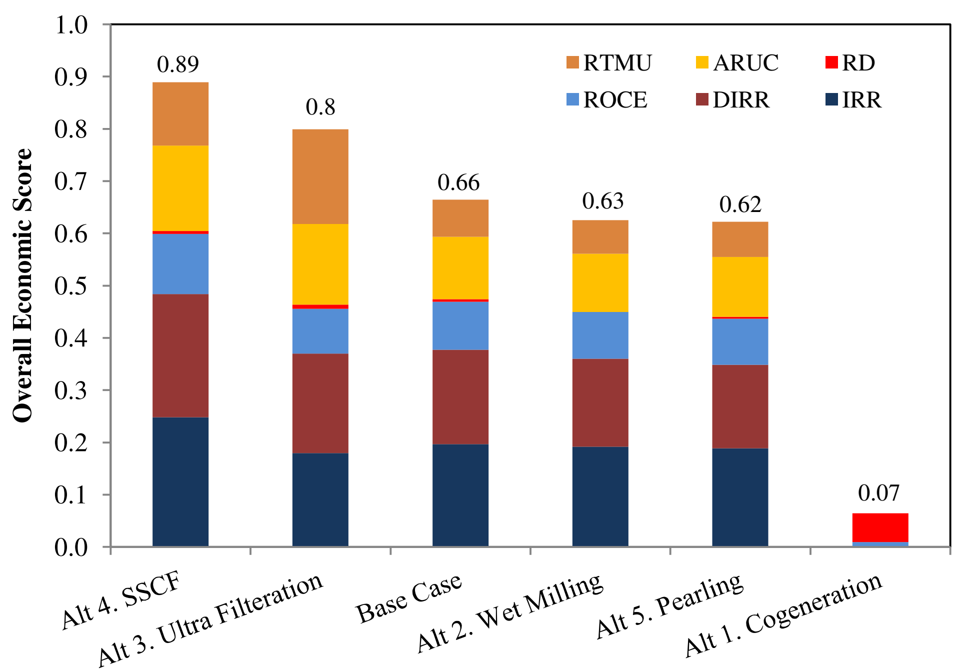



**Figure 4-7 Economic scores of alternatives for the PLA platform resulting from MCDM**

### 4.3.1.6 Competitiveness assessment and environmental analysis

In addition to economic analysis, multi-disciplinary assessments, including competitiveness analysis and environmental assessment, need to be conducted to support early stage decision making for investment strategies by answering the following questions: (1) What is the potential performance associated with each process alternative, taking into account different levels of technology risks? (2) What is the competitive position associated with each product portfolio that may lead to viable and long-term business models? and (3) What would be the environmental impacts or benefits associated with each investment option?

From a business point of view, a competitive assessment of biorefinery options is of critical importance to identify the most promising alternatives under different product portfolio potentials and to establish robust business strategies for long-term value creation. A market oriented assessment was performed by Diffo *et al.* (Diffo, Chambost et al. 201X) which considered various competitive market issues related to the context of the triticale-based biorefinery, including (1) competitive access to biomass (CAB) to assess the potential to secure low-cost access to biomass over the long-term, (2) product portfolio positioning (PPP) to evaluate the potential to capture market share and to secure a first-to-market position, (3) competitiveness on production costs (CPC) to assess the potential to compete on market prices against the best technology available and to create margins, (4) margins under price volatility (MPV) to evaluate the potential to create margins under the best and worst product price scenarios, and (5) technology strategy related to market competitiveness (TECH) to assess the flexibility potential of the process under market constraints.

Based on an LCA analysis, Liard (Liard 2011) used the significant end-point impacts, used by the IMPACT 2002+ impact assessment method, as criteria to be considered for evaluating the PLA alternatives. These are (1) human health (HH), (2) ecosystem quality (EQ), (3) GHG emissions (GHG), and (4) non-renewable resources (NRR). Taking into account the context of triticale as an energy crop, other criteria, not represented in the end-point categories, were considered likewise such as (5) land occupation (LO), (6) aquatic acidification (AA), and (7) fresh water input (W).

Based on the presented methodology, to identify the most promising alternatives in terms of each sustainability pillar, MCDM panels were convened that led to economic, competitiveness, and environmental scores for each alternative. As can be seen in Figure 4-8, the economic and competitiveness assessments resulted in somewhat similar alternatives ranking, especially for the two most promising alternatives (SSCF and ultra-filtration), as well as for the least promising investment option (cogeneration). The reason for this is that the cost-revenue basis is common for economic and competitiveness analyses. However, value creation potential is analyzed from two distinct points of view: (1) economic analysis assesses profitability and business viability potential, while (2) competitiveness analysis evaluates the robustness of the strategy in meeting short and longer term business model objectives. In addition, it should be noted that although there might be some similarities in the parameters used to evaluate the economic and competitiveness criteria, these two types of criteria have completely independent interpretations and thus for decision making purpose they are considered as independent criteria. The poor competitive performance of the base-case scenario can be attributed to the production of a lower volume of co-products, which weakened the competitive position of the product portfolio. The cogeneration alternative is capital intensive and it is sensitive to biomass prices, so offered relatively little economic or competitive potential, although it resulted in considerable environmental benefit.

The results in environmental analysis are not in agreement with the rankings in economic and competitiveness perspective. With the conflicts in rankings, no clear answer was obtained at this stage regarding which alternatives are sustainably promising for investment and should be further considered.

Thus aggregating these conflicting criteria into a sustainability index is crucial.

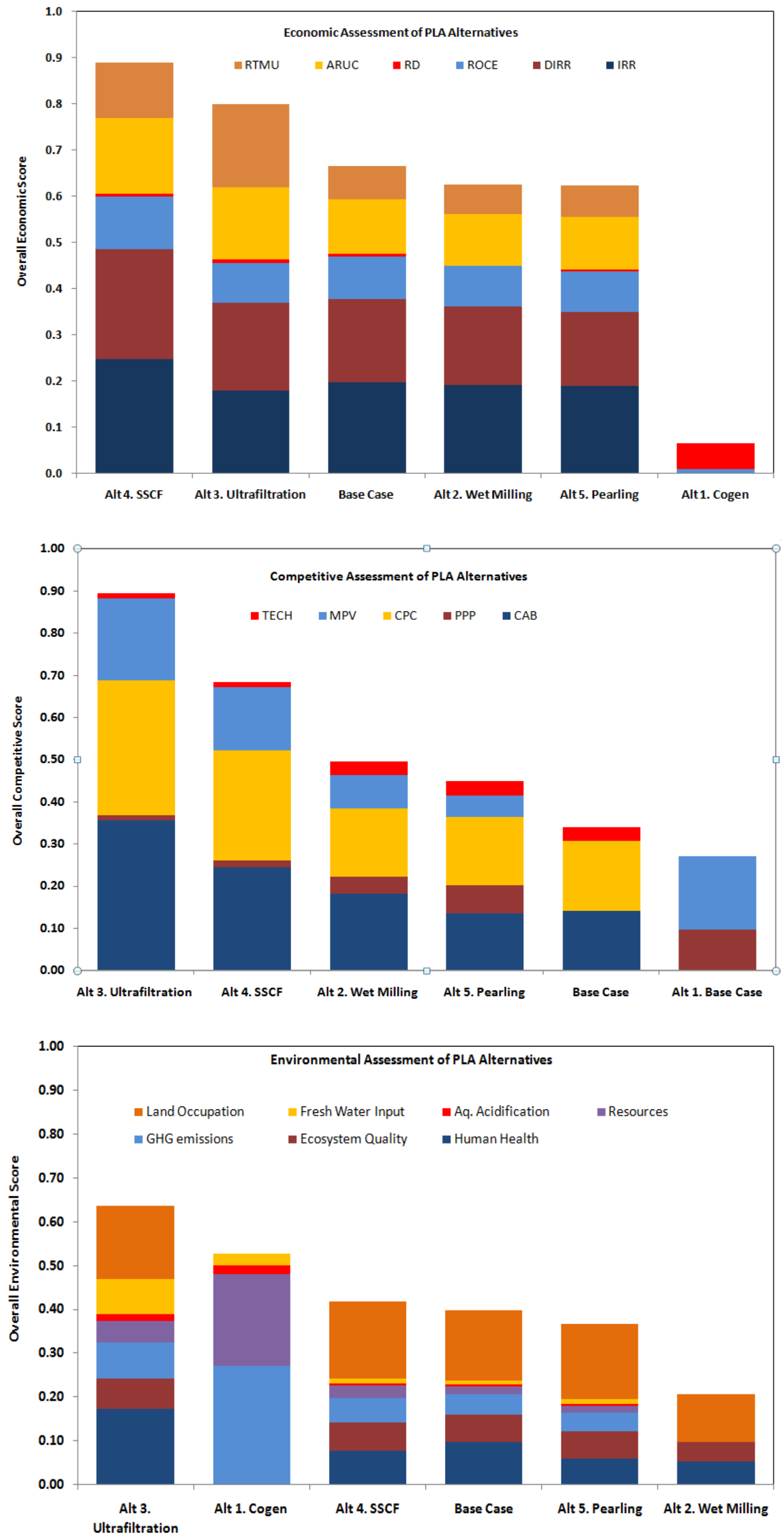



**Figure 4-8 Ranking of PLA production alternatives using economic, competitiveness, and environmental assessments**

### 4.3.1.7 Sustainability assessment

As mentioned before, aggregating the three sustainability dimensions for decision making potentially involves a large set of decision making criteria which well justifies necessity of criteria refinement. This has been done through a cascade of MCDM which each resulted in evaluating the relative importance of the criteria defined in each sustainability pillar. As a result a refined set of pertinent criteria in each sustainability pillar was identified as a result of conducted three MCDMs (Figure 4-9).

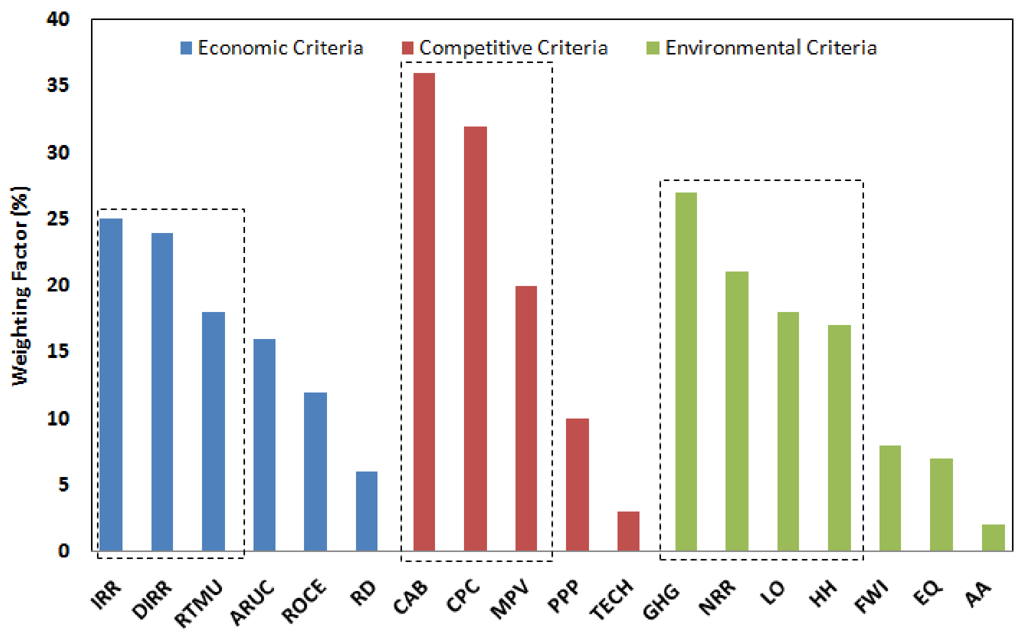



**Figure 4-9 Weighting factors of economic, competitiveness, and environmental criteria according to three MCDM panels**

From the economic perspective, among the profitability oriented criteria, IRR and DIRR were selected as the most important economic criteria due respectively to the importance of profitability in the biorefinery project and the need for project robustness. Moreover, among the business strategy oriented criteria, RTMU was selected as an important criterion due to the magnitude of project sensitivity to variations in the impacting parameters such as raw material and energy costs. From a competitiveness perspective (Diffo, Chambost et al. 201X), CAB, CPC, and MPV were selected as the most important criteria for decision making, due mainly to (respectively) (1) the competitiveness associated with securing access to feedstock and building a value proposal for farmers, (2) the potential to be cost-competitive and to provide a low-cost value proposal to the consumer, and (3) the potential to generate margins under volatility. Finally from an environmental perspective (Liard 2011), GHG, NRR, LO, and HH were selected as the most important criteria for sustainability assessment, taking into account (respectively) that (1) GHG mitigation is a priority in Alberta, with a likelihood of potential future regulations to favour large GHG emission reductions; (2) energy savings are crucial for biorefinery development considering the limited amount of resources available; (3) land use is a critically important issue in the context of the food-to-fuel debate; and (4) human health is a generically important concept when considering environmental impacts on human beings.

This set of refined criteria involving ten sustainability metrics (introduced in Table 4-3) was used as a basis for conducting an overall MCDM focussed on evaluating the degree of sustainability associated with each investment option.

## Table 4-3 Set of sustainability criteria for decision-making (Sanaei, Chambost et al. 2014)

| Sustainability Criteria (SC) | | Interpretation | Definition of Metric |
|---|---|---|---|
| Economic Criteria | IRR: Internal Rate of Return | Measures profit/risk ratio under normal market conditions. IRR should be greater than 20% as the minimum risk target for emerging industries to guarantee their **profitability in the short term** before considering any probable future improvement. | $NPV = \sum_{t=0}^{22} \frac{CF_t}{(1+IRR)^t} = 0$ |
| | DIRR: Downside Internal Rate of Return | Measures the viability of the business model to guarantee the **robustness** of the project by maintaining profitability (pessimistic IRR above 11%) under the worst predicted market conditions (maximum biomass price and minimum product price). It shows that the project can survive and continue production even under the worst predicted market conditions. | $NPV = \sum_{t=0}^{22} \frac{CF_t}{(1+DIRR)^t} = 0$ |
| | RTMU: Resistance to Supply Market Uncertainty | Measures the **sensitivity** of the project **to the fluctuation in market value of key parameters** in a biorefinery context (raw materials and energy). A project with high RTMU would be less sensitive to any change in raw material and energy prices to minimize its vulnerability to external sources of uncertainty. | $\frac{EBIT}{\text{cost of } (raw\ materials + Energy)}$ |
| Competitiveness Criteria | CAB: Competitive Access to Biomass | Represents the **ability to guarantee a supply of biomass** over the long-term while providing a competitive value proposal to farmers. It shows also the **potential to face volatility on biomass prices.** | $EBITDA \text{ per ton of biomass}$ |
| | CPC: Competitiveness on Production Costs | Shows **how competitive the alternative is** compared to the current benchmarked PLA production, as well as the potential to increase market share through a competitive pricing strategy and the potential to minimize the impacts of volatility due to competitors' pricing strategies to achieve good market share in the long term. | $\frac{\text{production cost benchmark} - \text{current production cost}}{\text{production cost benchmark}} \times 100$ |
| | MPV: Margin under Price Volatility | Shows the **potential to generate margins** under the lowest product market prices and to extract benefits from positive price fluctuations in those markets. It demonstrates as well the **potential to achieve an economically sustainable business model over the long term**. | $60\%\ \text{worst case } EBITDA + 40\%\ \text{best case } EBITDA$ |
| Environmental Criteria | GHG: Greenhouse Gas Emissions | Shows the potential contribution of a biorefinery project to **climate change** through GHG emissions in terms of the number of cars equivalent. | $\frac{\text{GHG emissions (kg } CO_2 \text{ equivalent)}}{\text{Yearly GHG emissions per average Canadian car (kg } CO_2 \text{ equivalent)}}$ |
| | NRR: Non-Renewable Resources | Shows **the amount of non-renewable resources consumed or saved** by the project in terms of energy compared to the reference case. | $\frac{\text{Fossil based energy consumption } (MJ)}{\text{Coal based available reserves } (MJ)}$ |
| | LO: Land Occupation | Shows the proportion (in %) of productive land used for the project compared to the total area used to produce wheat (for food purposes) in the Prairies. It therefore represents the **potential competition with food.** | $\frac{\text{Land occupation } (m^2)}{\text{Land occupation by wheat in the prairies } (m^2)}$ |
| | HH: Human Health | Shows **the impact contribution (in %) of the biorefinery project on human health** based on increased number of healthy years due to the absence of non-GHG pollution and especially particulate matter equivalent (PMeq) emissions (including PM, Sox, and Nox emissions), compared to other main activities around Red Deer. | Human health impact (DALY)/Human health impact (DALY) incurred by the total emissions of particulate matter (PM), SOx, and NOx in the area of Red Deer |

NPV: Net Present Value
CF: Cash Flow
EBIT: Earnings before Interest and Tax
EBITDA: Earnings before Interest, Tax, Depreciation and Amortization
DALY: Disability Adjusted Life Year

***Weighting of Sustainability Criteria***

This set of ten criteria were used in the final MCDM panel to evaluate sustainability of different PLA production alternatives. The multi-disciplinary panel involved five panellists from industry and academia, and was the same panel that participated in the three previously convened MCDMs.

In this last MCDM the IRR criterion was selected as the most important criterion by the panel, with an average target value of 28.8%. The average values of the numbers given by panel members to comparison for each criterion (as a result of applying trade-off method) were used to calculate weighting factors of the criteria. The calculated weights are presented in Figure 4-10.

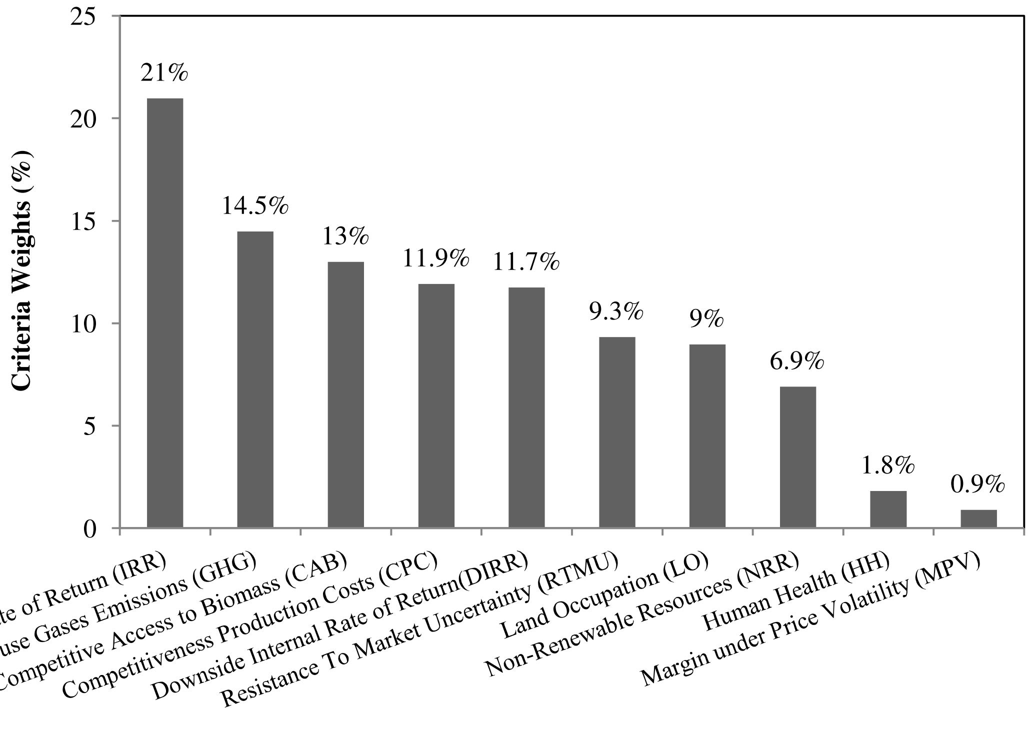



**Figure 4-10 Weights of sustainability criteria obtained in the overall MCDM**

Interestingly, the three first-ranked criteria had already been selected as the most important criteria in their own categories through the previously performed MCDMs: IRR in the economic driven MCDM, GHG in the environmentally driven MCDM, and CAB in the competitiveness driven MCDM. This sustainability MCDM exercise demonstrated that despite the conventional mentality about making decisions based only on economic criteria, both environmental and market competitiveness criteria are important, and can be more important than other economic criteria such as DIRR and RTMU in the context of this study.

The two least important sustainability criteria were HH and MPV. The low importance of the HH criterion can be explained by its associated scale, which is local opposite of the other defined environmental criteria. MPV has been recognized as an important criterion in concept, to consider in decision making, however in this case it did not help to differentiate among alternatives because the MPV values of all the alternatives were similar.

The standard deviation of the scores that the panel gave to one criterion in the trade-off activity, can represent the level of consensus among the panel on the relative importance of that criterion. For instance, the low standard deviation associated with given numbers to HH criterion, implies a high degree of consensus on selecting this criterion as one of the least important sustainability criterion. The lowest level of consensus among the panellists occurred for the NRR criterion due to disagreement among the panellists about the scale of the effect of this criterion: some panellists looked at this criterion on a regional scale and believed that in Alberta it could not be considered as an important issue. However, another group of panellists believed that it could have a high impact if viewed on a universal scale through an overall vision.

***Utility functions***

In this case study for each of criteria, the utility value of least preferred criterion value among the alternatives was set to zero (lower bound). Similarly, the utility value of the best criterion value among the alternatives was set to one (upper bound). For any criterion value in between the lower bound and the upper bound, the utility value has been calculated assuming a linear function (risk neutrality) that links these two boundaries. Exceptionally for IRR as the most important criterion, in which target value (28.8%) is higher than the maximum criterion value among the alternatives, the target value was set as the upper bound with utility value equal to one.

***Ranking of alternatives in terms of sustainability performance***

To define the overall sustainability performance associated with each alternative, a unique score ($SC_e$) was obtained using the weighting factors ($w_i$) and the calculated utility value associated with each sustainability criterion ($u_i$) using the following formula:

$$SC_e = \sum_{i=SC_1}^{i=SC_{10}} w_i . u_i \tag{4-1}$$

In Figure 4-11, all alternatives have been ranked using their overall sustainability scores. These scores indicate that the least promising alternative for PLA production from triticale is alternative 1 – cogeneration. In this alternative, GHG, NRR, and MPV were the most strongly contributing criteria, with GHG playing a major role in the overall score, because the values of the other criteria were the smallest among all the alternatives, and consequently their associated utility values were set to zero. Despite the promising environmental performance of this alternative, it remains a capital intensive investment option with a high level of sensitivity to biomass price because of the large quantity of biomass required. Moreover, it does not involve a value-added product portfolio, resulting in poor economic and market-competitive performance.

The overall sustainability scores show that the base case, alternative 2, and alternative 5 were ranked similarly. However the levels of technology and market risk are dissimilar and could play a major role in decision making, favouring the base case that involves existing commercial technologies and therefore the lowest level of risk.

It was concluded that the PLA production scenario maximizing electricity as a co-product through a straw-dedicated CHP unit was the least sustainable investment option and therefore it was screened out by the panel from the list of promising triticale-based biorefinery strategies to be further analyzed. On the other hand, the options featuring higher technology risk, which involve energy efficient separation processes (ultra-filtration) or more integrated processes (SSCF), obtained significantly better sustainability scores, due mainly to their low energy and raw materials consumption values. The MCDM results show that without considering environmental contributions to the sustainability score, two promising alternatives (SSCF and ultra-filtration) could not be distinguished. SSCF was favoured from an economic perspective, due mainly to its cost reduction because of process intensification, while ultra-filtration was favoured from a competitiveness perspective, due mainly to the competitive market position of its product portfolio. However, the better environmental performance of ultra-filtration, due mainly to reductions in lime and sulphuric acid consumption, did result in a slightly higher overall sustainability score for this alternative compared to SSCF. This confirms the importance of environmental contributions in differentiating among investment options from a sustainability point of view. These two alternatives are not distinguishable in terms of associated risk with them.

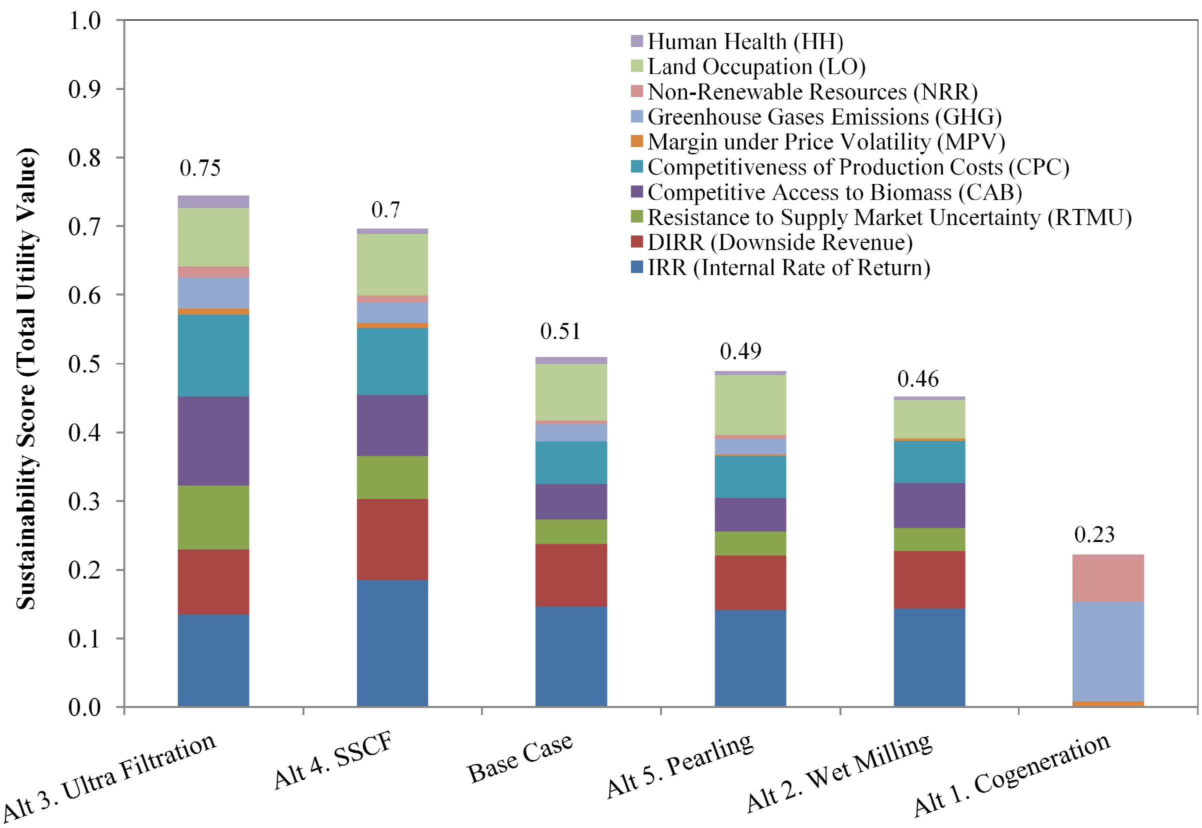



**Figure 4-11 Sustainability Scores of PLA Production Alternatives**

### 4.3.1.8 Critical analysis

The overview of what was done so far, presented in Articles 1 & 2, is shown in Figure 4-12.

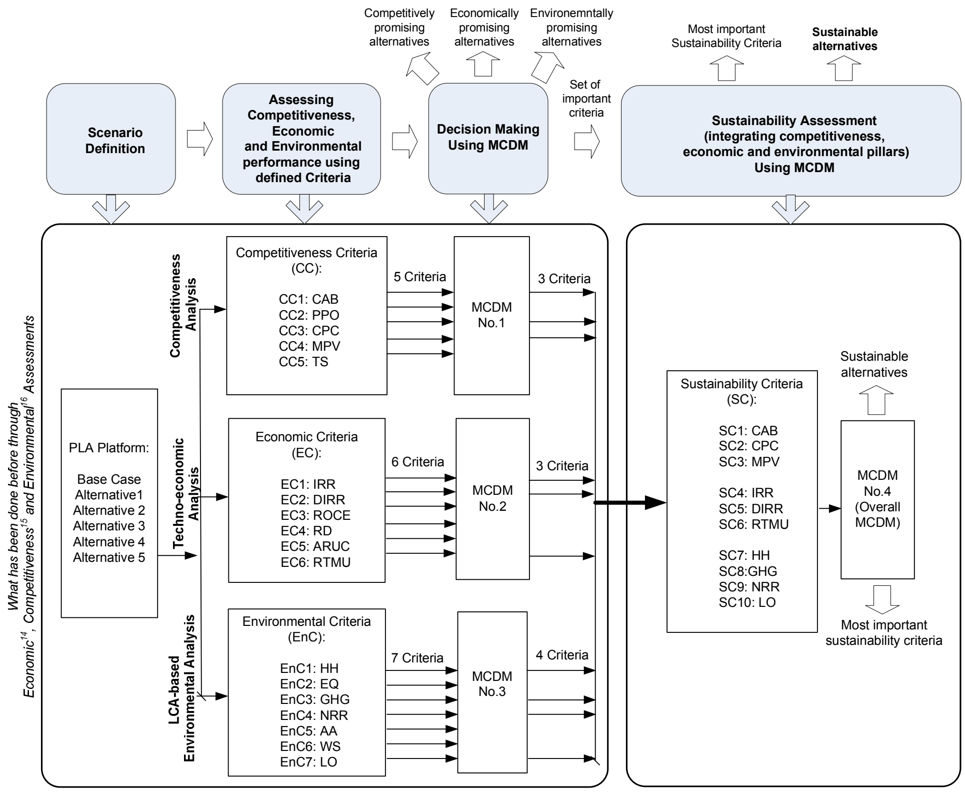



**Figure 4-12 Overview of sustainability assessment methodology for greenfield agricultural-based biorefinery strategies**

By following this part of thesis, we could successfully define a set of criteria in the context of biorefinery in a way that can be practical and interpretable for decision makers (stakeholders). The results of this section showed that the MCDM approach can be a great tool for (1) refining a set of necessary sustainability criteria into a set of important decision criteria to keep the decision making process manageable and also for (2) aggregating the identified important criteria into a sustainability index by which the design alternatives can be successfully ranked in terms of their sustainability performance.

As a result, the first sub hypothesis defined in this thesis could be answered in this section.

The developed methodology here will be applied in a retrofit forestry-based biorefinery context as well (explained in the following section), however with considering the following adjustments according to the suggestions that panelists came up with:

- Increasing the degree of independence in criteria definition by considering the economic and competitiveness criteria in one category and trade them off against each other. This would prevent probable redundancy of the criteria.
- Modifying the criterion representing downside performance of the project. The reason is that projecting the worst market condition by assuming high cost of biomass and low value of the product at the same time makes sense based on the history of the corn biorefinery. However, for new specialty bioproducts, it is probable that higher biomass prices will be passed on to the end-product customer.
    - This suggestion has been applied by replacing DIRR with a more representative criterion called Downside Economic Performance (DEP) that will be defined in section 4.3.2.4.
- Reflecting the concepts of technology and market risk in the decision criteria
    - This suggestion has been applied by defining two new criteria measuring technology and market risk.
- Implying a phased approach of implementation of biorefinery strategies in sustainability assessment.

### 4.3.2 Sustainability assessment of retrofit forestry-based biorefinery strategies under deterministic condition

The developed methodology for sustainability assessment explained in previous section, was applied in a retrofit biorefinery case study to identify the promising biorefinery strategies being integrated into a kraft pulp mill in Canada. This part of thesis summarizes what has been presented in Articles 3 and 4.

A simplified process flow diagram of the pulp production at the studied mill is presented in Figure 4-13.

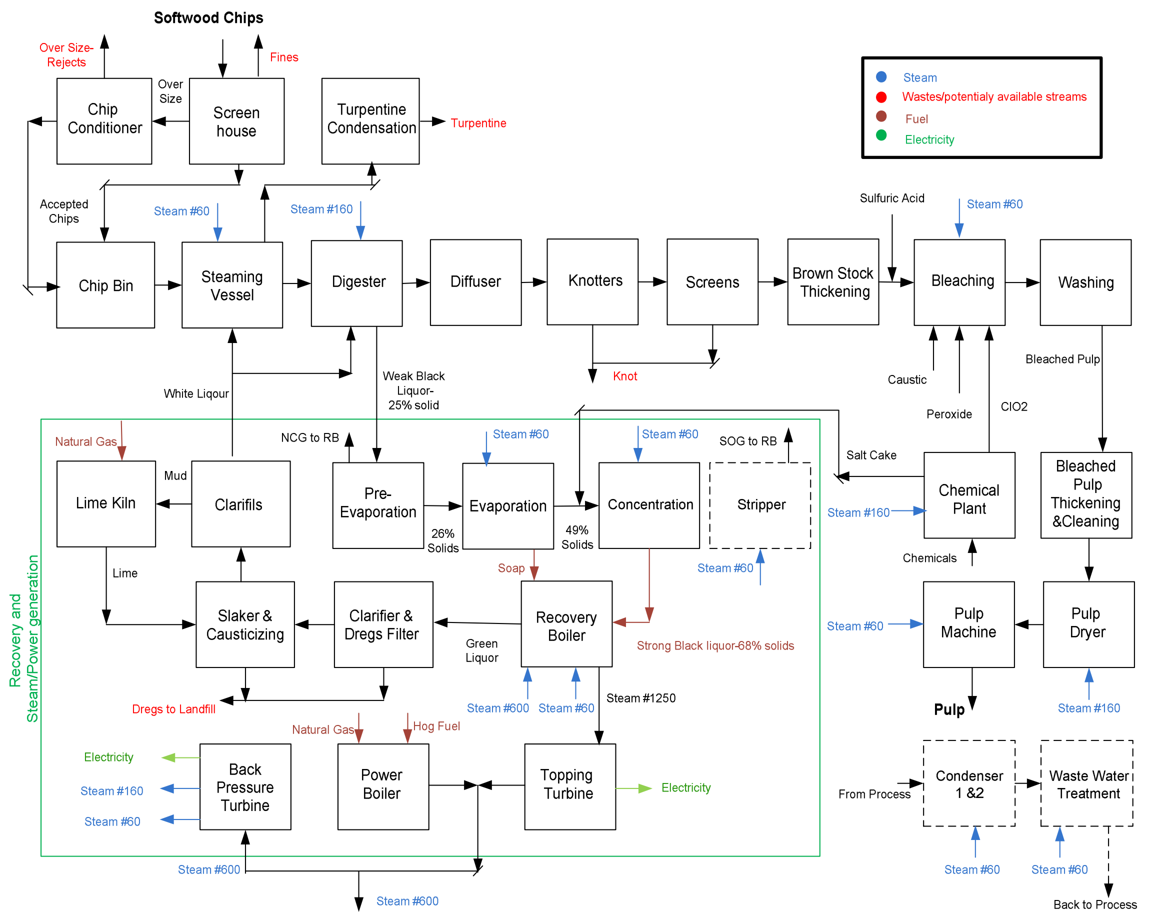



**Figure 4-13 Simplified process flow diagram of the studied mill**

#### 4.3.2.1 Biorefinery design

In order to identify biorefinery technologies which can fit well with the studied mill, first of all the unique characteristics of the mill were identified as following:

(1) Considering that the studied mill is energy self sufficient, and there is a saturated power grid in the province that mill is located in, it would be difficult to accrue large energy-related benefits from biorefinery such as green electricity production via combined heat and power (CHP) unit.

(2) Changing production bottleneck in the studied mill, not due to recovery boiler capacity, shows this fact that lowering costs of the core business by increasing pulp production capacity does not seem doable.

(3) Considering that nearby market opportunities are limited in the context of the studied mill and also access to markets further away is costly, when the local market can not be identified it would be better to target low volume/high value products (value-added products) in biorefinery strategy compared to large volume/low value products (commodity products).

(4) Access to large volume of hardwood chips potentially provides a competitive advantage over mills having access only to forest residuals. This fact shows that targeting biochemical processes to produce value-added lignin-based products seems more promising in the context of the studied mill.

Considering these and also taking into account the alternatives that R&D department of the company would like to assess, four biorefinery technologies finally considered to be assessed for the studied mill which are: (1) lignin precipitation (Alt.1) (2) organosolv treatment (Alt.2) (3) fast pyrolysis (Alt.3) and (4) concentrated acid hydrolysis (Alt.4) technologies.

#### 4.3.2.2 Phased approach

In the product portfolio of candidate technologies, lignin is the only co-product that exists in all alternatives. In phase I this stream has been targeted for the low value applications at the same time implying low level of technology and market risks. In organosolv treatment and concentrated acid hydrolysis as energy demanding candidates, lignin was considered to be burnt in phase I in order to produce additional steam and electricity at the energy island being able to feed energy to both the mill and the biorefinery process. In lignin precipitation technology which is a very low energy demanding option, lignin was targeted for carbon black substation in phase I as a low value commodity product. In fast pyrolysis, in phase I lignin content of bio oil is not extracted due to energy self sufficiency of fast pyrolysis technology, thus bio oil is sold to the market as it is.

In phase II the produced lignin in all biorefinery candidates would be used to be converted into the lignin-based value-added products. There is a wide range of value-added applications from lignin among which replacing phenol in phenol formaldehyde (PF) resins, polyols in polyurethane foams, polyacrylonitrile (PAN) in carbon fiber, dispersants, polymers (themroplastics) blends and composites and activated carbon are some of the important ones. Among these applications, two of them have been applied in this thesis depending on the type of lignin produced by the candidate biorefinery strategy. These include phenol substitution in PF resins production (for Alt.1, Alt.3 and Alt.4) and PAN replacement in carbon fiber production (for Alt.2). Despite of all advantages of using lignin in added value applications, there is a limiting factor that is about low relative reactivity of lignin because of its chemical structure. Thus lignin needs to be modified first in order to enhance its reactivity to an acceptable level (Hu, Pan et al. 2011). Enhancing lignin reactivity can be done by chemical, enzymatic or genetic modification processes among which chemical modifications are the most advanced processes with the maximum available information in literature. These modification processes would vary based on the type of lignin (kraft lignin, organosolv lignin, pyrolitic lignin) and the application requirements.

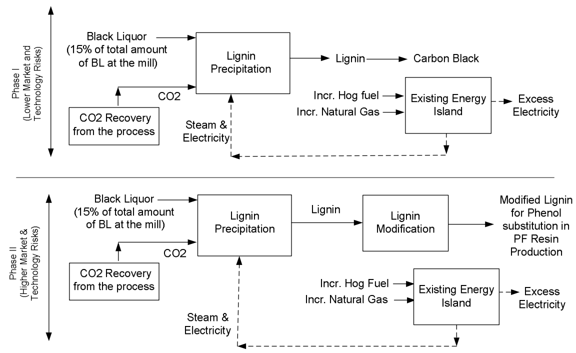
Phenol substitution in PF resin production is the most studied application from lignin in last decades (Malutan, Nicu et al. 2008). Phenol and phenol derivatives are increasingly taking attention in biorefinery context mainly due to an increase in the forecasted demand of PF resin and also an increase in the cost of petroleum-based phenol (Tymchyshyn and Xu 2010). In addition to the cost reduction as the most important advantage of using lignin in PF resins, it would result in reduction of the carcinogenic formaldehyde due to presence of a resin component which is already cross-linked (Gosselink 2011). There are several methods to modify lignin to increase its phenolic content for this specific application such as phenolation, methylolation, demethylation, glyoxaltion, oxidation and reduction among which phenolation and methylolation are the most studied ones (Hu, Pan et al. 2011). Considering this, for lignin precipitation and concentrated acid hydrolysis which their lignin has been targeted for phenol substation in PF resin production lignin is first reacted with phenol in an alkaline area to be modified through phenolation process and then will be sold as modified lignin to PF resin producers. Although in fast pyrolysis the considered value-added application is the same as for lignin precipitation and concentrated acid hydrolysis options, there is a difference that is about lignin extraction from the produced bio oil in fast pyrolysis compared to the other alternatives in which lignin is already produced as a coproduct in the process. Bio oil is a mixture of about 400 types of chemicals which 20% to 30% of it is phenolic fraction that has the potential to be extracted from bio oil (Sukhbaatar, Steele et al. 2009). Although bio oil can be directly modified and then be used for phenol substitution (Cheng, Yuan et al. 2012), extracting phenolic fraction of it from the other components and then modifying that fraction seems more efficient for this specific application.

There are several methods in literature for this purpose among which solvent extraction presented by Sukhbaatar *et al*. (Sukhbaatar, Steele et al. 2009) has been chosen in this thesis due to its cost advantages. In this process water and methanol are used in two steps to obtain water-insoluable pyrolytic lignin with between 20% to 25% yield based on bio oil weight.

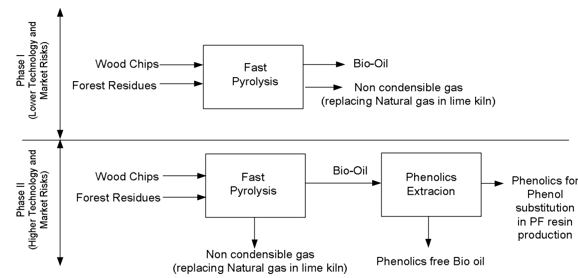
Phenol substitution by lignin at different levels (as high as 70%) , has been successfully tested and can be found in several available publications in open sources. However as it has been discussed by Pizzi (Pizzi 2006), these studies have not paid attention to this fact that the cost advantage would be possibly lost due to lengthening of the panel press time when we use lignin-phenol-formaldehyde resin as a wood adhesive with more than 30% substitution rate. Thus for the purpose of this study, 30% phenol substitution rate has been applied as the maximum rate at which the specification of the PF resin would be kept the same as it is needed. This rate is applied on total consumed phenol including the phenol used for modification of lignin itself and the phenol that is mixed with modified lignin to react with formaldehyde in order to produce PF resin. Assuming this, phenolation process would end with producing about 2.1 ton phenolated lignin from each ton of lignin (Cetin and Ozmen 2002).

The nature of produced lignin in Alt.2 (organosolv lignin) is slightly different from the others, enabling it to have more preferred specification. Thus it well justifies the reason of targeting lignin in this alternative for textile PAN replacement in carbon fiber production compared to the other alternatives in which lignin is used for phenol substitution.

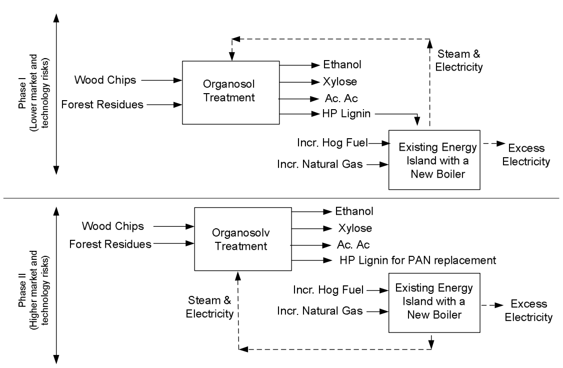
The schematic of the explained phases for the candidate biorefinery alternatives and a simplified process flow diagram of each considering the capacity of available biomass (Table 4-5) are shows respectively in Figures 4-14 and 4-15.




(a)




(c)

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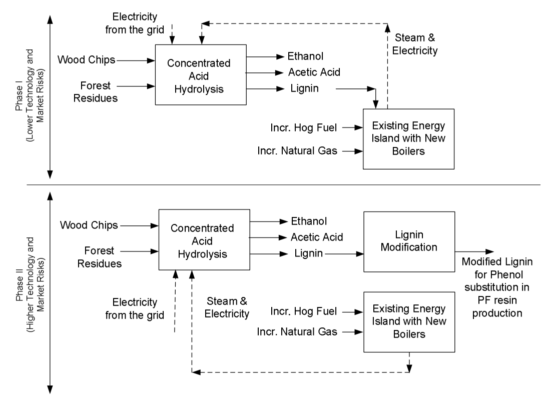



(d)

**Figure 4-14 Designed Phase I and Phase II for each biorefinery candidate: (a) Alt.1. Lignin Precipitation (b) Alt.2 Organosolv Treatment, (c) Alt.3: Fast Pyrolysis (d) High Concentrated Acid Hydrolysis**

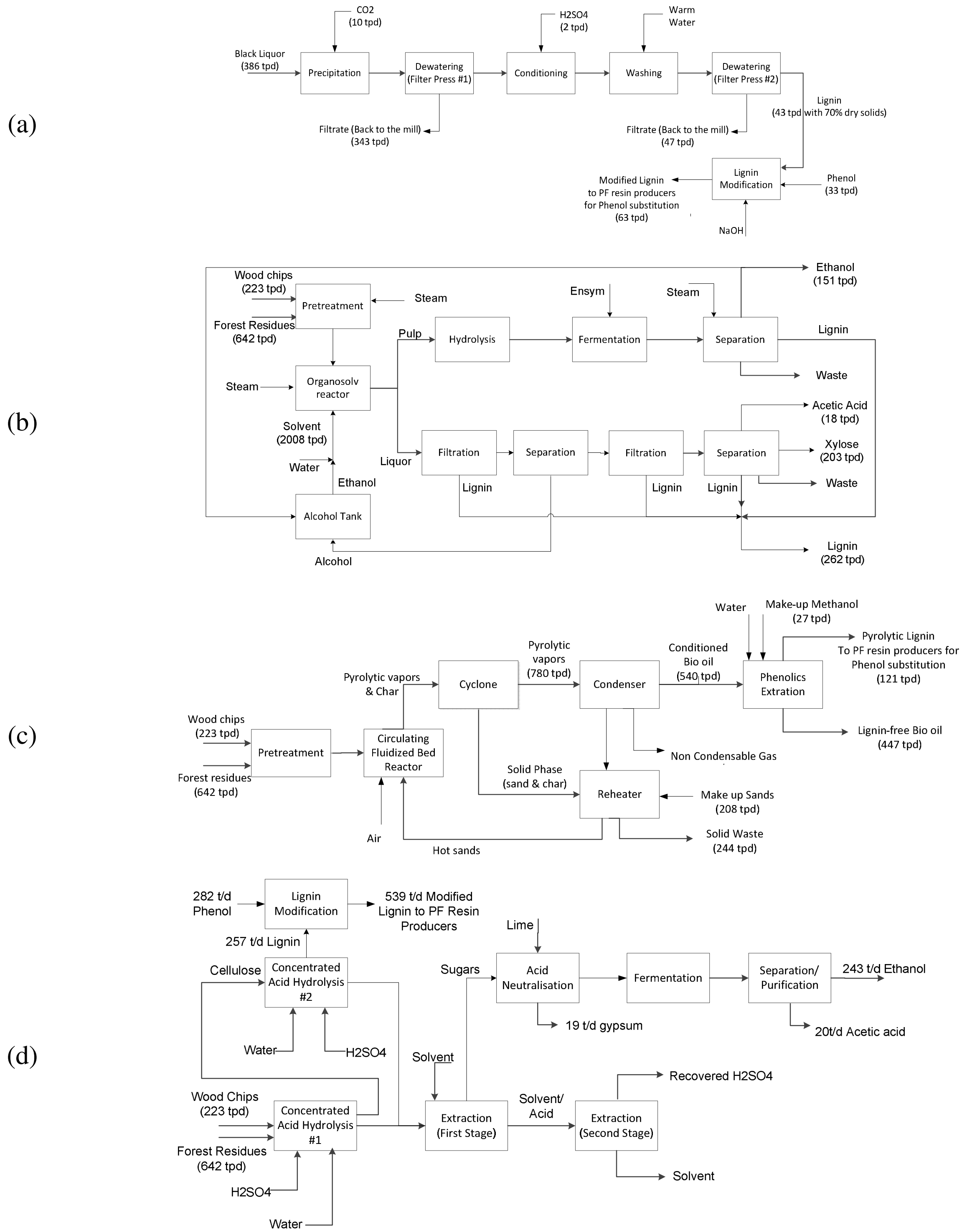



**Figure 4-15 Simplified process flow diagram for the Phase II of (a) Alt.1 Lignin precipitation, (b) Alt.2 Organosolv Treatment, (c) Alt.3 Fast Pyrolysis, (d) Alt.4 Concentrated Acid Hydrolysis**

### 4.3.2.3 Integration potentials

In a retrofit biorefinery context, there are several possible integration potentials with the existing facilities at the mill, which can mainly be categorized in three process, biomass and product sectors.

The major potential integrations in each of the mentioned sectors has been identified as follows:

- Potential integrations in process sector:
    - Energy island
    - Leftovers at the mill
    - Waste water treatment
    - Landfilling
    - Unused equipments
- Potential integrations in biomass sector:
    - Harvesting synergies
    - Material handling system
- Potential integrations in product sector:
    - Revenue diversification
    - Supply chain synergies

Each of these integration potentials and their associated costs are investigated in detail and presented in Appendix C. In this section a summary of one of the main component of each sector is briefly presented.

***Potential integrations in energy island***

The energy balance of the pulp production line shows that in winter time as the worst case, the consumption of high, medium and low pressure steam is respectively about 15, 91 and 215 t/h which all is provided by the existing energy island at the mill. Moreover, electricity consumption at the mill is about 30 MW while the energy island supplies more than this demand. Depending on the season the amount of excess electricity would be in the range of 2.5 MW to 7 MW. Taking all these into consideration, it could be concluded that the studied mill is almost energy self sufficient.

In order to identify how best the biorefinery plant can have benefit from the exiting energy island at the mill, the types and the capacities of currently available boilers were identified. The configuration of the existing energy island is shown in Figure 4-16. The existing boilers at the mill include: (1) a pretty new recovery boiler which is currently working with 75% of its nominal capacity and produce 290 tph steam, (2) two power boilers (90% of their energy is provided by hog fuel and the rest by natural gas) which totally have the nominal capacity of about 120 tph steam generation that are used mainly in winter time with 50% of their nominal capacity, (3) two gas boilers (working with natural gas) with the total nominal capacity of about 140 tph which are currently unused at the mill. In addition to these boilers, there were two turbines at the energy island including a back pressure turbine with the maximum capacity of 36 MW electricity production and a turbine with the maximum capacity of 15 MW electricity production. Taking this information into account and estimating steam and electricity consumption for each candidate biorefinery technology, integrated energy island has been designed. As an example the configuration of the integrated energy island has been illustrated for Alt.2 in Figure 4-17.

Based on the designed integrated energy island, the amount of incremental fuel that should be fed to the boilers was estimated. In design perspective, for energy consumption at the mill always winter time as the worst case has been taken into account. However for the design purpose, for incremental fuel consumption the average of mill's fuel consumption at winter and summer time has been subtracted from the total fuel consumption in integrated energy island.

Among the candidate biorefinery strategies, fast pyrolysis technology is the only option with no energy integration with the mill due to the energy self sufficiency of this technology.

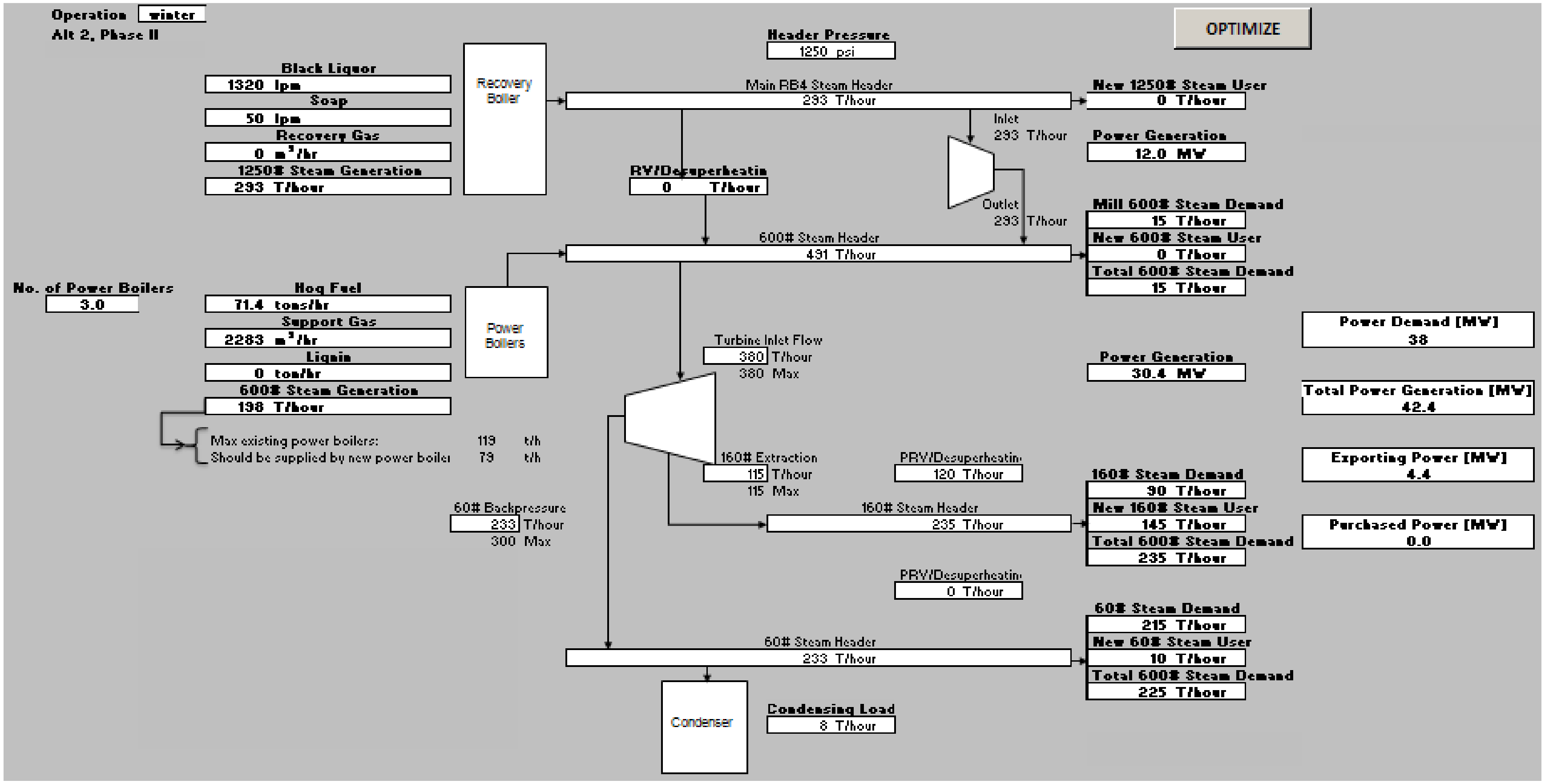



**Figure 4-16 Integrated energy island in Alt.2, Phase II**

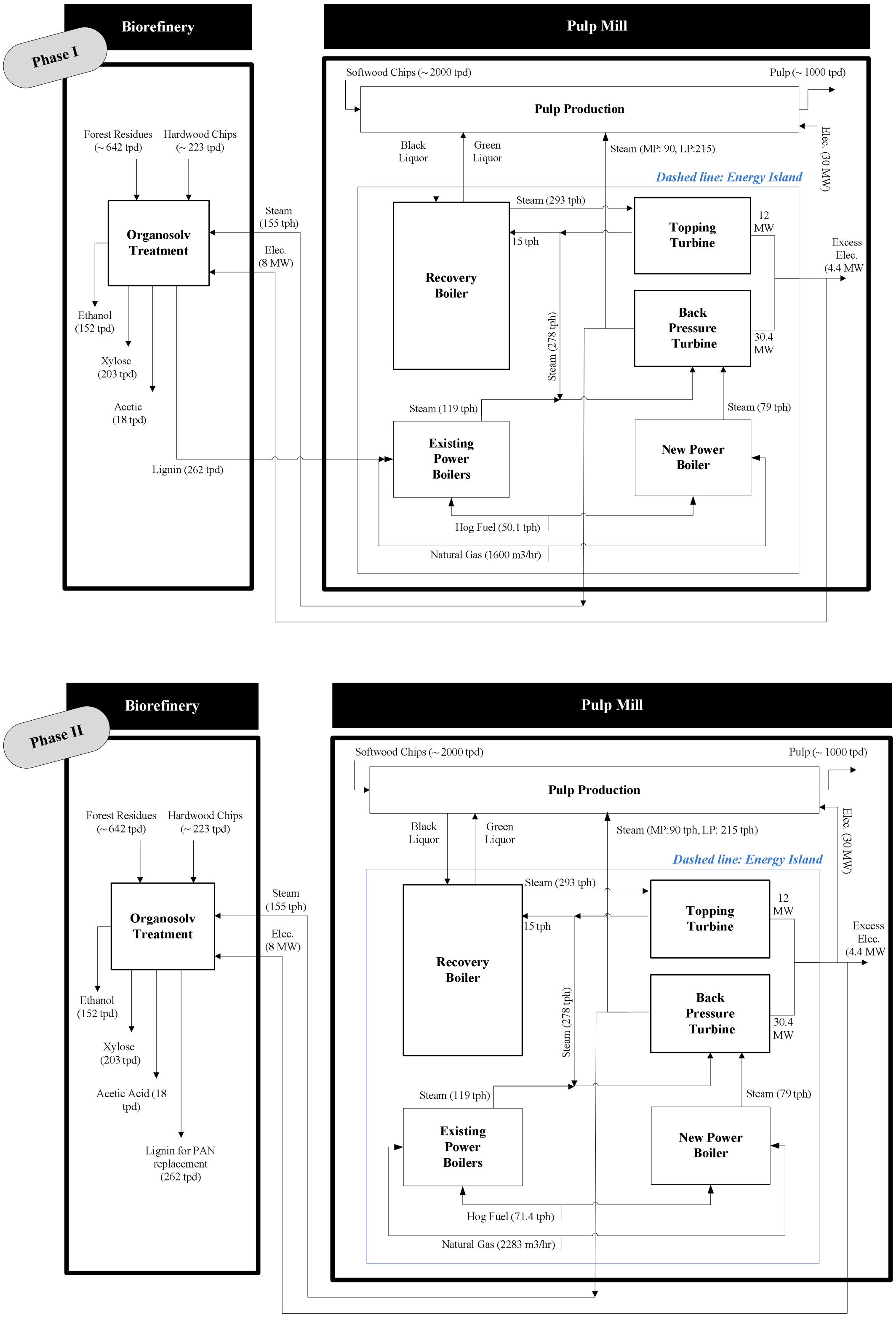



**Figure 4-17 Energy integration between the biorefinery process and the mill**

The results of energy integration for all the alternatives can be found in Table 4-4.

**Table 4-4 Energy and fuel consumption of biorefinery alternatives**

| Phase I | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Biorefinery Elec. Cons. (MW) | Biorefinery Steam Cons.[a] (tph) | Inc. HF Needed (t/h)[c] | Inc. NG Needed ($m^3$/h)[c] | Burnt Lignin (t/h) | Excess Elec. (MW)[c] | New boiler /No. |
| Alt.1 | 1.2 | 0 | 19.4 | 880 | 0 | 3.5 | No |
| Alt.2 | 8 | LP:10, MP:145 | 42 | 1600 | 11 | 4.4 | Yes/1 |
| Alt.3 | 3.8 | 0 | 8.1 | 0 | 0 | 3 | No |
| Alt.4 | 12.6 | LP:19 MP:110 HP: 62 | 54.2 | 1992 | 11 | -0.2[b] | Yes/2 |
| Phase II | | | | | | | |
| | Biorefinery Elec. Cons. (MW) | Biorefinery Steam Cons.[a] (tph) | Inc .HF Needed (t/h) | Inc. NG Needed ($m^3$/h) | Burnt Lignin (t/h) | Excess. Elec. (MW) | New boiler /No. |
| Alt.1 | 2.2 | 0 | 19.4 | 880 | 0 | 2.5 | No |
| Alt.2 | 8 | LP:10, MP:145 | 63.3 | 2383 | 0 | 4.4 | Yes/1 |
| Alt.3 | 4.8 | 0 | 8.1 | 0 | 0 | 2 | No |
| Alt.4 | 13.2 | LP:19 MP:110 HP: 62 | 75.6 | 2676 | 0 | -0.8[b] | Yes/2 |

HF: Hog Fuel
NG: Natural Gas
LP: Low Pressure Steam
MP: Medium Pressure Steam
HP: High Pressure Steam

a: Energy consumption has been estimated by process simulation and also the information provided by technology providers.
b: Negative value shows the amount of needed electricity which can not be provided at the mill and should be bought from the grid.
c: The cost of hog fuel, natural gas and electricity is assumed respectively about 30 $/t,0.017 $/m3 and 68.6 $/MWh

### *Material handling system*

The available biomass at the studied mill which can be supplied through seven forest lands around the mill in a 240 km radius includes hard wood chips and forest residues. Forest residues would consist of softwood and hardwood waste (chipper bark and limb) and hardwood roundwood waste (roundwood limbs and tops). The capacity of each type of available biomass along with its delivered cost at the mill gate is presented in Table 4-5. The estimated biomass price comprises biomass purchased cost, load, transportation and stumpage cost estimated by the biomass procurement experts at the mill.

Existing material handling system at the mill mainly includes scales, two dumpers, two stackers and conveyor system. Due to the risk of mixing softwood used for pulp production and hardwood which will be fed to the biorefinery plant, their material handling system should be essentially separated. As the possible synergies, the existing scales can be shared between these two plants, while just one more dumper should be added to the two existing dumpers at the mill, in addition a new stacker and a new feeding system (conveyors) would be needed to feed required biomass to the future biorefinery plant. Taking this into accounts, 11 MM$ as the cost of new dumper, new stacker and also new feeding system has been addressed in economic analysis for the capacity of biomass.

**Table 4-5 Biomass availability supplied by seven forest lands around the studied kraft mill**

| Biomass Type | Capacity (gmt/day) | Annual bone dry | Capacity (odt/day) | Average price ($/gmt) |
|---|---|---|---|---|
| | Wet basis | | Dry Basis | |
| 1. Wood Chips | | | | |
| Hardwood Chips | 396 | 55.6% | 220 | 53 |
| Reject oversize softwood chips (existing at the mill) | ~ 5 | 61.4% | ~ 3 | Energy equivalent cost (currently burned at the mill) |
| 2. Forest residues | | | | |
| 2.1. Hardwood waste | 99 | 55.6 % | 55 | 44 |
| 2.2. Softwood waste | 835 | 61.4 % | 513 | 51 |
| 2.3. Hardwood roundwood waste | 133 | 55.7 % | 74 | 49 |
| **Total** | **1468** | **-** | **865** | - |

***Revenue diversification***

The product portfolio in each biorefinery candidate along with the incremental revenue at the mill has been presented in Table 4-6. Some ideas as possible integration potentials of biorefinery products with the existing facilities outside the mill for secondary transformation have been also suggested as future opportunities. For instance the produced bio oil via fast pyrolysis (Alt.3) can be transported to the existing refinery facilities located in a plant very close to the mill, by which bio oil can be upgraded by hydrodeoxydation for producing drop in fuel transportation fuels.

**Table 4-6 Product portfolio and the associated revenue**

| Products | Price ($/t) | Capacity (Phase II) tpd | Revenue (Phase II) MM$/y | Capacity (Phase I) tpd | Revenue (Phase I) MM$/y |
|---|---|---|---|---|---|
| **Alt.1: Lignin Precipitation** | | | | | |
| Modified lignin for phenol substitution | 1270 [a] | 63 | 26.7 | 0 | 0 |
| Carbon black | 945 | 0 | - | 22 | 6.8 |
| Excess electricity | 68.8 [b] $/MWh | 2 MW | 1.3 | 3.5 MW | 1.9 |
| Total | - | - | 28 | - | 8.7 |
| **Alt.2. Organosolv Tretment** | | | | | |
| Lignin for PAN replacement | 1556 [c] | 262 | 135.9 | 262 | - |
| Ethanol | 689 | 152 | 34.9 | 152 | 34.9 |
| Xyloe | 200 | 203 | 13.5 | 203 | 13.5 |
| Acetic Acid | 568[d] | 18 | 3.4 | 18 | 3.4 |
| Excess electricity | 68.6[b] $/MWh | 4.4 MW | 2.4 | 4.4 MW | 2.4 |
| Total | - | - | 190.1 | - | 54.3 |
| **Alt.3: Fast Pyrolysis** | | | | | |
| Bio oil | 308 [e] | 0 | 0 | 540 | 55.5 |
| Phenolics free bio oil | 240 [f] | 446.4 | 35.8 | 0 | - |
| Phenolics | 1270 | 121 | 51 | 0 | - |
| Non condensable gas | 0.0172 $/m3 [g] | 204 | 1.6 | 204 | 1.6 |
| Excess electricity | 68.6 $/MWh [b] | 2.1 | 1.1 | 3 | 1.7 |
| Total | - | - | 89.5 | - | 58.8 |
| **Alt.4: High concentrated acid hydrolysis** | | | | | |
| Modified lignin for phenol substitution | 1270 | 539.4 | 228.3 | 0 | - |
| Ethanol | 689 | 220 | 50.5 | 220 | 50.5 |
| Acetic acid | 568 | 20 | 3.7 | 20 | 3.8 |
| Total | - | - | 282.5 | - | 54.3 |

a: Applying 10% discount on the current price of phenol
b, g: Provided by the host mill
c: (Naska 2011)
d: Recent price from Global data
e: 10% less than energy equivalent price of heavy fuel oil
f: energy equivalent price after removing phenolic compounds

### 4.3.2.4 Economic and competitiveness assessment

A set of economic and competitiveness criteria previously identified as the important criteria, are first adjusted based on the summarized suggestions in section 4.3.1.8, and are then considered in this case study. They are introduced in Table 4-7.

***Economic criteria***

In economic perspective, three conventional economic criteria have been considered in this study including Internal Rate of Return (IRR) representing project profitability, Return on Capital Employed (ROCE) showing investment efficiency and Total Capital Investment Cost (TCI) representing capital intensiveness of the project. Moreover, four unconventional criteria are added to the list of decision criteria which include Downside Economic Performance (DEP) representing project robustness under poor market condition for products in order to address market risks, Short-term Business Viability (SBV) representing profitability of Phase I , Phase I Implementation Capability (PIC) representing capability of targeted biorefinery strategies to be implemented at the mill in order to address technology risks and Resistance to Supply Market Uncertainty (RTMU) representing project sensitivity to the market price of energy and chemicals as two main components of production cost in biorefinery context. These new criteria are more described as following.

Given the risk associated with volatility in the market price of bioproducts, a minimum level of economic viability of the project must be possible under poor market condition assuming that such condition would last for a finite time in the order of months. The reason is that investors should consider their ability to sustain cash flow for that finite period of time. In the current thesis, this concept has been introduced through DEP criterion in which poor market condition is defined as the lowest annual product portfolio value over the last five years, expressed on a monthly basis. This has been evaluated in monthly basis for some products and yearly basis for more emerging products considering the fact that monthly basis data are not publically available for the emerging products. It is assumed that this poor market condition would last for one third a year while for the rest of the year market would be at its normal condition. This criterion is measured in terms of the averaged margin created in a year, considering both poor and normal market condition former lasting for one third and latter for two third of a year.

Taking into account the risk associated with emerging biorefinery strategies, profitability of Phase I as the short term strategy is a pre-requisite for investment in biorefinery. However a reduced short-term profitability would be acceptable relative to the strategic objectives. This has been addressed by SBV criterion which is defined as the profitability of Phase I when it will be proceed till the end of production length, representing the worst case scenario in which switching into Phase II can not be pursued.

Another new criterion which is defined in this thesis is PIC addressing the capability of each technology to be implemented at the full scale to be first to the market given the risk associated with project execution. PIC criterion is defined as a combination of three sub-components including (1) the level of technology maturity (in terms of largest operating plant), (2) process scalability (in terms of how much the targeted scale of Phase I is far from the designed scale of the candidate technology), and (3) the ability of implementing Phase 1 (in terms of possibility of implementation over 24 months). In order to aggregate these three sub-components, arbitrarily a weighting factor ($W_j$) has been attributed to each as of 50% for technology maturity because it is a show stopper, and 25% to each of the second and the third sub-components. This criterion has been quantified by attributing three possible numbers to each sub-component representing different levels of their performance. These numbers are 1, 3 and 5 that are respectively showing low, medium and high performance ($A_j$). For instance, for the first sub-component which is about technology maturity, if the candidate technology has been commercialized, it can get 5, if it is at demonstration scale it gets 3 and if there is only a pilot plant for that technology, it can not get more than 1. Applying this scoring approach and taking into account the attributed weights, one score ($PIC_i$) according to the following equation is obtained for each candidate technology as the value of PIC criterion.

$$\mathrm{PIC_i} = \sum_{j=1}^{3} \mathrm{W_j} \, . \, \mathrm{A_j} \tag{4-2}$$

In addition to these criteria, the RTMU criterion was also taken into account which addresses project sensitivity to raw material and energy cost fluctuations.

***Competitiveness Criteria***

In addition to economic performance, competitiveness of the candidate biorefinery strategies were evaluated through three criteria including Competitive Access to Biomass (CAB), Competitiveness on Production Costs (CPC) and Quality Revenue (QR) as the identified important competitiveness criteria. The CAB criterion defined by Diffo *et al.* (Diffo, Chambost et al. 201X) represents the potential to secure access to low-cost biomass over the long-term.

The CPC criterion represents the potential to compete on market prices against the existing producers(Diffo, Chambost et al. 201X), defined in this study as a maximum amount of discount that can be applied on the minimum existing product sales price in last five years, resulting in minimum possible margin created by the product portfolio.

The QR criterion shows the benefits on margin creation and revenue stabilization associated with added value products in a diversified product portfolio. This criterion is defined as a proportion of total revenue that belongs to the added value products.

**Table 4-7 Economic and competitiveness criteria**

| Criteria | Interpretation (result of conducted MCDM I) | Metric |
|---|---|---|
| IRR: Internal Rate of Return | IRR measures overall project profitability under normal market conditions. It should preferably be greater than a minimum target value for long-term investments and further increased relative to the riskiness of the option -Higher IRR is preferred as this represents a higher profitability. | $\mathrm{NPV} = \sum_{t=0}^{22} \frac{\mathrm{CF_t}}{(1+\mathrm{IRR})^t} = 0$ |
| DEP: Downside Economic Performance | DEP measures the financial performance of the biorefinery strategy during poor market conditions. Higher DEP is preferred as a measure of project robustness, ie that the project can survive even under unfavourable market conditions. | $\mathrm{DEP} = \left(\frac{4 * \left(\frac{\mathrm{EBIT}}{\mathrm{Revenue}}\right)_{@\mathrm{Poor\ market}} + 8 * \left(\frac{\mathrm{EBIT}}{\mathrm{Revenue}}\right)_{@\mathrm{Normal\ market}}}{12}\right) * 100$ |
| ROCE: Return On Capital Employed | ROCE measures the cash generated relative to the invested capital for a biorefinery strategy and is widely used as a measure by the investment community. It expresses the efficiency of the investment measured by how much the biorefinery strategy generates cash flow from investments. Higher ROCE is preferred because it indicates better return on invested capital. | $\mathrm{ROCE} = \frac{\mathrm{EBIT}}{\mathrm{TCI}}$ |
| RTMU: Resistance to Supply Market Uncertainty | This criterion measures sensitivity of the biorefinery margin to the cost of energy and chemicals. More robust biorefinery strategies are less sensitive to changes in energy and chemicals price and are less affected by these external sources of uncertainty. | $\frac{\mathrm{EBIT}}{\mathrm{Cost\ of\ Chemiclas} + \mathrm{Cost\ of\ ENergy}}$ |
| TCI: Total Capital Investment Costs | TCI is the amount of capital that must be raised in order to execute the project. There is a larger challenge to assemble larger capital amounts. | $\mathrm{TCI} = \mathrm{FCI} + \mathrm{WCI}$ |
| SBV: Short term Business Viability | SBV measures project profitability as IRR in the short-term under normal market conditions which supports longer term corporate transformation. Larger SBV values is preferred representing greater margin in short term which accordingly supports Phase II implementation. | $\mathrm{NPV} = \sum_{t=0}^{22} \frac{\mathrm{CF_t}}{(1+\mathrm{SBV})^t} = 0$ |
| PIC: Phase I Implementation Capability | PIC is an aggregated measure of technology risk that considers technology maturity (pilot demonstration etc), scale-up requirement to commercial scale, and ability to execute the Phase I technology in 24 months. Higher value of PIC is preferred because it represents lower technology risk in Phase I, and represents an opportunity to be faster to the market in Phase II. | $\mathrm{PIC} = 0.5 * \mathrm{Maturity\ score} + 0.25 * \mathrm{Scalability\ score} + 0.25 * \mathrm{Imlementation\ capability\ score}$ |
| CAB: Competitive Access to Biomass | CAB represents the ability to guarantee supply of biomass in competitive environment. The margin on biomass is a fundamental competitive factor related to securing feedstock over the longer-term, since it is a measure of capacity to pay more to retain cutting rights and to be competitive against other proponents seeking to use the same type of biomass. | EBITDA per ton of biomass |
| CPC: Competitiveness on Production Costs | CPC shows how competitive the biorefinery product portfolio production costs are relative to market prices (and thus pre-existing producers), and is an indication of the project to penetrate existing markets and achieve market share in the short term, to guaranty market position in the longer term. A higher value of CPC is preferred as it shows that products can be manufactured below market prices, and thus the investor can better negotiate take-off agreements to penetrate the market and gain market share. | $\mathrm{CPC} = 100\% - \frac{\mathrm{Production\ Costs}}{\mathrm{Revenue}_{@\mathrm{Poor\ market\ condition}}} * 100$ |
| QR: Quality Revenue | QR measures the ability of biorefinery strategy to maintain strong margins due to added value products in the product portfolio. The greater the value of QR as a percentage of total revenue, the stronger the biorefinery strategy. | $\frac{\mathrm{Revenue\ from\ value\ added\ products}}{\mathrm{Total\ revenue}}$ |

***Economic and competitiveness criteria evaluation***

The values of these criteria for four candidate technologies have can be found in Appendix D. These criteria are completely conflicting and thus making decision using them in order to identify the promising alternatives in terms of economic and competitiveness performance is not easy. For instance some criteria such as IRR, ROCE, CPC, DEP and RTMU shows that Alt.1 is one of least promising options while based on PIC, TCI, SBV and QR criteria, this alternative is the most preferred investment option. Therefore aggregation of these criteria is crucial enabling decision makers to rank the alternatives considering all the defined criteria simultaneously. In order to meet this objective, a relative importance for each criterion has been evaluated by conducting an MCDM panel (MCDM I).

The multi-disciplinary panel for the MCDM involved six panelists from both industry and academia with various backgrounds, including biorefinery, energy, economics, market, and environmental expertise. This could ensure that expertise in the critical dimensions that should be considered in any strategic decision-making has been captured.

In this MCDM, not surprisingly IRR criterion was selected as the most important criterion, with an average target value of 30%. Using the trade-off method, weighting factor for each criterion in this category was quantified. The obtained weights can be found in Figure 4-18.

As can be seen in this figure, the first-ranked criteria in the context of this study are Internal Rate of Return (IRR), Competitiveness on Production Costs (CPC), Phase I Implementation Capability (PIC), Downside Economic Performance (DEP) and Return on Capital Employed (ROCE). Moreover the two least important criteria in this category are Quality Revenue (QR) and Total Capital Investment Cost (TCI). The low importance of QR criterion can be explained by this fact that although the concept of this criterion is really important, in the context of the results since all the alternatives show a good performance, this criterion could not help the panelists to well differentiate the alternatives. In addition, the low importance attributed to TCI is because according to panelists' opinion, investment efficiency (ROCE) is important not necessarily the amount of money that investors should put on the table for investing in a project (TCI).

The lowest level of consensus among the panelists occurred for the SBV criterion due to disagreement among them about the metric by which this criterion has been measured. The SBV was calculated as the project profitability for the case that there would not be a chance to switch into Phase II, meaning that Phase I would continue working for a whole production length. However panelists believe that this metric can not well represent the short term profitability due to the assumed production length for Phase I which is beyond their definition for short term vision.

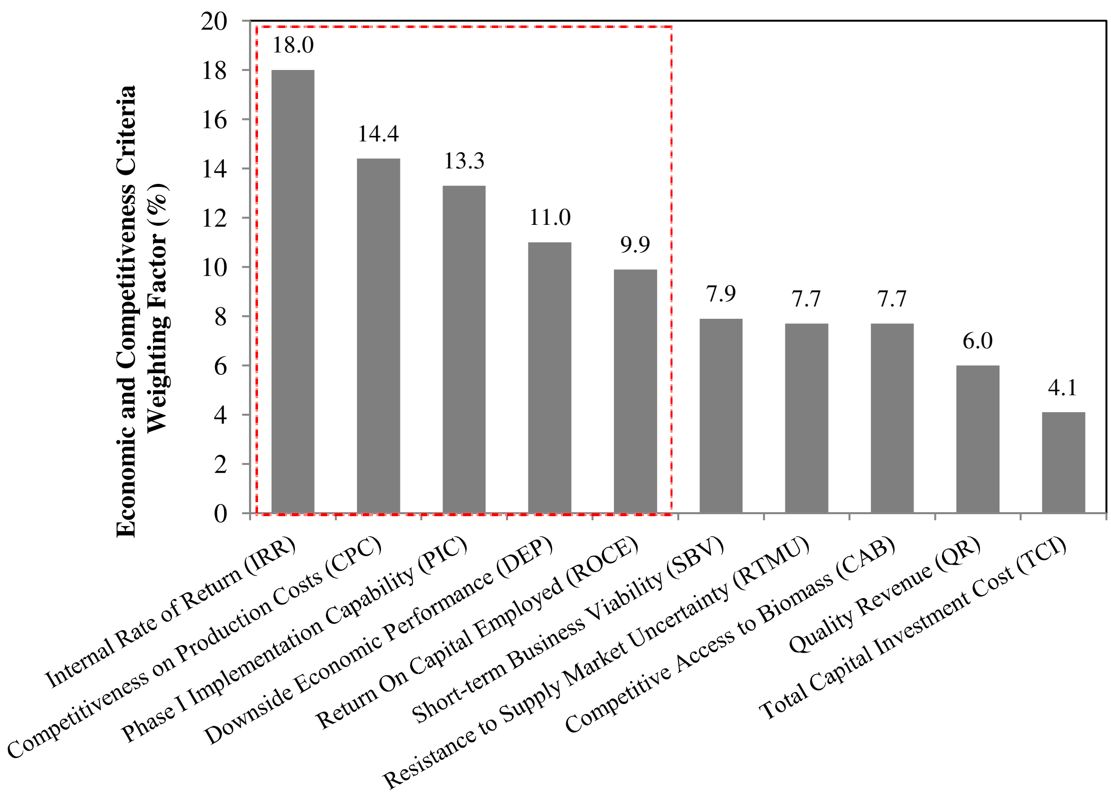



**Figure 4-18 Weighting factor of economic and competitiveness criteria**

Applying the obtained weighting factors and utility values of the criteria, economic and competitiveness score was calculated for each design alternative that is shown in Figure 4-19. These scores indicate that the least promising alternatives in terms of economic and competitiveness performance are lignin precipitation (Alt.1) and concentrated acid hydrolysis (Alt.4). The main reason that Alt.1 does not show a promising performance is that, in opposite of the common mills in Canada, the bottleneck at the studied mill is not its recovery boiler and therefore extracting lignin from black liquor would not lead to increase the pulp production capacity. The main reasons of non promising economic performance of Alt.4 are mainly due to its high operating cost as a result of considerable usage of chemicals and also its capital intensiveness.

On the other hand, the scores show that the organosolv treatment (Alt.2) and the fast pyrolysis (Alt.3) are the most preferred technologies in the context of the studied mill in terms of economic and competitiveness performance. For Alt.2 this success is mainly due to the scores coming from CPC, DEP and ROCE criteria. The high values of CPC and DEP criteria in this alternative is because even low end market condition can not dramatically influence their margin due to the high value as revenue to production cost ratio. In Alt.2 and Alt.3 the annual revenue considering poor market condition for one third of the year would be respectively 88% and 32% more than the production costs. Whereas Alt.1 and Alt.4 in which their revenue at the same condition is respectively 3% and 1% less than the production costs. In addition, although the Alt.2 is a capital intensive option, the investment efficiently represented by ROCE is considerably high due to the margin created because of high revenue coming from lignin stream targeted for PAN replacement in carbon fiber production.

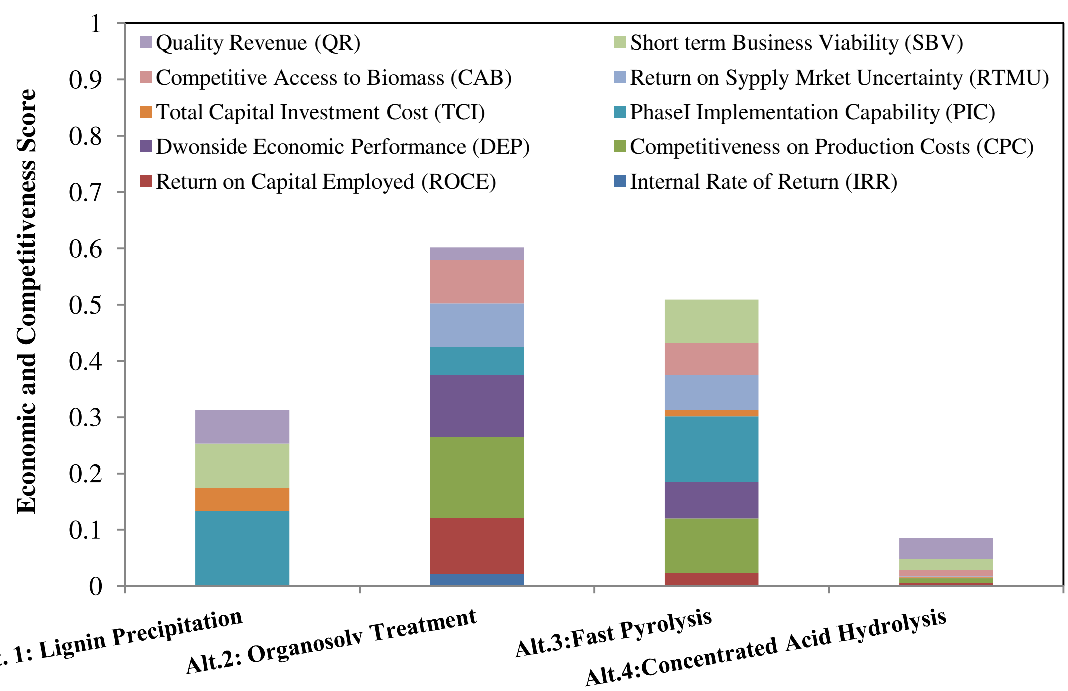



**Figure 4-19 Economic and competitiveness score of biorefinery alternatives**

#### 4.3.2.5 Environmental assessment

The environmental performance of the same strategies has been assessed by Batsy et al. (Batsy, Lesage et al. 2013) using a similar approach presented in this study by conducting another MCDM (MCDM II) with the same panelists. Similarly, the main objective of that MCDM was to attribute a relative importance to each environmental criterion in order to identify the most important environmental criteria and consequently to rank the alternatives in terms environmental performance. Eight environmental criteria were defined including Greenhouse Gas emission (GHG), Non-Renewable Energy Consumption (NRE), Respiratory Organics (RO), Carcinogens (C), Ionizing (I), Respiratory Inorganics (RI) and Water Turbined (WT). The MCDM results show that among these eight criteria, three of them were selected by the panelists as the most important environmental criteria in the context of this study that can be used then with the selected economic and competitiveness criteria for the purpose of sustainability assessment. These selected environmental criteria are Greenhouse gas emissions (GHG), Non-Renewable Energy (NRE) and Respiratory Organics (RO) respectively with 33%, 23.6% and 15.7% relative importance. The interpretation of this set of important environmental criteria and their values for four studied alternatives are presented in Appendix D.

Ranking the alternatives in terms of environmental performance shows that most environmental friendly option is high concentrated acid hydrolysis while it was the least preferred option in economic and competitiveness perspective. This shows that ranking the alternatives in terms of each sustainability pillar is quite conflicting. It justifies the necessity of considering these two sets of criteria at the same time and making a decision by aggregating them into a unique index as sustainability performance.

#### 4.3.2.6 Sustainability assessment

The five selected most important economic and competitiveness criteria as a result of MCDMI plus three selected most important environmental criteria as a result of MCDM II employed for sustainability assessment of the candidate strategies. This set of eight sustainability criteria were used in the third MCDM with the same panelists. The trade-off activity in this panel resulted in relative importance of the sustainability criteria presented in Figure 4-20 using which biorefinery alternatives could be ranked in terms of their sustainability performance in deterministic condition (Figure 4-21).

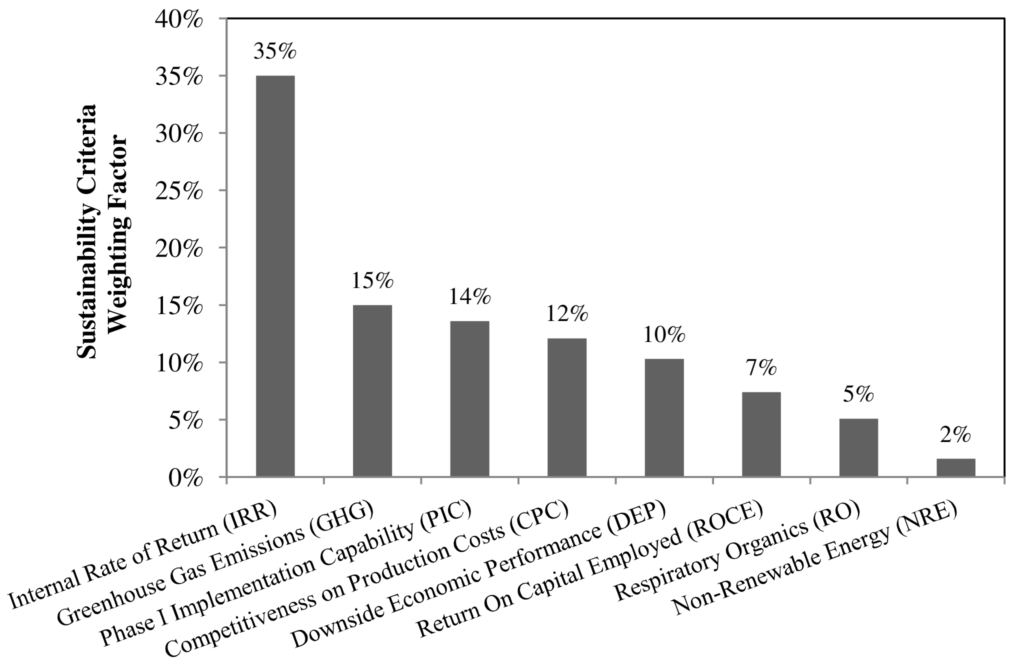



**Figure 4-20 Weighting factors of sustainability criteria**

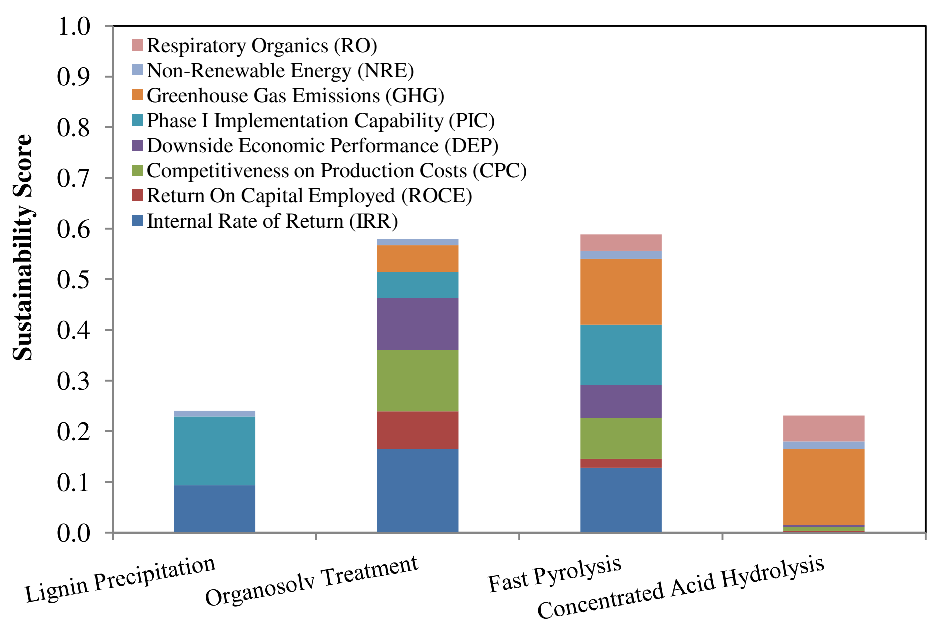



**Figure 4-21 Sustainability score of biorefinery alternatives**

Interestingly, the two first-ranked criteria were the criteria that had already been selected as the most important criterion in their own category through previously performed MCDMs: IRR in the economics-driven MCDM (MCMD I) and GHG in the environmental-driven MCDM (MCDM II). This exercise demonstrates that despite the conventional mentality about making decisions based only on profitability-oriented criteria, other criteria such as environmental criteria, competitiveness criteria and also non conventional economic criteria addressing technology and market risks are very important to be considered for making strategic decisions. These criteria can be even more important than some conventional economic criteria, such as ROCE.

Another conclusion that can be drawn from these results is that despite of conventional procedures that determine the relative importance of the decision criteria just based on their concept, both the concept and the context of the results are critical to be considered for determining the relative importance of the decision criteria. For instance, although NRE is really important in its concept to be considered in any sustainability assessment, in this study it has obtained a very low weighting factor. This has happened because all the alternatives in this study show much better performance than the acceptable level for NRE, and this is why the panelists believe that NRE can not help them for distinguishing between the alternatives.

The evaluated overall sustainability scores show that by considering the environmental criteria, the score of fast pyrolysis alternative is increased in a way that it would be almost equally preferred as organosolv treatment. Whereas taking just economic and competitiveness performance into account, that could end up with identifying the organosolv treatment as the most preferred option. In the case of high concentrated acid hydrolysis, despite of its promising environmental performance, it remains non promising option in terms of sustainability due to its poor economic and competitiveness performance. Thus, lignin precipitation and concentrated acid hydrolysis are the two non-sustainable alternatives that can be screened out from the list of promising transformational strategies for the studied mill.

#### 4.3.2.7 Critical analysis

In this part of thesis, a new set of decision criteria were defined in the context of integrated forest biorefinery, then were refined into a set of important criteria and at the end were aggregated into a unique sustainability index using MCDM approach.

Successfully applied decision making methodology in the retrofit forestry-based biorefinery context could provide the required information to compare this context with the greenfield agricultural-based biorefinery strategies in order to identify the driving forces of each for investing in biorefinery projects.

The results in this thesis show that although in greenfield agricultural-based biorefinery context, generally added value product platforms (PLA and biocomposite) seem more profitable than commodity product platform (ethanol), producing commodity products still can be profitable for investors. However in retrofit forestry-based context, biorefinery strategies can be successful only if they target added value products otherwise they would not be profitable. This difference can be attributed mainly to the difference between biomass price in these two contexts. Lower price of agricultural residues can justify profitability of greenfield agricultural-based biorefinery strategies that target large volume commodity products. In contrast forestry biomass is much more expensive at large volume because we need to go further away from the mill in order to supply a large volume of forest residues which can drastically increase its transportation cost which consequently increases the biomass price.

Although so far sustainable biorefinery strategies could be identified in deterministic condition, there is always a high level of uncertainty associated with information at the strategic level of design, which can cause decision fail if it is ignored in project selection. Thus for making a realistic decision, sustainability decision making should be done under uncertainty and also taking into account risk attitude of decision makers. However, this has not been addressed in the methodology presented in this section which is the main limitation for it. In order to address this issue, the next section in this thesis has been designed.

### 4.3.3 Sustainability assessment of biorefinery strategies under uncertainty

This part of thesis summarizes what has been presented in Article 5 to show how decision making process in evolved by addressing uncertainty.

There are three natures of data uncertainty evaluation among the defined decision criteria in study including (1) data uncertainty in quantitative economic and competitiveness criteria, (2) data uncertainty in semi-qualitative criterion (PIC) representing technology risk and (3) data uncertainty in environmental criteria.

The main source of data uncertainty in first group is market uncertainty in terms of uncertainty in price of the input variables (e.g, biomass price, products sales price, etc.), and uncertainty in the estimated investment cost, as the inputs to techno-economic model. However the nature of data uncertainty in PIC as the only semi-qualitative criterion is different. In deterministic condition PIC was evaluated as a combination of three sub-components each quantified by three scores of 1, 3,5 respectively representing the low, medium and high performance. In order to address uncertainty in evaluating this criterion, all the possible combinations of attributed scores (1,3,5) to its sub-components has been considered ending with obtaining the all possible values for PIC. Despite of economic and competitiveness criteria, the source of data uncertainty in environmental criteria is uncertainty in mass and energy balance data as the input to LCA-based environmental analysis model.

This thesis does the best to address all these uncertainties realistically and practically.

#### 4.3.3.1 Economic and competitiveness analysis under uncertainty

The uncertainty in economic and competitiveness analysis mainly comes from the uncertainty in market-based input data to the techno-economic model including biomass price, products sales price, energy and chemicals price besides uncertainty in estimated investment cost.

***Uncertain variables***

According to the presented methodology in Chapter 3, as the first step for uncertainty analysis, uncertainty ranges are forecasted through developing three perspectives. In the biorefinery context, due to difficulty of predicting minimum and maximum possible values for the variables because of the rare and sparse information in this field, considerable efforts for data gathering and data interpretation is needed for having meaningful forecasted numbers. It can be a whole activity itself however in this thesis it has been addressed using the available information and also having discussions with several experts in this field. As a result, for each variable three market prediction models have been identified based on three of pessimistic, optimistic and realistic perspectives. This will make decision makers sure that these numbers can capture all possible market models that may happen in future of biorefinery. For each variable, three numbers for each perspective are required including minimum possible, most probable (modal) and maximum possible value. As an example, Table 4-8 demonstrates this approach for forest residues price as one of uncertain economic variables in this thesis, in which numbers are presented in terms of increase or decrease compared to the deterministic value. This approach has been applied to all identified uncertain variables in techno-economic model which include: wood chips price, forest residue price, fuel price (hog fuel an natural gas), chemicals price, estimated capital investment cost, sales price of lignin-based products (phenol, PAN, carbon black) and sales price of commodity products (ethanol, acetic acid, C5 sugars).

**Table 4-8 Forest Residues Forecasted Price Scenarios**

| Forest Residues Price | Value | | Justifications |
|---|---|---|---|
| Deterministic | 83.3 $/bdt | | Provided by the studied mill |
| Pessimistic Perspective | Min | 0% | Market model:<br>• In future generation of biorefinery, more technologies would be adapted to convert low quality biomass (residues) to bio products. This is why the demand for forest residues would increase and consequently its price would increase.<br>• Biomass price would increase dramatically due to activating biorefinery projects leading to more competitiveness on access to biomass<br>• Increase in fossil fuel price would cause increase in harvesting cost and consequently it ends with increase in biomass price<br>• Legislations (food-to-fuel) causes increase attention to lignocellulosic biomass which leads to an increase in the price due to increase in competitiveness.<br>• More social acceptance (increased interest in using waste material and increase in demand of green products) leads to increase in price.<br>• More governmental support can cause increase in biomass price in future in paper companies perspective (e.g in Ontario: target is no coal in 2015- they stabilize biomass price at the price of coal for utilities- Government can make the biomass price competitive because of decrease in biomass price but at the same time increase in demand will cause increase in price!)<br>• If nuclear and alternative power (including hydrogen economy) demand for bioenergy would diminish, the demand of biomass would increase and consequently the price of it goes up. |
| | Modal | +40% | |
| | Max | +80% | |
| Realistic Perspective | Min | -20% | Market Model:<br>• Biomass price will have the same variation that have had in last 5 years |
| | Modal | 0% | |
| | Max | +20% | |
| Optimistic Perspective | Min | -45% | Market Model:<br>• Alternative biomass (MSW) will be more consumed in future (competitiveness): if technologies can be adapted to use this cheap feedstock it can lead to dramatic decrease in the price of forest residues.<br>• More mature harvesting technologies in future leads to decrease the cost of biomass preparation which ends with lower price of biomass.<br>• More governmental support for using waste materials can cause decrease in biomass price in future. |
| | Modal | -15% | |
| | Max | +20% | |

***Sensitivity analysis***

Using the identified minimum and maximum possible value for each variable, a sensitivity analysis was performed for each candidate alternative to investigate that how much IRR (as the most important criterion) value is changed by changing each variable. As an example, Figure 4-22 shows the results of sensitivity analysis for organosolv treatment (Alt.2). In this figure the number on two sides of each bar represents the minimum and maximum possible number for each variable. As can be seen in this figure among all uncertain variables, four of them including lignin price, forest residues price, ethanol price and hog fuel price are the most important variables that changing them could result in considerable decrease or increase (more than 2% ) in IRR value.

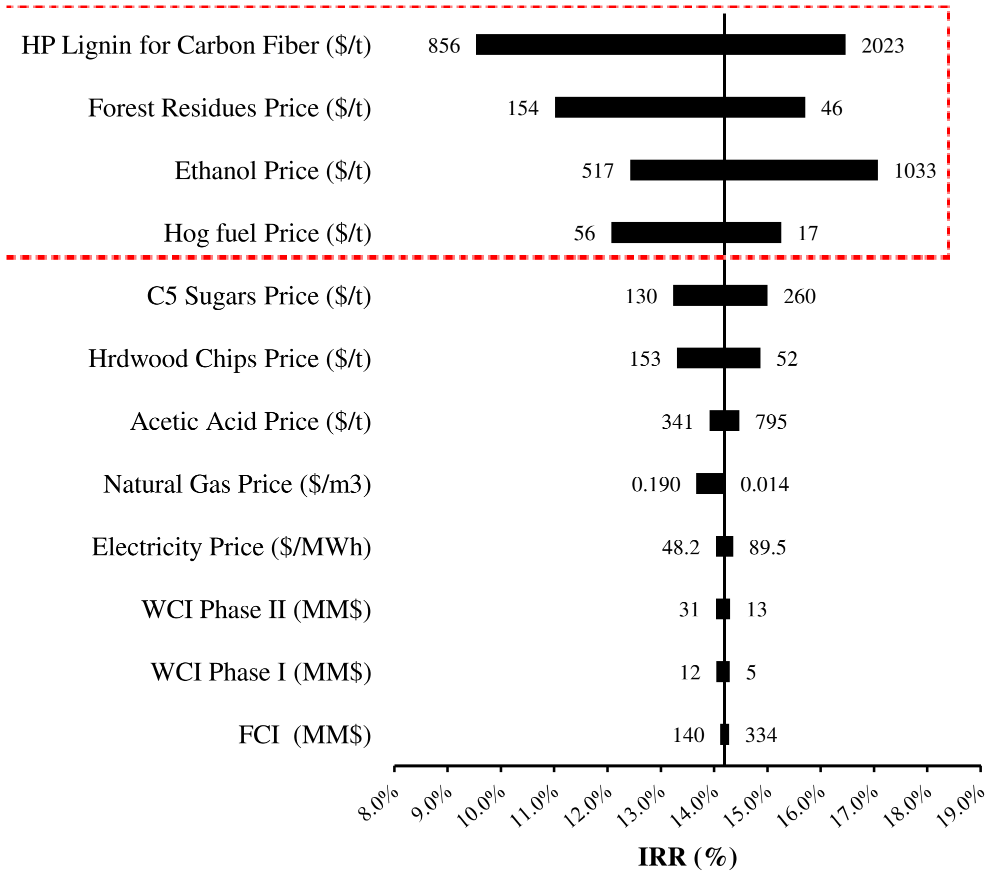



**Figure 4-22 Sensitivity analysis of organosolv treatment (Alt.2)**

The results show that in lignin precipitation (Alt.1), four variables including hog fuel price (17 to 55 $/t), phenol price (729 to 1778 $/t), natural gas price (0.014 to 0.19 $/m3) and carbon black price (520 to 1229 $/t) are the most important uncertain variables. The important uncertain variables in fast pyrolysis (Alt.3) option include bio oil price (231 to 462 $/t), fixed capital investment cost (109 to 233 MM$), forest residues (46 to 154 $/t), phenol price (729 to 1778 $/t) and natural gas price (0.014 to 0.19 $/m3). The important uncertain variables in the case of concentrated acid hydrolysis (Alt.4) are ethanol price (517 to 1034 $/t), forest residues price (46 to 154 $/t) and phenol price (729 to 1778 $/t).

***Monte Carlo Analysis***

After identifying the important uncertain variables in each technology following the previous step, it should be investigated that how much all decision criteria would be affected by changing these important uncertain variables. This will be done by Monte Carlo analysis. The first step in this method is developing probability distribution function of each uncertain variable. Given the minimum available information about the uncertain variables, triangular distribution function as one of the simplest type of distribution functions has been selected in this study. For each variable three triangular distribution functions are developed based on pessimistic, realistic and optimistic perspectives according to the following equation:

$$P(x) = \begin{cases} \dfrac{2(x-a)}{(b-a)(c-a)} & a \le x \le c \\ \dfrac{2(b-x)}{(b-a)(b-c)} & c \le x \le b \\ 0 & \text{otherwise} \end{cases} \qquad (4\text{-}3)$$

Where a is the minimum possible value, c is the most likely (modal) value and b is the maximum possible value.

In Figure 4-23, green, blue and black distribution functions respectively represent the optimistic, realistic and pessimistic perspective for forest residues price as one of identified important uncertain variable. However in Monte Carlo method just one distribution function is required for each variable. Thus these three distribution functions need to be aggregated.

***Aggregation of probability distribution functions***

Among the available aggregation methods, linear opinion pool has been used in this study. This method needs to attribute weighting factor to each distribution. In order to prevent over emphasizing the extreme mentalities (pessimistic and optimistic), in this thesis higher weight has been considered for realistic perspective (60% importance) whereas optimistic and pessimistic perspective that 20% importance has been given to each. In Figure 4-23, probability distribution function shown in red is a result of aggregating three distribution functions.

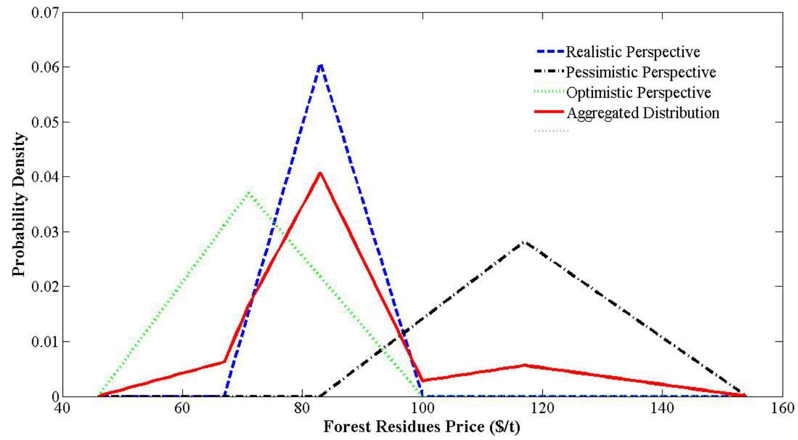



**Figure 4-23 Probability distribution function of forest residues price as an uncertain variable**

***Sample generation (rejection sampling method)***

In Monte Carlo method in each iteration, a random value should be generated from each uncertain variable using which the objective function (decision criteria) can be evaluated. Generating random values from a conventional distribution function can be simply done using the reverse of cumulative distribution function (CDF). However the aggregated probability distribution function of the uncertain variables in this thesis has an unconventional form. There are different techniques for sample generation from unconventional distribution functions among which in this thesis Rejection Sampling (so called Acceptance-Rejection) method has been chosen. This method would generate samples from the unconventional and complex distribution (p(x)) using a simpler distribution (q(x)) which is called target distribution function, where $p(x)<M*q(x)$ and $M>1$. The target distribution is normally a uniform distribution function at maximum density of the studied unconventional distribution function. The procedure that is followed in this method is that at first a random value (x) is taken and the ratio of its density based on the studied distribution (p(x)) and the target distribution (Mq(x)) is obtained. Then a random value (u) between zero and one is taken, if the calculated ratio would be higher than u, the generated random x is accepted otherwise it would be rejected. This sampling method is applied on all variables of each biorefienery alternative. Figure 4-24 shows an example of the generated samples on all important uncertain variables for organosolv treatment option (Alt.2).

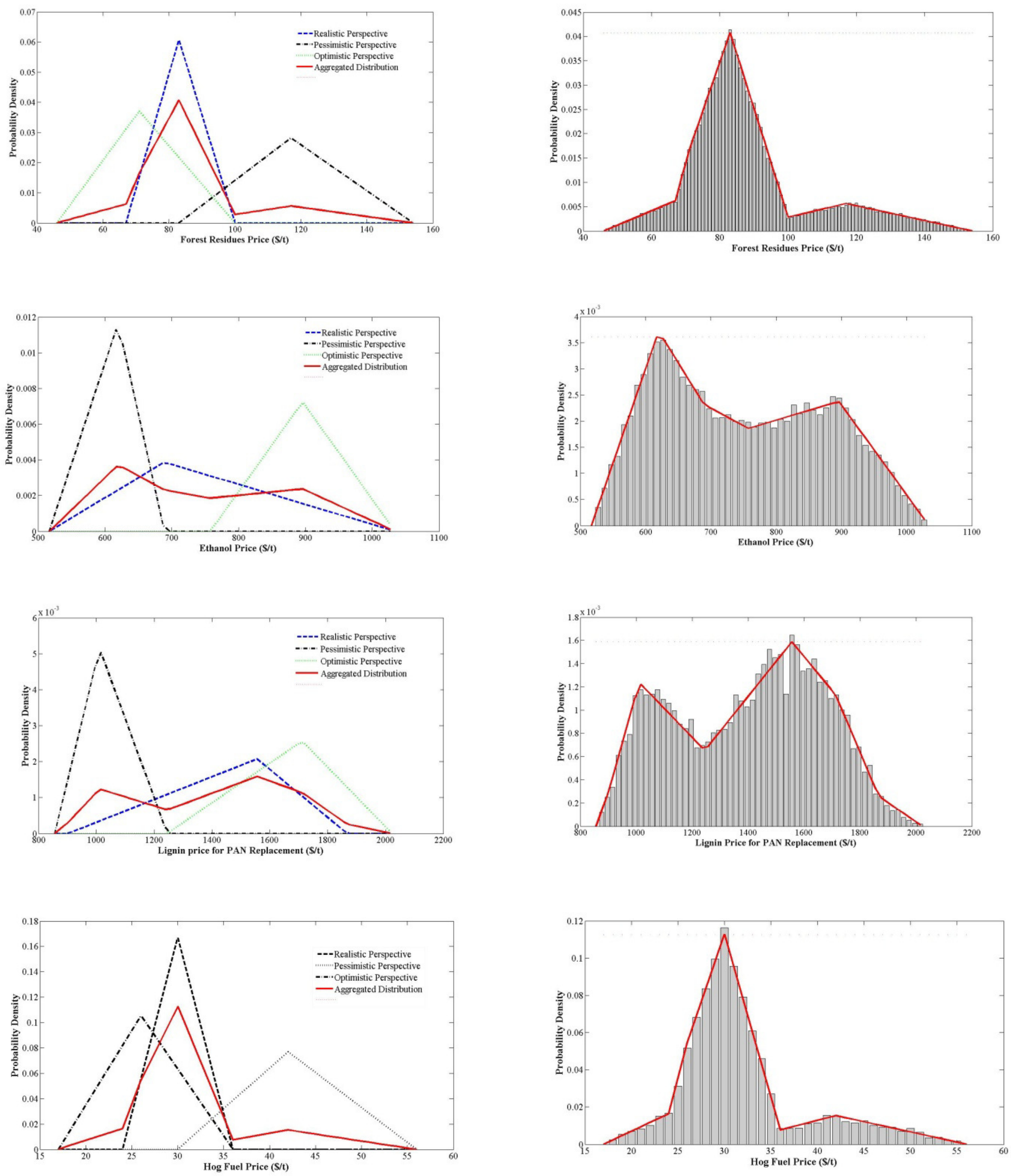



**Figure 4-24 Distribution functions of important uncertain variables (left side) and the generated samples from aggregated distribution function (right side), both for organosolv treatment option (Alt.2)**

***Probability distribution functions of decision criteria***

Depending on the level of required accuracy, the number of iteration in Monte Carlo analysis is changed normally from 1000 to 10000 iteraions. In order to decrease computational time, in this thesis, 1000 iterations are applied. In Monte Carlo method, using the random values generated from uncertain variables, in each iteration all economic and competitiveness criteria are evaluated and finally presented as probability distribution function. The results show that all economic and competitiveness criteria are not necessarily normally distribution. Some of them have skewed tail on one side. The best type of distribution that could fit well with the observed pattern was Weibull distribution with the following formula:

$$f(x, \lambda, k) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^{k}} & x \geq 0 \\ 0 & x < 0 \end{cases} \tag{4-4}$$

As an example, probability distribution function of IRR for organosolv treatment (Alt.2) is shows in Figure 4-25.

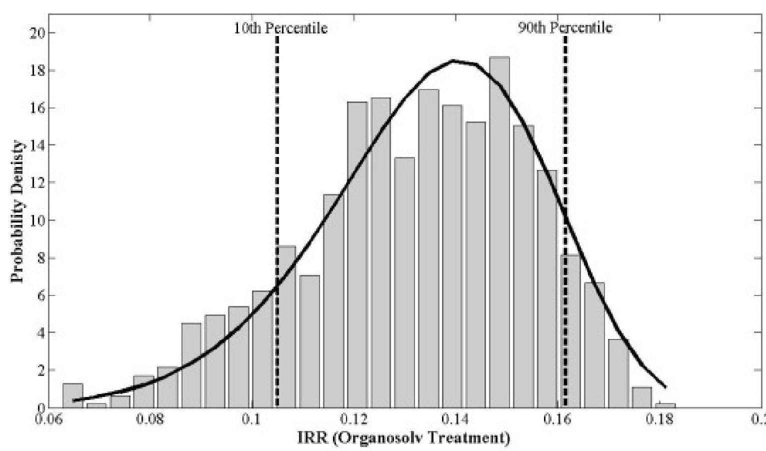



**Figure 4-25 A sample of probability distribution function of Internal Rate of Return (IRR) as an economic/competitiveness criteria for organosolv treatment (Alt.2)**

### 4.3.3.2 Environmental analysis under uncertainty

The data uncertainty in economic analysis was mainly due to the uncertainty in market data, while the source of uncertainty in environmental assessment belongs to mass/energy balance data. Batsy et al. (Batsy, Lesage et al. 2013) evaluated a set of environmental criteria under uncertainty for the same biorefinery alternatives assessed in this study, using Monte Carlo analysis in SimaPro software for developing probability distribution function of the environmental criteria. In order to develop probability distribution function of the uncertain mass/energy input data, a minimum and a maximum possible value to each input value has been attributed according to the level of uncertainty associated with it depending on where it has been extracted. Using a triangular distribution function for these input variables, probability distribution function of the environmental criteria has been developed. As can be seen in Figure 4-26, the type of distribution function that could fit well is lognormal distribution function.

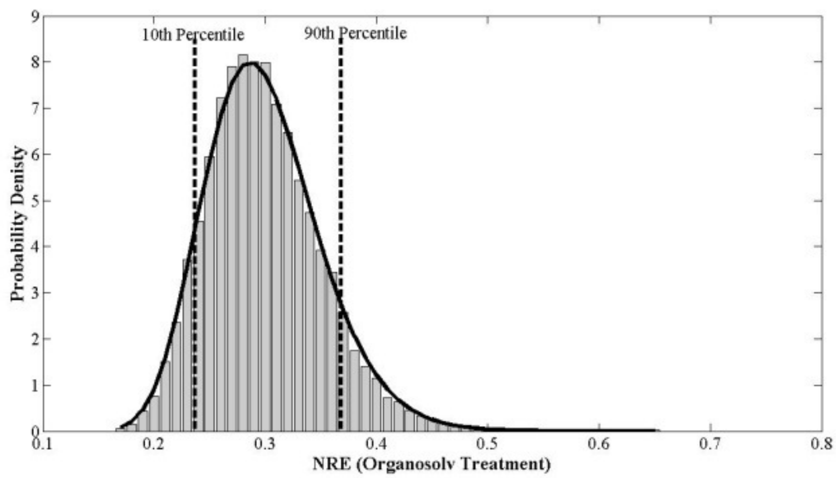



**Figure 4-26 A sample of probability distribution function of Non-Renewable Energy as one of environmental criteria for organosolv treatment (Alt.2) (Batsy, Lesage et al. 2013)**

### 4.3.3.3 Decision making under uncertainty

After developing probability distribution function of all decision criteria, they have been used in an MCDM panel (MCDM IV) in order to investigate how much involving uncertainty in evaluated criteria can change the relative important of the criteria in decision making process.

The distribution function of eight sustainability decision criteria for all four biorefinery alternatives are shown in Figure 4-27. This figure clearly shows that making decision directly using all these distribution functions is not straightforward.

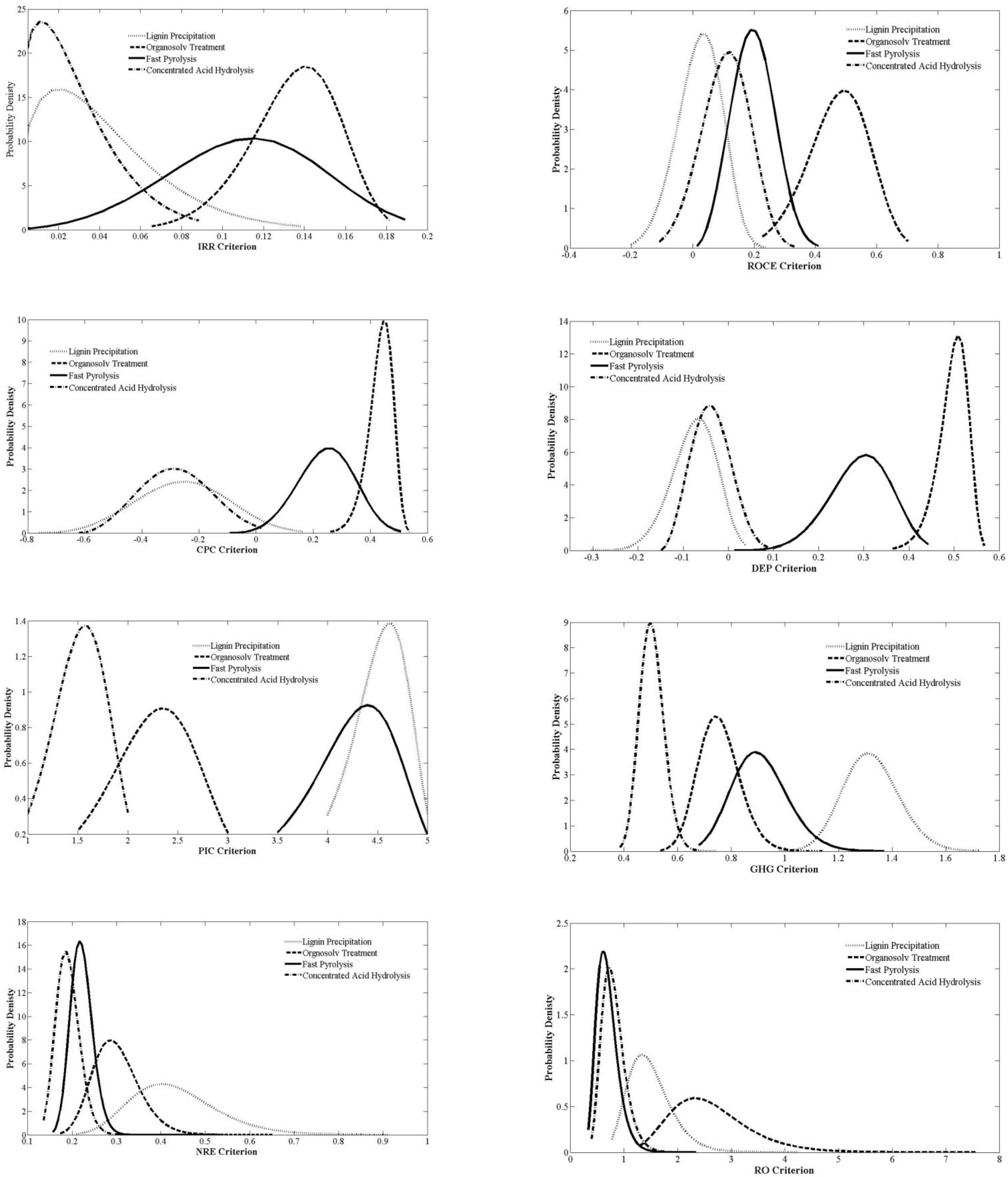



**Figure 4-27 Distribution functions of the sustainability decision criteria for all four biorefinery alternatives**

Instead of presenting all these distributions to decision makers, in order to make these information more interpretable, just three values from each distribution function has been extracted including the most probable (modal) criterion value, maximum probable value at 90% percentile and the value at 10% percentile as minimum probable value resulting in the plots shown in Appendix E. Those results were used in an MCDM panel to evaluate the relative importance of decision criteria under uncertainty.

The results of panel activity show that weighting factors of the criteria are completely changed after addressing uncertainty in the evaluated decision criteria.

As can be seen in Figure 4-28, in deterministic condition panelists had chosen IRR as the most important criterion, however after looking at the criteria values under uncertainty, they changed it into ROCE. The main reason is that the minimum and maximum probable values of IRR show that there is a considerable overlap between IRR values of some alternatives (Alt.2 with Alt.3 and Alt.1 with Alt.4) and therefore they are not as distinguishable as they were in deterministic condition. Thus, although IRR was still very important for the panelists in terms of its concept, considering the context of the results in uncertain conditions, IRR is not anymore the best criterion to help decision makers differentiating the alternatives. Therefore they chose ROCE that likewise is a profitability-oriented criterion and helps decision makers in differentiating between the alternatives due to the lower level of overlap between the alternatives. Not only for the most important criterion, but also for some other criteria, relative importance has been changed. For instance quantifying uncertainty in PIC as a semi-qualitative criterion could give a clearer picture of this criterion that could make panelists more sure that although this criterion may not be as precise as a quantitative criterion, nothing is missing in evaluating it after involving uncertainty. Thus the relative importance of it has been increased in some extent.

Among the decision criteria, the relative importance of NRE, RO and DEP is not changed. The reason for NRE criterion is that, even considering the minimum and maximum probable values, still all alternatives are much below the lower bound (100%) meaning that they all show a very good performance in terms of this criterion and thus using NRE would not help panelists to distinguish between the alternatives. Therefore they have given the same weighting factor they had given to it before. The weighting factor of RO shows that panelists has not increased its importance mainly because the large bars in this criterion shows the high level of uncertainty in

RO values influencing panelists not to change the low weighting factor they had given to this criterion in deterministic condition. In deterministic condition using DEP criterion, panelists could well distinguish the alternatives which still is consistent after addressing uncertainty. This is why they have not changed the relative importance of this criterion.

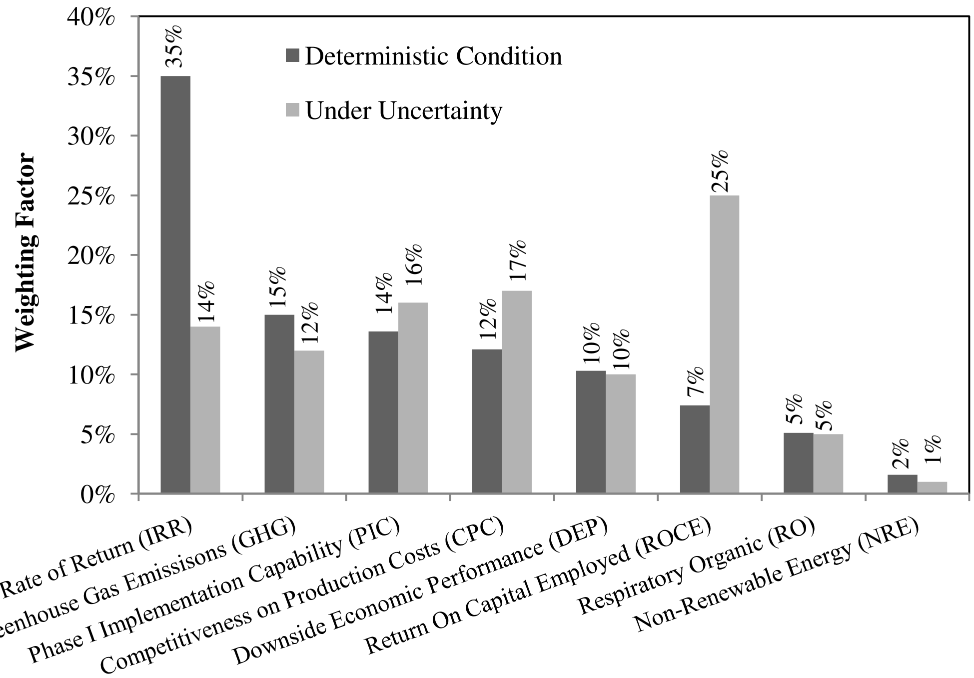
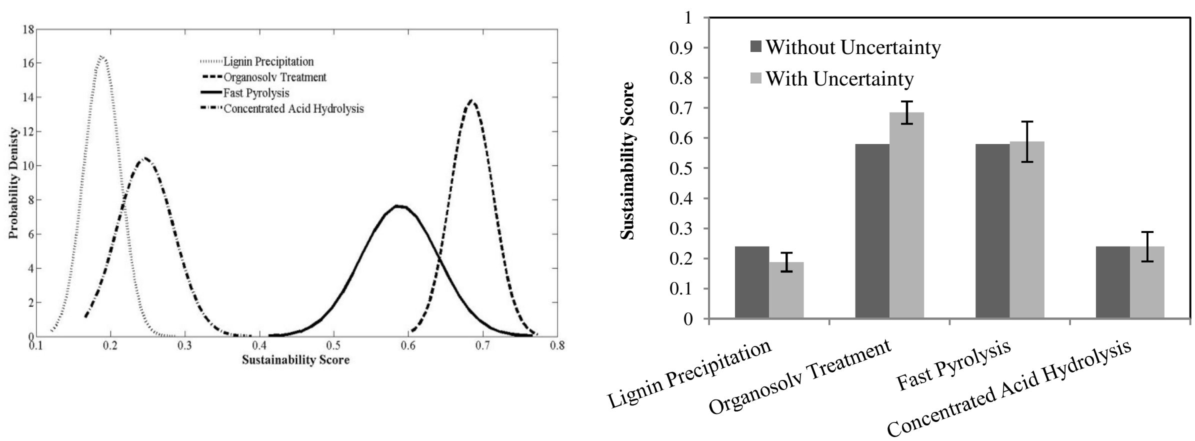



**Figure 4-28 The effect of considering uncertainty on the weighting factors of the sustainability criteria**

The low standard deviation associated with given numbers to NRE criterion, implies a high degree of consensus on selecting this criterion as the least important criterion in the context of this study.

Using the obtained weighting factors and employing evaluated utility value of the decision criteria in each iteration of Monte Carlo, sustainability score of the alternatives is evaluated in each iteration that are shown in Figure 4-29(a). As can be seen in this figure, there are two distinct categories of alternatives including sustainable alternatives (Alt.2 and Alt.3) with higher sustainability scores (between 0.5 to 0.75) and less sustainable alternatives (Alt.1 and Alt.4) having lower sustainability score (between 0.15 to 0.3). In order to investigate that how much the ranking of the alternatives in terms of sustainability has been affected by incorporating uncertainty in decision making, three values are extracted from each probability distribution function shown in Figure 4-29(b) including the modal value and minimum (10% percentile) and maximum (90% percentile) probable values. As can be seen in this figure, new rankings confirm that lignin precipitation and concentrated acid hydrolysis are not promising biorefinery transformational strategies in the context of the studied mill, which is consistent with the results in deterministic condition. Although in deterministic condition, promising alternatives including organosolv treatment and fast pyrolsyis were not distinguishable in terms of sustainability score, addressing uncertainty in sustainability evaluation, shows that under any circumstances, organosolv treatment option will have better performance than fast pyrolysis for the context of the studied mill. The reason is that, the maximum possible sustainability score of the fast pyrolysis option is almost the same as minimum possible sustainability score of the organosolv treatment alternative.




(a)

(b)

**Figure 4-29 Sustainability score of the biorefinery alternatives under uncertainty**

Figure 4-30 shows contribution of each decision criterion in sustainability score of the alternatives, comparing the results in uncertain condition with deterministic condition.

In one hand, the drastic decrease in IRR weighting factor resulted in decrease in the score of almost all alternatives except Alt.4 in which IRR did not have any contribution in sustainability score in deterministic condition, because this alternative had the minimum IRR value among the alternatives and so its utility value was zero. In another hand, increase in weighting factor of

ROCE resulted in an increase in contribution of this criterion in the sustainability score of almost all alternatives except lignin precipitation (Alt.1) in which utility value for this criterion is zero because this alternative has the minimum ROCE value among the others. More increase in ROCE score in Alt.2 compared to Alt.3 is the main reason of higher overall sustainability performance for Alt.2. Since the utility value of this criterion for Alt.2 is higher than Alt.3, an increase in the weighting factor of this criterion could affect more its overall score.

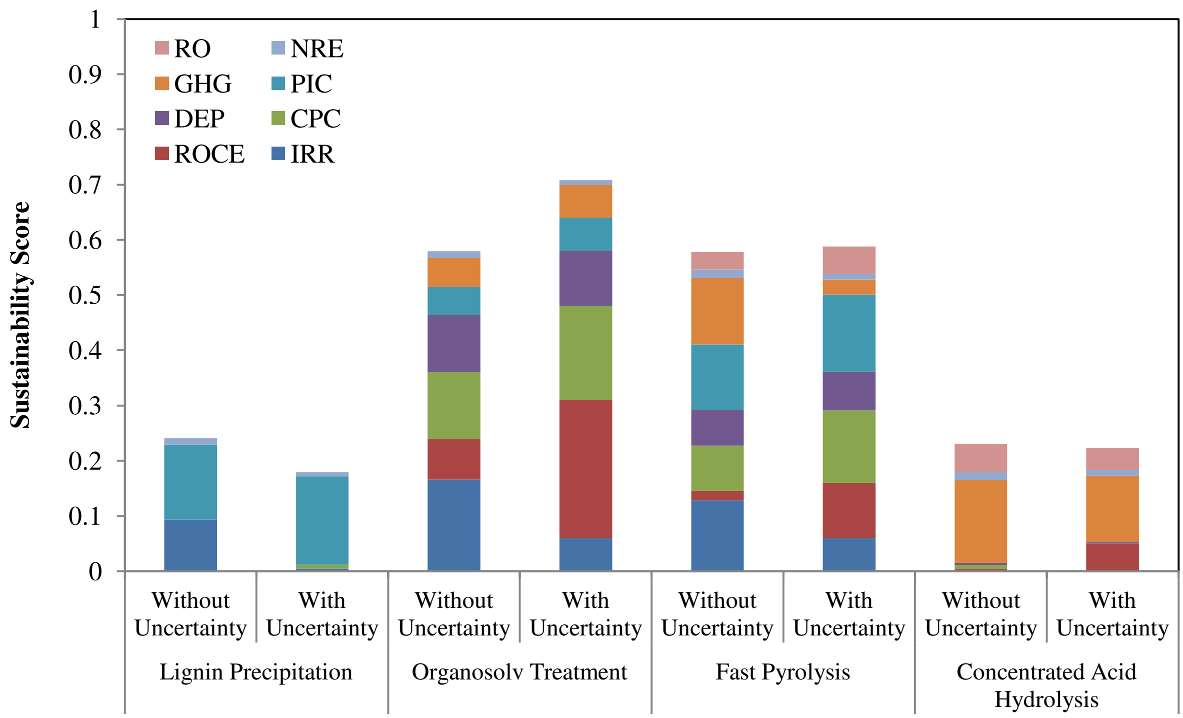



**Figure 4-30 The effect of considering uncertainty on the sustainability scores**

### 4.3.3.4 Critical analysis

The results in this section clearly showed that evaluating sustainability criteria under uncertainty gives a clear and realistic picture of the possible performance of each design alternative which can cause decision to become more transparent enabling stakeholders to make a better decision.

However the results of this section demonstrated how the relative importance of the decision criteria was affected by involving uncertainty in criteria values. For instance results showed that by addressing uncertainty in criteria evaluation, the most important criterion is switched from internal rate of return (IRR) with 35% importance in deterministic conditions, into return on capital employed (ROCE) with 25% importance. Finally addressing uncertainty in decision making could help decision makers to screen out more options at the strategic level of design, due to showing the preference of the organosolv treatment compared to the fast pyrolysis while they were equally preferred in deterministic condition. It can be concluded that involving uncertainty in strategic decision making would change the basis of design.

Uncertainty involvement caused decision become more objective which is especially important when more options are supposed to be compared.

The achievements in this section could meet a part of second sub-objective defined in this thesis.

### 4.3.4 Economic and competitiveness assessment of biorefinery strategies addressing risk attitude of decision makers

#### 4.3.4.1 Setting the preference boundaries for decision criteria

In order to develop utility function of the economic and competitiveness criteria (introduced in Table 4-7) considering risk attitude of the panelists, the panel were asked first to set a lower and an upper bound for each criterion that below the former and above the latter they would not have any preference among the alternatives.

For IRR criterion, they believe that the minimum acceptable IRR in bioeconomy should be 12% meaning that any IRR value below 12% is not good to the same extent. In addition, for a risky emerging industry like biorefinery, panelists believe that any IRR value above 25% will be good enough to convince decision makers to invest on biorefinery technologies.

For ROCE criterion, as the main indicator for the stakeholders to attract investors, panelists did not consider it at the entire enterprise level but the expected ROCE value at project level in an enterprise. Thus their boundaries (12%, 30%) are much above the ROCE value that forest products companies are currently experiencing.

Panelists believe that for added value products, capability of applying discount on products sales price is very critical in order to be competitive in the market to secure the market share. This is why they think investors should be able to give at least around 5% discount being able to compete with the competitors in the market who has provided the same product with minimum sales price within the last five years. Thus the average lower bound for CPC has been set at 5%. In addition, according to the panelists' opinion, the projects that can survive after applying more than 20% discount on products sales price are very good to the same extent, meaning that CPC's upper bound is set at 20%.

Regarding DEP criterion, they believed that the alternatives that in worst market condition are still able to make margin on their revenue (for instance 1% overall margin), they are acceptable; otherwise for any margin below 1% they are not distinguishable. Moreover, decision makers thought that creating 10% overall margin considering worst market condition for a finite period of time in a year is a dreams-come-true and any DEP value above that boundary would be all good. Taking this into account, the lower and the upper bound for DEP has been respectively set to 1% and 10%.

In order to attribute a lower bound to PIC criterion, panelists assumed minimum required level of implementation capability. For them, having a pilot scale is a pre-requisite for investing in a biorefinery technology. This means attributing score 1 to all three sub-components of PIC criterion ending with 1 as the lower bound for PIC. However for the upper bound, panelists agreed that any investment option that is at the commercial scale with the production capacity by 20% less than the designed capacity in this study will be good at the same extent even if they can not be implemented within two years. This means attributing score 5 to first sub-component of PIC with 50% importance, score 3 to second sub-component of PIC having 25% importance and score 1 to the third sub-component of PIC which has 25% importance. These scores would result in score 3.5 as the overall PIC value to be set as the upper bound.

For setting the lower bound of TCI criterion, panelists have assumed that for low capital intensive projects, investors should be able to provide at least 50% of the required investment cost. In order to evaluate the upper bound, they took into account 50 MM$ as the maximum amount that the studied forest products company can afford to invest in transformation strategies, then they assumed that this amount would be 25% of the total required capital. The reason is that for high capex projects, government may support up to 50% of the investment cost as subsidy and assuming that 25% of the investment cost can be provided by potential partners in future, the remained amount for the investor would be 25% of the total amount. These assumptions ended up with 170 and 20 MM$ respectively as the lower and the upper bound for TCI.

In order to set a lower bound for CAB criterion, panelists assumed that investors should be ready at least for 25% to 30% increase in biomass price in future. It means that in the case of this study that the most expensive biomass costs about 95 $/t, we need to be able to pay about 30 $ more per ton of supplied biomass to stay competitive for having access to biomass in future. Considering that bioeconomy would grow fast in future, most probably there would be more competitors for getting biomass which causes dramatic increase in biomass price. Thus panelists believe that any project that can pay more when at least biomass price will be almost doubled in price, will be good at the same extent.

For SBV criterion, panelists believe that since in short term normally commodity oriented strategies are targeted to be pursued, they do not expect large margin and consequently high profitability. Thus slightly below the cost of capital would be acceptable. In addition, for setting the upper bound they believe that 10% less than the upper bound of long term profitability shown by IRR criterion is acceptable that for any value above it they can not have any preference among the alternatives.

In order to set the lower and the upper bound for QR criterion, panelists made analogy with chemical and petrochemical industry. In addition, they also took into account this fact that if the revenue out of added value products will be below 40%, the product portfolio can not be considered diversified enough in the context of biorefinery industry. According to these assumptions, they selected 40% as the lower bound and 80% as the upper bound.

Although setting the boundaries of RTMU was so challenging, panelists tried to make a link between the terms used in RTMU metric with the operating costs that was more tangible for them to set the benchmark for it. Assuming that the cost of chemicals and energy is normally about 30% to 50% of the total production costs, for the alternatives with RTMU value below 1 we can conclude that the revenue would be less than 30% to 50% of the operating costs. These alternatives would not be able to create 30% to 50% profit on production cost and so they all are not favorable. In addition, panelists believe that if the profit can be almost two times more than production costs (RTMU at about 6), the alternatives would be all very interesting in a way that panelists can not even distinguish them in terms of favorability.

Based on the way environmental criteria have been assessed, the only boundary that can be set is the lower bound as 100%. It means that any biorefinery technology that would have the same or worst environmental performance compared to the competitive product portfolio would not be acceptable and its utility value would be equal to zero. However assigning an upper bound is very challenging.

#### 4.3.4.2 Lottery making for utility formulation

After setting the boundaries for each criterion, through an MCDM panel activity (MCDM V), the attitude of decision makers toward risk is assessed in order to formulate the utility function of each criterion. For each criterion panelists have been asked to imagine a risky situation in which in order to select a biorefinery project to invest on, they would be given a black box inside which there are two biorefinery projects that they must pick up one of these with the closed eyes. For example, there would be 50% chance that the project they pick up would have ROCE=12% (lower bound of ROCE) and 50% chance that it would be a project with ROCE=30% (upper bound of ROCE). Then panelists are asked to compare this risky situation with a proposed biorefinery project with a minimum guaranteed acceptable value of ROCE. They will be asked this question that “How much ROCE as a minimum guaranteed value for a proposed project would convince you not to go with the gamble and you would agree to invest on the proposed biorefinery project with a certain ROCE instead of picking up a project from that black box?”. The number of ROCE they give as the answer to this question is called Certainty Equivalent (CE) value.

For instance, a panelist who agrees to give up trying his/her chance in the gamble, and he/she accepts to invest on a proposed project with ROCE value the same as expected value in the gamble (0.5*12%+0.5*30%=21%), is a risk neutral person. Whereas a risk averse panelist who selects ROCE=18% as certainty equivalent that is lower than 21% as the expected ROCE value in the gamble. It means that he/she prefers to get even lower ROCE value but being sure about it instead of taking any risk to get higher ROCE value (ROCE=30%). In opposite, the third category of panelists who are risk prone, they prefer to try their chance to get ROCE=30% by going with the gamble even if it is risky and they may end up with ROCE=12%. They prefer it compared to getting a project with lower ROCE value but guaranteed. The CE value given by this category of decision makers is higher than the expected value. For instance, they would agree to give up going with the gamble, only if the proposed certain amount would be 29%.

Following the same procedure, lotteries were made for each criterion using the lower and the upper bounds and each panelist was asked to compare the lottery with a certain project proposal. Using the given numbers (CE values) by panelists, their attitude toward risk for each criterion has been measured. One panelist can be risk averse for one criterion and risk prone or risk neutral for another.

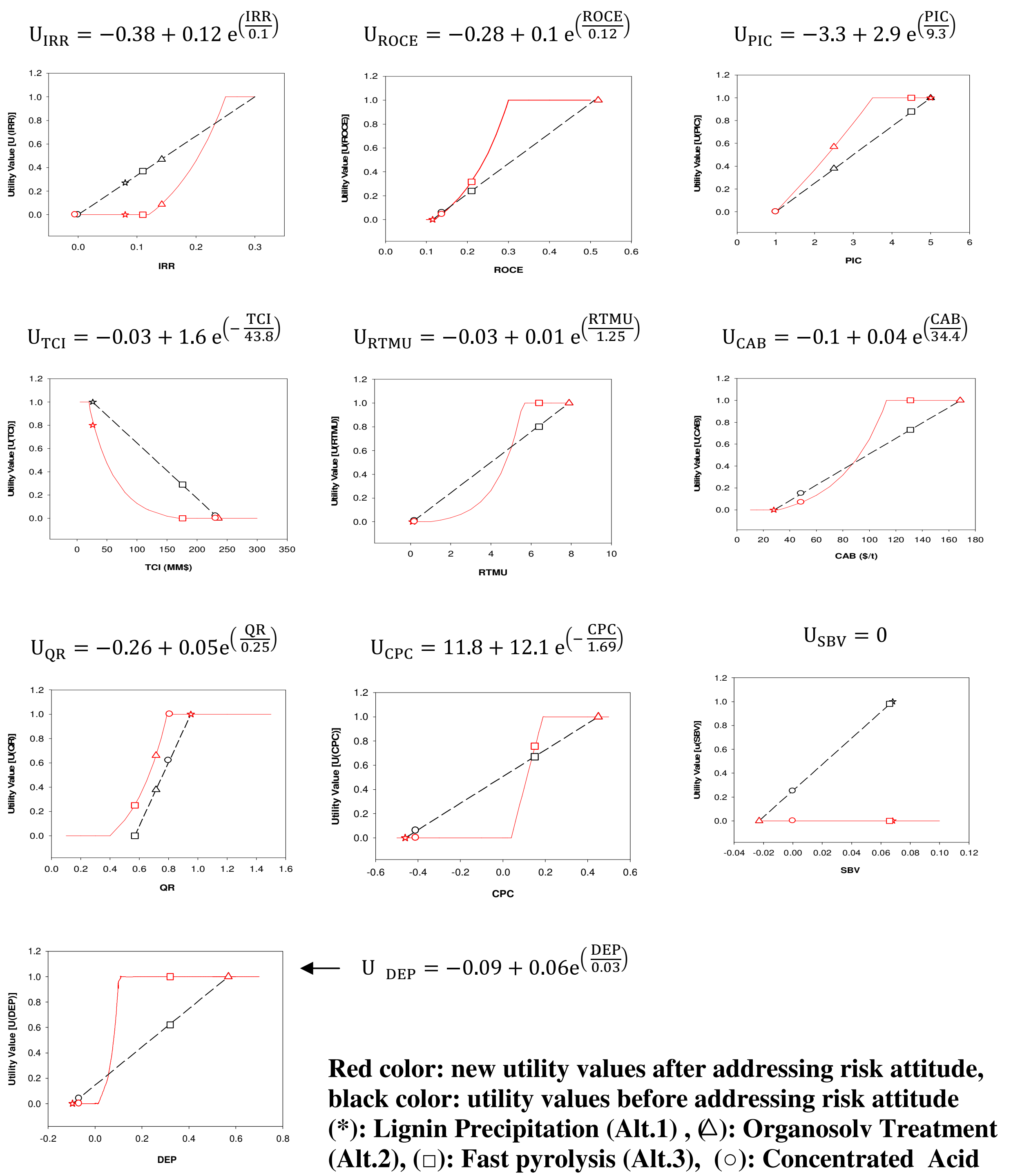
After obtaining the average CE values, the values of A and B and RT parameters are calculated based on the equations (3-6) to (3-8) introduced in Chapter 3, using which the utility functions are developed based on equation (3-5). The boundaries, CE, A, B and RT values are all reported in Appendix F.

The obtained utility functions of all economic and competitiveness criteria are shown in Figure 4-31. If we assume a line between the lower bound and the upper bound of each criterion, when the shown red curve is located above that arbitrary line, it means that decision makers are risk averse in that region. However when the shown red curve as the new utility function is located below that arbitrary line, it means that decision makers are risk prone in that region. For instance in RTMU criterion, it is clear that the red curve is below an arbitrary line that links ($x_{RTMU}$ =1, $U_{RTMU}$=0) and ($x_{RTMU}$ =6, $U_{RTMU}$ =1) respectively as the lower bound and the upper bound, meaning that decision makers are completely risk prone for this criterion. Whereas PIC criterion in which the red curve is exactly located on the arbitrary line between ($x_{PIC}$ =1, $U_{PIC}$=0) and ($x_{PIC}$ = 3.5, $U_{PIC}$ =1) meaning that decision makers are risk neutral in the context of this criterion.

Although for some criteria there were some risk averse panelists, by making the average of CE values given by all panelists, finally it has been equal (risk neutral) or higher (risk prone) than the expected value. Thus none of red curves presented in Figure 4-31 shows a risk averse attitude. Individuals can be risk prone or risk averse, however generally there is a panel dynamic that determines the overall risk attitude of decision makers.

Among the alternatives, biggest change in utility values belong to Alt.3 in which utility value of almost all criteria except IRR, TCI and SBV, has been increased based on the new utility function after addressing risk attitude of decision makers.

Among the criteria, the dramatic change in utility values is seen for SBV criterion, in which all utility values become to zero according to the new utility function. It confirms that addressing risk attitude of decision makers can have a dramatic effect on the final decision.




**Red color: new utility values after addressing risk attitude, black color: utility values before addressing risk attitude (*): Lignin Precipitation (Alt.1) , (△): Organosolv Treatment (Alt.2), (□): Fast pyrolysis (Alt.3), (○): Concentrated Acid Hydrolydid (Alt.4).**

**Figure 4-31Utility functions of economic and competitiveness criteria**

### 4.3.4.3 Decision making

In multi attribute utility theory (MAUT) which has been used in this thesis as a decision making tool, weighting factors ($w_i$) are obtained by solving the following matrix as a result of indifferent judgment between the alternatives:

$$\begin{bmatrix} 1-u_k(x^B_{k,m=1}) & -1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 1-u_k(x^B_{k,m=N}) & 0 & \cdots & -1 \\ 1 & 1 & \cdots & 1 \end{bmatrix} \begin{bmatrix} w_1 \\ \vdots \\ \vdots \\ w_N \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} \quad \forall m \neq k \tag{4-5}$$

Where $u_k$ represents utility value of the most important criterion in each comparison. Thus these weighting factors would be changed as soon as the utility function of the most importance criterion is changed. Therefore addressing risk attitude of decision makers that affected utility function of all criteria, can indirectly affect the weighting factors likewise.

The new weighting factors of the economic and competitiveness criteria after addressing risk attitude of decision makers compared with their values in deterministic condition is shown in Figure 4-32. This figure shows that addressing risk attitude of decision makers can result in exaggeration of the difference between the relative importance of more important criteria and less important ones. It means that in the context of this study, relative importance of the criteria which had obtained higher weighting factors in deterministic condition has been increased while the relative importance of the criteria which had low weighting factors in deterministic condition has been decreased. Thus after addressing risk attitude of decision makers important criteria become even more important whereas less important criteria that become even less effective in decision making.

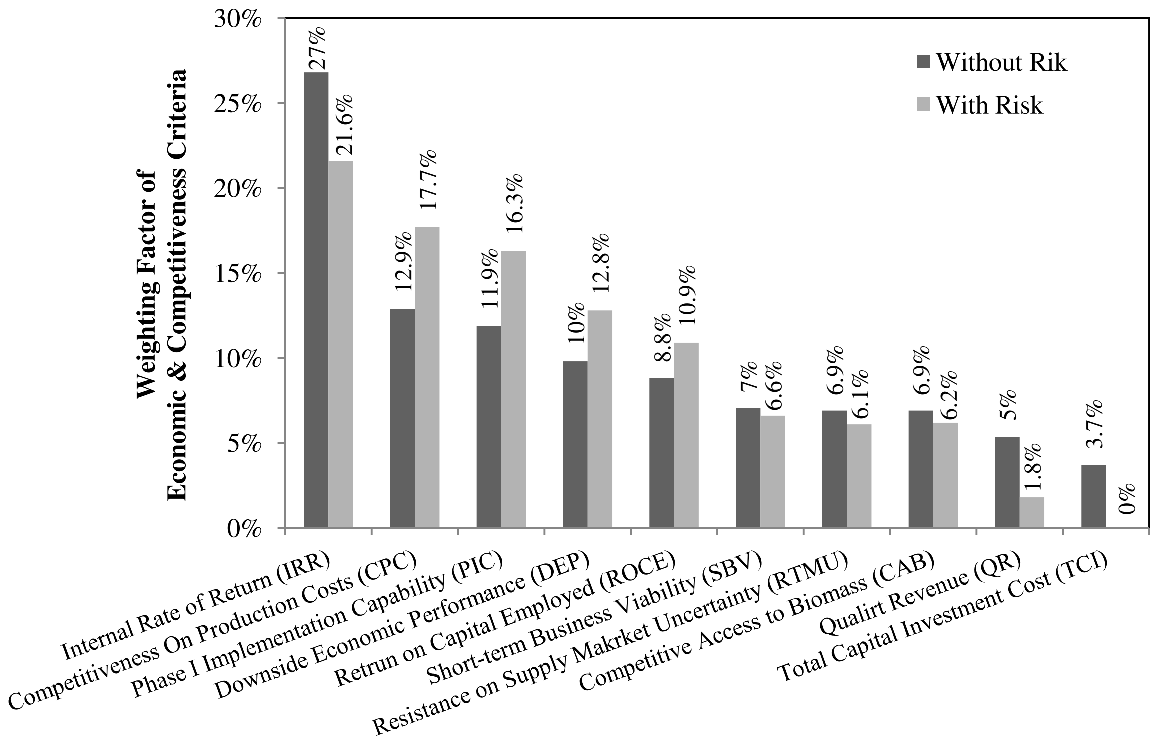



**Figure 4-32The effect of considering non-linear utility function on the weighting factors of the economic and competitiveness criteria**

Using the obtained weighting factors and utility functions after addressing risk attitude of decision makers, economic and competitiveness score of the alternatives has been calculated. As can be seen in Figure 4-33, the economic and competitiveness score of Alt.1 (lignin precipitation) is decreased considerably, for Alt.2 and Alt.3 it is slightly increased and for Alt.4 it seems almost unchanged. Since TCI weighting factor has become 0%, its contribution in economic score in Alt.1 has been eliminated. In this alternative, IRR does not have contribution anymore in the final score, because according to the new utility function for IRR, this alternative has obtained utility value equal to zero. A decrease in weighting factor of the QR criterion has resulted in decrease in contribution of this criterion in the economic score of lignin precipitation.

In all alternatives, SBV and TCI criterion do not have contribution anymore in the economic and competitiveness score. For SBV it is because utility function of this criterion has become a line at zero and for TCI the reason is that this criterion has lost its relative importance after addressing risk attitude of decision makers.

In Alt.2 (organosolv treatment) the main differences belong to the contribution of IRR and CPC in the economic and competitiveness score. The former is decreased due to decrease in utility value based on the new utility function and also decrease in IRR weighting factor. This decrease has been compensated by increase in CPC contribution due to the increase in weighting factor of this criterion in a way that at the end final score of this alternative has not been changed considerably. In Alt.3 (fats pyrolysis), the economic and competitiveness score has been slightly increased because except IRR and SBV, the utility value of all the criteria are increased according to new utility functions.

Generally it can be concluded that there are two categories of alternatives including organosolv treatment (Alt.2) and fast pyrolysis (Alt.3) as the economically promising alternatives and lignin precipitation (Alt.1) and concentrated acid hydrolysis (Alt.4) as non promising strategies in terms of economic and competitiveness performance. The difference between these two categories of alternatives has become much clearer after addressing risk attitude of decision makes.

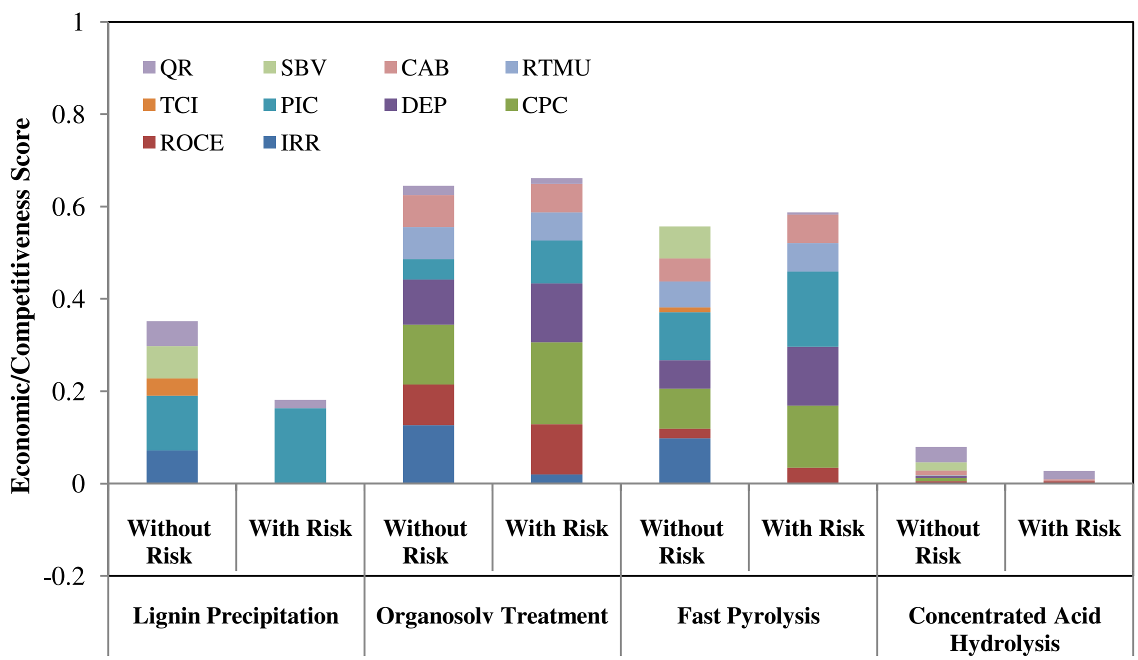



**Figure 4-33 The effect of considering non-linear utility function on Economic/Competitiveness Score**

#### 4.3.4.4 Critical analysis

The strategic decision for biorefinery selection as emerging technologies with their won associated risks, is not made by individuals but with multi disciplinary stakeholders who together can be risk averse or risk prone. In order to make a realistic and wise decision, the level of risk aversion among the stakeholders should be quantified and taken into account for strategic design decision making. This part of thesis showed how quantifying risk attitude of decision makers can affect utility function representing decision makers' preference. Based on mathematics behind MCDM, whenever utility function of the most important criterion changes, the weighting factors are changed accordingly. Thus addressing risk attitude of decision makers indirectly changed the weighting factors as a result of changing utility function. At the end, applying reformulated utility functions and also new weighting factors could help decision makers to better differentiate between non-promising alternatives and promising ones.

### 4.3.5 Sustainability assessment under uncertainty and addressing risk attitude of decision makers

It had been shown in section 4.3.3.7 that involving uncertainty in sustainability assessment can change the basis of decision making mainly due to a change in relative importance of the criteria. In addition the results of risk attitude assessment in previous section showed that addressing risk attitude of decision makers can also change the basis of decision making mainly by changing the utility function and as a consequence of it, changing the weighting factors of the decision criteria. Thus addressing the attitude toward risk can be as important as addressing uncertainty in decision making. For example if something that happened for SBV criterion in this thesis, in which utility function became zero for all values after addressing risk attitude of decision makers, will happen for several criteria, the final decision may change dramatically.

Thus, addressing both uncertainty and risk in a practical and realistic manner is crucial to guarantee the success of strategic decision making.

Applying the obtained utility function for the most important criterion on matrix calculation in MCDM IV ends with new weighting factors for sustainability criteria shown in Figure 4-34.

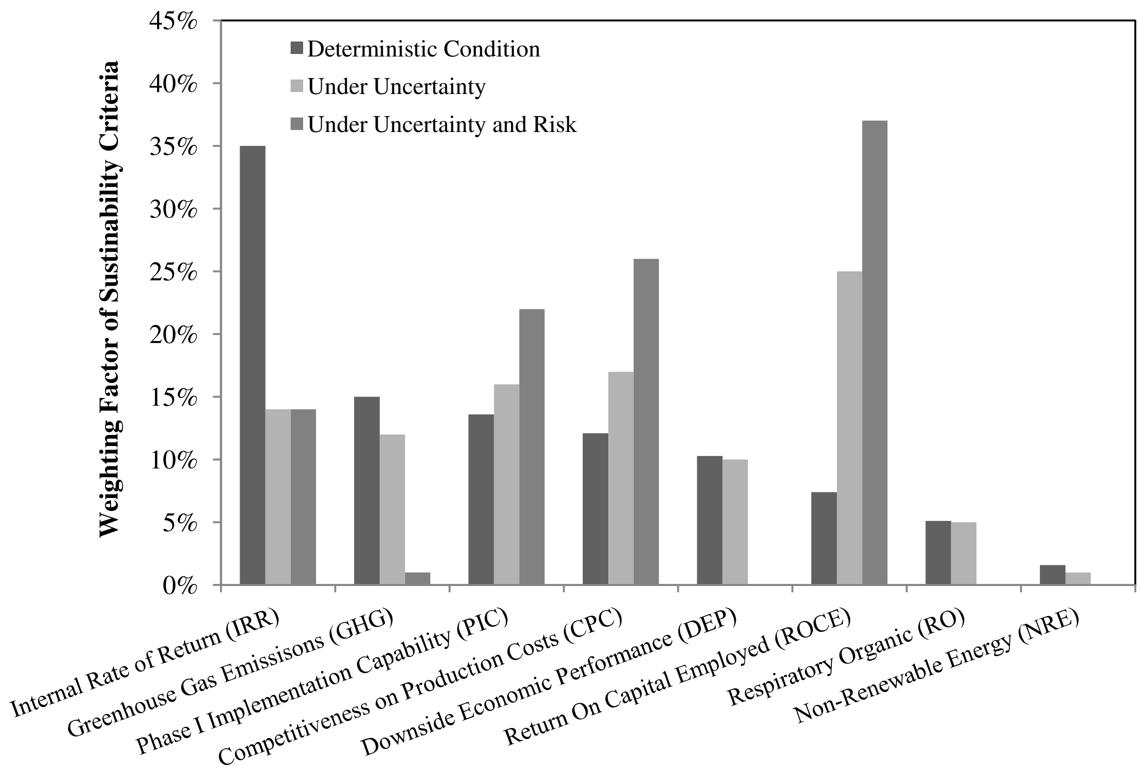
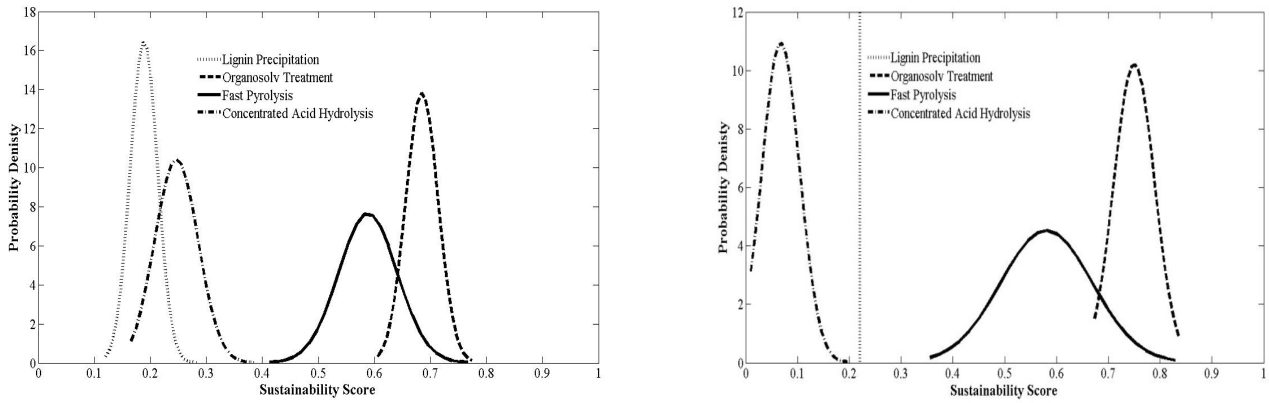



**Figure 4-34 Weighting factors of sustainability criteria after addressing uncertainty and risk**

Using Monte Carlo analysis method, in each iteration a random value is generated from the probability distribution function (PDF) of each criterion value and according to the new utility function which has been developed for each criterion it will be converted into a utility value. At the end, by applying new weighting factors of the criteria, sustainability scores of all alternatives are calculated in each iteration. This procedure will be repeated at least for 1000 iterations, and finally the results would be in the form of PDF for the sustainability score of each alternative. These PDFs are shown in Figure 4-35 in comparison with the obtained PDFs by involving just uncertainty in decision making. As can be seen in this figure involving risk attitude of decision makers on top of uncertainty analysis, could result in exaggerating the difference between the alternatives in a way that organosolv treatment (Alt.2) is more shifted toward higher sustainability score while concentrated acid hydrolysis (Alt.4) and lignin precipitation (Alt.1) are shifted toward lower sustainability scores, whereas fast pyrolysis (Alt.3) which is almost unchanged.




(a) (b)

**Figure 4-35 Probability distribution function (PDF) of sustainability scores of the alternatives (a) under uncertainty (b) under uncertainty and risk**

Extracting three values from these PDFs including the modal, minimum probable value (10% percentile) and maximum probable value (90% percentile) ends with the bars that are shown in Figure 4-36. This figure clearly shows that, although involving uncertainty in decision making, could help decision makers to better distinguish between the promising alternatives (Alt.2 and Alt.3), involving both uncertainty and risk attitude of decision makers can help even more in this regard by exaggerating the difference between these alternatives. In addition, although the differences between the non-promising options was not clear even after involving uncertainty, as soon as risk and uncertainty are both taken into consideration, the worse performance of acid hydrolysis (Alt.4) compare to lignin precipitation (Alt.1) becomes more clear.

Using the most probable value of each criterion and applying the criteria weighting factors, the contribution of each criterion in sustainability score has been shown in Figure 4-37. As can be seen in this figure, considerable increase in weighting factor of ROCE, CPC and PIC criteria and also increase in their utility values after addressing risk attitude of decision makers could cause an increase in the contribution of these three criteria in sustainability score. This huge increase could compensate the decrease in contribution of other decision criteria in a way that finally sustainability score of Alt.2 and Alt.3 is increased. In contrast, a considerable decrease in weighting factor of the GHG criterion could result in huge decrease in sustainability score of concentrated acid hydrolydid (Alt.4).

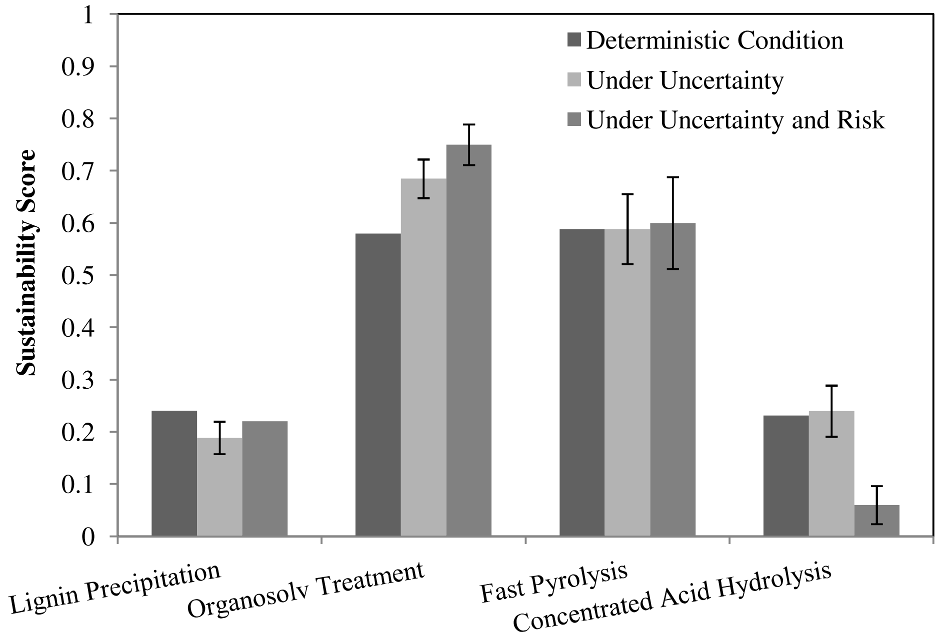



**Figure 4-36 Sustainability scores after addressing uncertainty and risk**

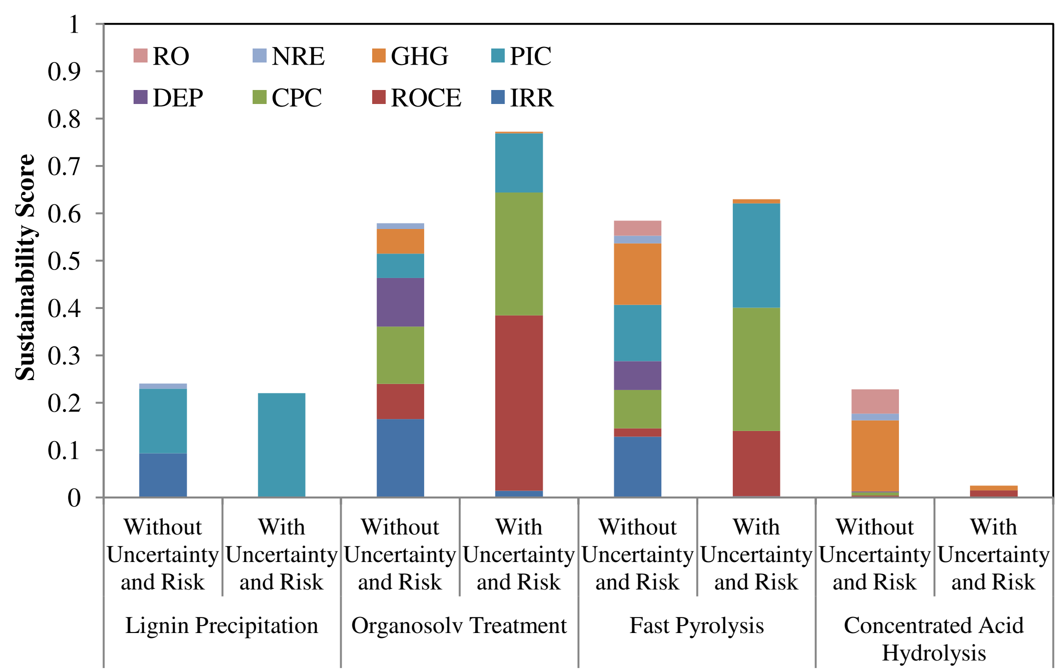



**Figure 4-37 Criteria contribution in sustainability score after addressing uncertainty and risk**

#### 4.3.5.1 Critical analysis

One of the achievements in this thesis was showing that addressing risk attitude of decision maker on top of involving uncertainty in strategic decision making could more differentiate between the alternatives and consequently enabled decision makers to screen out more options at the strategic level with more confidence. Although involving uncertainty in decision making, could help decision makers to better distinguish between the promising alternatives (Alt.2 and Alt.3), involving both uncertainty and risk attitude of decision makers can help even more in this regard by exaggerating the difference between the promising alternatives. In addition, although the difference between the non-promising options was not clear enough even after involving uncertainty, as soon as risk and uncertainty are both taken into consideration, the worse performance of acid hydrolysis (Alt.4) compare to lignin precipitation (Alt.1) becomes more clear.

Considering these two concepts (uncertainty and risk) at the same time gave a clearer picture of the possible performance of each design alternative which caused decision to become more transparent.

The results in this section could meet the second sub-objective defined in this thesis.

# CHAPTER 5 GENERAL DISCUSSION

Biorefineries can be stand-alone or integrated into the existing facilities, which the former has gained more attention in the agricultural industry while the latter is targeted for the forestry sector. Biorefineries in both contexts can have various possible configurations because of the variety of biomass, production processes and products. However not all biorefinery strategies are sustainable, and each strategy has its particular associated risks.

Using the investor perspective it is critical that unsustainable strategies as undesirable investment options are screened out from the list of biorefinery possibilities during the strategic early design stage. The main reasons that justify why companies should pay more attention to project selection properly at the strategic level of decision making are:

- Limited financial resources, which can only be allocated to the promising long-term strategies
- The risk of ending up with wrong decision due to the complexity of considering several conflicting objectives for project selection using sparse and uncertain available information at this level of design.

Thus if the conflicting sustainability objectives, uncertainty and risk attitude of decision makers are not addressed in strategic decision making, the results may mislead decision makers and they may end up with a wrong decisions.

Considering that, the main objective followed in this thesis was to develop a systematic approach for early stage design decision making by evaluating sustainability criteria under uncertainty and quantifying risk attitude of decision makers, and to illustrate it in two case studies in both a greenfield and a retrofit context.

## 5.1 Retrofit design and phased implementation approach

In order to better design biorefinery strategies in a retrofit context, forest products companies need to identify all potential integrations between the existing facilities at the mill and the candidate biorefinery strategies, and reflect them in sustainability assessment.

It has been done systematically in this thesis by exploring the mill first, identifying its characteristics and investigating all potential integrations in three sectors of biomass, process and product. All associated cost synergies as a result of identified integration potentials have been then addressed in both economic and competitiveness analysis and environmental assessment.

In addition, in order to reduce the risks associated with penetrating to the product market and because of immaturity of biorefinery technologies, and also due to the lack of capital for investors, the implementation strategy that companies normally follow need to be reflected in sustainability assessment. It was successfully done by phased implementation approach in this thesis. For each biorefinery technology, Phase I is defined representing minimum market risk for the core business transformation, whereas Phase II which involves the technology that when implemented, typically results in manufacturing of value-added products ending with higher revenue but with higher risk. Applying this approach, more realistic picture of project implementation could be reflected in sustainability assessment.

## 5.2 Sustainability criteria

In order to meet sustainability objectives, a set of criteria need to be defined by which biorefinery design alternatives can be assessed from different perspectives. In contrast to conventional analyses which often only consider short-term profitability metrics for decision making, this work took into account complementary criteria representing business oriented performance, potential environmental footprint, technology and market risks and market competitiveness as critical indicators of the sustainability. This thesis has introduced a set of intelligent sustainability criteria among which three of new defined criteria are introduced as follows:

- <u>Downside economic performance (DEP)</u> representing market risk:
    - Given the risk associated with volatility in the market price of bioproducts, a minimum level of project economic viability must be possible under poor market conditions assuming that it would last for a finite time in the order of months.
    - This criterion is defined as economic performance of the project under poor market condition in terms of the average margin created in a year relative to revenue, considering both poor and normal market conditions former lasting for

one third and latter for two third of the year. Poor market condition has been defined as the lowest annual product portfolio value over the last five years expressed on a monthly basis, representing worst market condition.

- This criterion was interpreted by panelists as *"a criterion that measures the financial performance of the biorefinery strategy during poor market conditions. Higher DEP is preferred as a measure of project robustness, ie the project can survive even under unfavorable market conditions."*

- <u>Phase I Implementation Capability (PIC)</u> representing technology risk:
  - Given the risk associated with project execution, the capability of each technology to be implemented at the full scale should be addressed. For the biorefinery strategy, we must implement Phase I technology in the short-term, and then switch it into Phase II as the longer term strategy.
  - This criterion is defined as a combination of three sub-components including (1) the level of technology maturity (in terms of largest operating plant), (2) process scalability (in terms of how much the targeted scale of Phase I is far from the designed scale of the candidate technology), and (3) the ability of implementing Phase 1 (in terms of possibility of implementation over 24 months). In order to aggregate these three sub-components, arbitrarily a weighting factor has been attributed to each as of 50% for technology maturity because it is a show stopper, and 25% to each of the second and the third sub-components. This criterion has been quantified by attributing three possible numbers to each sub-component representing different levels of their performance. These numbers are 1, 3 and 5 that are respectively showing low, medium and high performance.
  - This criterion was interpreted by panelists as *"an aggregated measure of technology risk that considers technology maturity, scale-up requirement to commercial scale, and ability to execute the Phase I technology in 24 months. Higher value of PIC is preferred because it represents lower technology risk in Phase I, and represents an opportunity to be faster to the market in Phase II."*
- <u>Resistance to Supply Market Uncertainty (RTMU):</u>

- Given the risk associated with variations in production costs because of supply market volatility, the level of sensitivity of the project to these parameters should be tested.
- This criterion is defined as project sensitivity to the market price of energy and raw materials as two main components of production cost in biorefinery context.
- This criterion was interpreted by panelists as *"a criterion that measures sensitivity of the project to the fluctuation in market value of key parameters in a biorefinery context including raw materials and energy. A project with high RTMU value would be less sensitive to any change in raw materials and energy prices to minimize its vulnerability to external sources of uncertainty."*

The results of decision making employing these criteria showed that the design alternatives with the best performance on conventional profitability-oriented criteria do not necessarily achieve the best economic performance. This confirms the necessity to consider the introduced complementary criteria in strategic decision making in biorefinery context.

## 5.3 Criteria refinement and decision making in deterministic condition

Aggregating the three sustainability dimensions (economic, competitiveness and environmental) for decision making means potentially involving a large set of decision making criteria, which can increase drastically the level of inconsistency and making a single day decision-making process impractical. The only remedy would be screening out less important criteria in the studied context that can not help decision makers to well distinguish the alternatives. This has been done in this thesis through criteria refinement procedure using a cascade of multi criteria decision making (MCDM) panels, one MCDM at the time employing the defined criteria in each sustainability pillar.

In this thesis applying the proposed approach could decrease eighteen sustainability criteria into a set of eight important criteria using which decision making process could become manageable. By conducting an MCDM for economic and competitiveness pillar, a set of ten necessary criteria could be refined into a set of five important criteria. Similarly conducting second MCDM employing environmental criteria could refine a set of eight necessary criteria into a set of three important ones.

Although this process can be somehow time intensive, it can keep decision making manageable and consequently help stakeholders to make a better decision.

Another outcome of performing such MCDM panels is ranking the alternatives in terms of each sustainability pillar. However, normally these ranking are in conflict, and therefore all these criteria need to be aggregated by another MCDM into a unique index by which design alternatives can be ranked in terms of sustainability performance.

This decision making technique (MCDM) is more applicable for the strategic level of decision making by which non-promising biorefinery strategies can be screened out from a list of all possible candidates, enabling decision makers to identify the options that can be further analyzed at the next levels of design. Therefore this method of project selection at the early stage design has a major contribution in cost reduction and time saving. Although MCDM can be used in any decision making context, in order to find a unique solution at the next levels of design (tactical and operational levels), multi-objective optimization techniques are more appropriate.

In this thesis by following the mentioned procedure, among six candidate triticale-based biorefinery design alternatives for PLA production in a greenfield context, two alternatives were identified as the most sustainable investment options. These alternatives featured higher technology risk, involving energy efficient separation processes (ultra-filtration) and more integrated processes (SSCF: sumiltaneous saccharification and fermentation). Similarly, among four candidate alternatives in retrofit forestry-based biorefinery context in this study, two promising options including organosolv treatment and fast pyrolysis, could be identified as more sustainable strategies by screening out unsustainable strategies (lignin precipitation and concentrated acid hydrolysis) from the list of candidate biorefinery strategies.

By following the sections 5.2 and 5.3, the first sub-objective in this thesis could be met.

## 5.4 Sustainability assessment under uncertainty

There is a high level of uncertainty associated with information at the strategic level of design, which can cause decision fail if it is ignored in project selection. Thus a right decision can be guaranteed only if different sources of uncertainty can be well addressed in projects evaluation.

Evaluating sustainability criteria under uncertainty would give a clear picture of the possible performance of each design alternative which can cause decision to become more transparent enabling stakeholders to make a better decision.

In this thesis, addressing uncertainty in decision making could help decision makers to screen out more options at the strategic level of design, due to showing the preference of organosolv treatment compared to fast pyrolysis while they were equally preferred in deterministic condition. Uncertainty involvement resulted in decision become more objective which is especially important when more options are supposed to be compared.

The conclusion that can be drawn from sustainability assessment under uncertainty in this thesis is that, involving uncertainty in decision making always would change the basis of decision making and sometimes change the final decision.

## 5.5 Quantifying risk attitude of decision makers

In strategic decision problems, decision makers would always face risk as a potential outcome of uncertain events, which is an inseparable component of any business especially in biorefinery context as emerging technologies with different associated technology and market risks. Moreover, whenever risk exists, each individual decision maker would have their own attitude toward risk. The decision for biorefinery strategy is not made by individuals but with multi disciplinary stakeholders who together can be risk avers or risk prone. In order to make a realistic and wise decision, the level of risk aversion among the stakeholders should be quantified and taken into account for strategic design decision making.

In this thesis, risk attitude of decision makers were quantified using lottery making through a panel activity. Addressing risk attitude of decision makers on top of involving uncertainty in decision making could help decision makers to even more differentiate between promising alternatives identified in deterministic condition, by exaggerating the preference of organosolv treatment compared to fast pyrolysis. This could consequently enable them to screen out more options at the strategic level with more confidence.

The main advantage of this work was involving both uncertainty and risk in decision making realistically and practically, in a way that can be interpretable for the decision makers. Once these concepts are understood by the senior management of companies that are considering corporate transformation, then consensus building can be objectively and systematically accounted for, and a better decision can be made.

By following sections 5.4 and 5.5, the second sub-objective of this thesis could be met.

## 5.6 Systematic approach for biorefinery strategic decision making

The overall systematic approach developed in this thesis could illustrate the strength of the combination of MCDM tool with Monte Carlo analysis method and lottery-based risk assessment approach for distinguishing between product-process options using sustainability perspective under uncertainty and considering risk attitude of decision makers in strategic level of design.

This systematic approach could help decision making in number of ways:

- Decision making problem could be well structured for stakeholders,
- The knowledge could be transferred on a range of sustainability criteria to decision makers having diverse backgrounds,
- It raised awareness and respect of the panel members for the interpretation of the sustainability criteria,
- Uncertainty as an inseparable part of any strategic decision making could be addressed practically and realistically in decision making approach,
- The diverse conflicting criteria were compared and weighed on a comparable basis, taking into account not only the importance of the criteria in their concept, but also considering in the context of the results and the level of uncertainty associated with each,
- It could reflect the expertise of decision makers in the field, their preferences and their attitude toward risk practically and realistically,
- The results of preferred and less preferred design alternatives could be well justified systematically explained,
- It could provide the discussion and negotiation among the decision makers (stakeholders) ending up with building consensus among them for the final decision

In order to apply this decision making approach in industry, the following elements should be taken into account:

- Although this approach can have too much information for stakeholders making them sometimes less motivated to participate, they should keep in mind the associated advantages of making a right strategic decision and necessity of applying an appropriate tool helping them in this regard.
- This process can be time intensive compared to the conventional way of making strategic decision currently used in organizations, and stakeholders need to dedicate some full day panel meetings that sometimes is a big challenge. However, they should get properly informed about the unique advantages of establishing this approach for strategic decision making in their company to guarantee their future success.
- Considering this fact that the decision making result depends on the panel and is not necessarily reproducible, the key multidisciplinary decision makers who commonly make strategic decisions in the organization should participate these panel sessions.
- Since the developed method is a human-based process, the expertise of the conductor of this method is crucial in order to prevent improper demonstration.

By developing this systematic approach, the main objective of this thesis could be met.

# CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Contribution to the body of knowledge

Considering the developed methodology and the obtained results of demonstrating it using two case studies, the main contributions to knowledge of this thesis can be summarized as follows:

- Defining a new set of practical and interpretable sustainability criteria in the context of biorefinery which can address different aspects of the project performance including economic and competitiveness performance along with technical and market risks associated with candidate biorefinery strategies.
- Among all new defined criteria, we can mainly refer to Downside economic performance (DEP) addressing market risk, Phase I Implementation Capability (PIC) addressing technology risk, and Resistance to Supply Market Uncertainty (RTMU) as a business oriented economic criterion representing sensitivity to supply-market uncertainties
- Adjusting sustainability pillars for the context of biorefinery, by replacing social pillar with competitiveness in order to address (1) the success of the product portfolio to get the market share and their capability to be competitive with the existing producers, and (2) the competitiveness capability for having access to biomass..
- Introducing a method to refine a set of necessary sustainability criteria into a set of important decision criteria using a cascade of multi criteria decision making (MCDM) panels, and then aggregating those conflicting important criteria into a unique sustainability index employing MCDM.
- Applying retrofit design (evaluation of all integration potentials between the mill and biorefinery) and phased implementation approach in biorefinery design for integrated forest biorefinery context.
- Incorporation of three concepts of sustainability, uncertainty and risk attitude of decision makers in strategic decision making for biorefinery context:
    - This has been done by applying a systematic approach which combines MCDM with (1) Monte Carlo analysis to quantify uncertainty associated with sustainability criteria, and with (2) lottery-based risk assessment method to quantify risk attitude of stakeholders.

  - Investigating the influence of addressing uncertainty and risk attitude of stakeholders in strategic decision making for sustainability assessment of biorefinery strategies by comparing the identified promising biorefinery strategies (as the final decision) with and without risk and uncertainty.

## 6.2 Future work

The major opportunities to extend the developed approach in this thesis within future works are as follows:

- Applying the developed systematic approach with industrial panels:
  - This work is a balance between incorporation of new ideas in strategic decision making- statistical uncertainty evaluation and addressing risk attitude of decision makers- and practicality of it. For being practical, the goal is to have an interface with multidisciplinary panel members which can have interpretable outcomes and definitions that can be rigorous to be well communicated. The decision making approach proposed in this thesis, is highly empirical and depends on a great deal on the expertise of the panel host. The experience gained through the application of the methodology should cumulate for further improvement on the practical aspects of the methodology.
- Incorporating the issue of unlikely scenarios and future environmental policy in strategic decision making:
  - Risk and uncertainty in design decision making at the early stage is substantial and this work presents a practical methodology for a comprehensive assessment of these concepts in the context of biorefinery. However, there are still other sources of uncertainty that might be considered in a given panel, specially the issue of unlikely scenarios and future environmental policy.

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# APPENDICES

**APPENDIX A –** Article 1: Systematic Assessment of Triticale-Based Biorefinery Strategies: Techno-Economic Analysis to Identify Investment Opportunities

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# APPENDIX A – Article 1:

## Systematic Assessment of Triticale-Based Biorefinery Strategies:

## Techno-Economic Analysis to Identify Investment Opportunities

# Systematic Assessment of Triticale-Based Biorefinery Strategies: Techno-Economic Analysis to Identify Investment Opportunities*

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**Abstract**

In recent years, interest has increased in biorefineries that use a variety of biomass residues and non-food crops. Triticale (*X Triticosecale Wittmack*) is a human-developed crop that has the potential to become a preferred industrial energy crop for the biorefinery because of its capacity to grow on marginal land, its higher yields compared to existing cereal crops such as wheat, and its non-competition with food-based crops. However, implementation of the triticale-based biorefinery will require the identification of sustainable strategies and as its sustainability pillar, the identification of economically promising strategies. In this study, the economic performance of several triticale-based product-process scenarios, including the production of ethanol, polylactic acid (PLA) and thermoplastic starch polymer, have been assessed through the evaluation of six economic criteria. These conflicting criteria have been evaluated in a multi-criteria decision making (MCDM) panel, demonstrated for PLA platform, which has made it possible (1) to rank the alternatives by their economic performance, and (2) to identify a set of the most important criteria to be used in a sustainability study. The MCDM results show that the alternatives with the best performance on profitability-oriented criteria do not necessarily achieve the highest overall economic score. This suggests the need to consider both business strategy-oriented criteria and profitability-oriented criteria in strategic decision making. The MCDM results show that the internal rate of return, the downside internal rate of return, and the resistance to supply market uncertainty with relative weights of 24.8%, 23.6%, and 18.1% respectively, are the most important of the criteria assessed.

Keywords: Biorefinery, Triticale, Techno-economic, Economic Criteria, Multi-Criteria Decision making (MCDM).

## 1 INTRODUCTION

Interest has increased in recent years concerning the implementation of new generations of biorefineries using a variety of biomass residues and non-food crops. As a consequence of this interest, the agricultural sector in Canada has looked closely at integrating biorefinery activities into its current processes as a strategy to potentially enhance the competitiveness of the future industry. One of the biomass crops that may be used as biorefinery feedstock is triticale (*X Triticosecale Wittmack*). This crop has attracted much interest, especially in Alberta, Canada, because it has characteristics similar to wheat while does not interfere with the food chain. This energy crop is a hybrid of wheat and rye and brings together the advantages of both crops: the high yield potential and grain quality of wheat, and the environmental tolerance of rye (http://en.wikipedia.org/wiki/Triticale, 2013). The unique advantages of triticale include its ability to grow on marginal land, higher yields compared to wheat, and non-competition with food-based crops, position triticale as a promising energy crop for the biorefinery industry[1]. The Canadian Triticale Biorefinery Initiative (CTBI) Network is a research and development program which has focused on developing triticale as an industrial biorefining crop for Canada (http://www.ctbi.ca, 2013). Their achievements have shown that a variety of possible triticale-based product-process combinations exist. However, not all these options are necessarily sustainable, and no study to date has sought to identify the most promising triticale-based biorefinery strategies.

In early-stage strategic decision making for investment in triticale-based biorefinery strategies, unsustainable options should be screened out, leaving the most promising. To achieve this goal, the sustainability of strategies must first be assessed. As one of the pillars of sustainability assessment, this study focuses on economic evaluation of triticale-based biorefinery strategies using techno-economic analysis.

Most of the available techno-economic studies in the biorefinery context are limited to generally commodity product platforms, specifically biofuels, with a particular focus on lignocellulosic-based bioethanol. For instance, a valuable review has been presented by Gnansounou[2], analyzing techno-economic studies of lignocellulosic bioethanol production in the United States and Europe. Moreover, Hamelinck *et al.*[3] have carried out the techno-economic analysis of a biorefinery context under different time frames (short-, middle-, and long-term views), but it also is limited to lignocellulosic-based bioethanol production. In the context of biofuels, beside all efforts extended to analyze bioethanol production, recently biobutanol is also gaining increasing attention.[4,5] However, to identify promising investment opportunities, it is critically important to look at a broad and diverse range of possible strategies, diversified from commodity to more value-added products, to assure investors of finding a sustainable strategy which can be economically-viable in a long-term view. The case study examined in this work considers three product platforms ranging from commodity to more value-added products: bioethanol, polylactic acid (PLA) and thermoplastic starch polymer (TPS/PLA blend), all using both triticale grain and straw.

Most published techno-economic studies use internal rate of return (IRR) or net present value (NPV) as evaluation criteria. However, from the investor perspective, biorefinery projects should not only be profitable in the short-term, but also should have a robust business model that enables value creation over the long-term while mitigating risks, and guarantee business viability during unfavorable market conditions. Moreover, promising biorefinery strategies should be able to maintain a competitive position in the market through the characteristics of the product portfolio, in that they are less affected by volatility in the market price of any single product. Therefore, not only profitability-oriented criteria, but also criteria that can address the business perspective, must be considered for evaluating the likelihood of economic success of different investment opportunities. A global criteria framework consisting of economic criteria in a biorefinery context has been introduced in some studies such as what have been presented by Corbière-Nicollier *et al.*[7] and Patel *et al*[8]. In addition, some of the main economic metrics used by stakeholders have been presented by Hytönen *et al.*[9] Using certain of these metrics, this study introduces a set of economic criteria, including not only profitability-oriented but also business strategy-oriented criteria, which can address critical aspects of the economic performance of biorefinery projects.

Criteria for different investment opportunities are often conflicting, in which case multi-criteria decision making (MCDM) is a valuable method for resolving conflicting outcomes.[10] Similar approaches have been presented by Hytönen *et al.*[11] and Cohen *et al.*[12], in the context of biofuels production, the former for the economic evaluation of F-T liquids production scenarios and the latter for the identification of promising biorefinery technologies to produce bioethanol.

Aside from the economic pillar, the sustainability assessment of triticale-based biorefinery strategies must consider other aspects[13], including the environmental[14] and competitiveness[15] performance of biorefinery strategies. These three pillars can be considered simultaneously using MCDM to assess the overall sustainability of the various triticale-based biorefinery strategies.[16] The European Network of Biosynergy[17] has applied MCDM for assessing biorefinery sustainability, however with a narrow range of criteria. There are few studies in literature which have employed MCDM using a set of conflicting criteria to identify sustainable biorefinery strategies at the strategic level of design.[8,18,19] The drawback of most of these studies is that they have attributed arbitrary weighting factor to each criterion instead of quantifying its relative importance using a systematic approach. There are some studies in literature focusing on analyzing the uncertainty in the relative importance attributed to decision criteria in decision making.[20] However it should not be seen as an uncertainty. In any MCDM decision making process, if the panel is changed there is a high probability that the criteria weights and consequently ranking of the alternatives would be different. However changing the results by changing the panelists (stakeholders) should not be seen as an uncertainty of the results but it is a result of different objectives in different companies according to their mission and vision. For instance, when one company is leading more towards developing sustainable products and penetrating the green market, for decision makers in that company, environmental criteria would be more important than for others companies.

In order to assess the overall sustainability of the studied platforms and their associated alternatives, the best approach is probably not to use all the economic criteria such as those presented in this study, but to identify the most critical economic criteria, and use these with environmental and competitiveness criteria to keep decision making manageable. Buchholz *et al.*[21] have shown that MCDM can be used as a tool to refine a long list of criteria to an appropriate set of criteria in a biorefinery context.

This study aims to improve existing methods using MCDM in techno-economic analyses, in the context of the triticale-based biorefinery, resulting in the identification of economically promising strategies. At the same time the presented approach in this study would result in determining the most critical economic criteria for subsequent use in sustainability assessment.

## 2 METHODOLOGY

### 2.1 Scenario definition

The triticale-based biorefinery scenarios have been defined on three product platforms, in which both triticale grain and straw are used as feedstocks. These three product platforms are (1) bioethanol, (2) polylactic acid (PLA), and (3) a blend of thermoplastic starch (TPS) and PLA. The scenarios defined on each of these three platforms have been presented in greater detail by Chambost *et al*.[1] The product-process scenarios in each platform include (1) a base case (Figure 1) representing the minimum-technology-risk option while maximizing the production capacity of the main product, and (2) several alternatives (Table 1) to the base case that involve higher technology risks, but can potentially lead to improved returns. The minimum risk base case for each product platform has been defined using two assumptions: (1) the use of existing commercial/conventional technologies on the grain line, and (2) use of the most proven processes on the straw line to decrease the uncertainty in production of second-generation bioproducts. In the base cases of the bioethanol, PLA, and TPS/PLA blend platforms, the grain processing lines have been defined based respectively on the Husky (http://www.huskyenergy.com, 2013), NatureWorks[22], and Entek (http://www.entek-mfg.com, 2013) technologies. For each base case platform, a set of process alternatives have been defined (Table 1). Mass and energy balances for these have been presented by Chambost *et al.*[13] assuming a target volume of about 151.5 MM L/y for ethanol, 100,000 t/y for PLA, and 75,000 t/y for the TPS/PLA blend. This target was set based on market analysis[15] and considering the production capacity of existing producers.

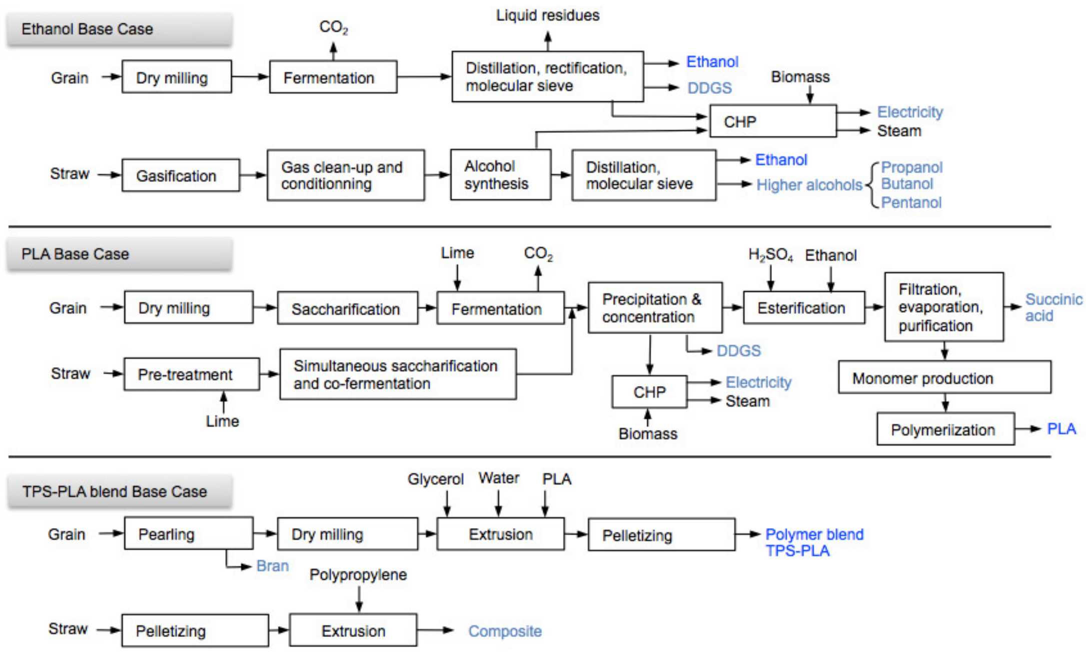


Figure 1: Block flow diagram of base-case scenarios for the 3 biorefinery platforms

Table 1: Summary of process alternatives considered for the 3 biorefinery platforms

| Alt. | Modifications to the Base-Case Process | | | Justification/Characteristics |
|---|---|---|---|---|
| | Ethanol | PLA | TPS/PLA Blend | |
| 1 | Use straw in combined heat and power (CHP) unit. | | | To investigate the effect of minimizing market risk in the straw line by producing electricity instead of bioproducts. |
| 2 | Replace the dry milling unit in the grain line with a wet milling unit. | | | To investigate the role of producing an extra value-added co-product (protein). This also results in purer starch in the main flow. |
| 3 | Replace gasification in the straw line with a process consisting of a pressurized low-polarity water (PLPW)[21] pre-treatment, resulting in Xylitol production as a by-product from the extracted C5 sugars. | Replace conventional separation in both grain and straw lines with ultra-filtration and electro-dialysis. | Add mechanical pulping for pre-treating straw. | -On the ethanol platform: to investigate the effect of replacing a thermochemical with a biochemical pathway in the straw line.<br>-On the PLA platform: to investigate the effect of implementing a more efficient separation unit, leading to less energy consumption and to the production of acetic acid as a co-product.<br>-On the TPS platform: to investigate the effect of extracting cellulose for use in the production of biocomposites. |
| 4 | Replace the conventional separation and purification process in the grain line with pervaporation-fermentation followed by a molecular sieve. | Simultaneous saccharification and fermentation in the grain line. | - | -On the ethanol platform: to investigate the effect of enabling an integrated continuous process, which results in energy savings.<br>-On the PLA platform: to investigate the effect of process integration, resulting in energy savings. |
| 5 | Add a pearling unit before milling in the grain line. | | - | To investigate the effect of increased purity in the main flow and reduction in the size of the other units. |

## 2.2 Economic evaluation

The overall methodology employed in this study for economic evaluation of the process alternatives, as shown in Figure 2, can be divided into two major parts: techno-economic analysis (Steps I to IV) and decision making (Steps V to VIII).

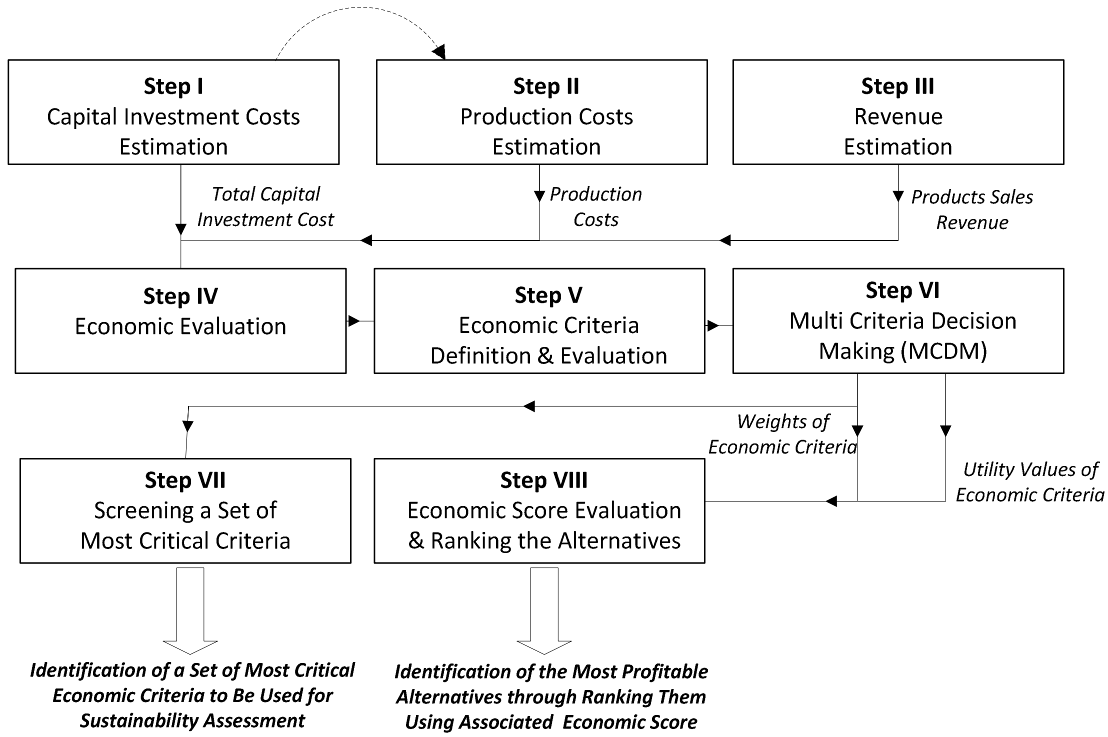


Figure 2: Economic evaluation and decision making methodology used in this study.

*2.2.1 Techno-Economic Analysis*

Techno-economic evaluation is a conventional methodology[29] in which the technical performance of a system is analyzed and the results are used to assess the economic performance. The first four steps in this methodology—(I) capital investment cost estimation, (II) production cost estimation, (III) revenue estimation, and (IV) economic evaluation comprise the conventional techno-economic methodology.

The investment cost in Step I has been estimated using large-block analysis[24], in which (a) the cost the main process technology is supplied by technology developers, and (b) costs of the different process blocks are estimated using a common evaluation methodology so that they can be compared on a relative basis. The biomass feedstock cost used in Step II has been extracted from Melendez *et al.*[25]. Annual revenue in Step III was estimated using the sale price of each product based on the market analysis study by Diffo *et al.*[15] Finally, the economic analysis was performed in Step IV by assembling the outputs of Steps I to III. The major assumptions of the techno-economic analysis have been summarized in Table 2.

Table 2: Major assumptions for techno-economic analysis.

| Parameter | Value |
|---|---|
| Construction period | 2 years |
| Production length | 20 years |
| Production period | 8000 h/y |
| Production capacity in first year | 50% of nominal capacity |
| Production capacity in second year | 75% of nominal capacity |
| Production capacity from third year | 100% of nominal capacity |
| Subsidies | No subsidy |
| Scrap | 100% land and 0% for process and infrastructure |
| Loan | 100% equity |
| Income tax | 40% |
| Contingencies | 5%–7% of FCI (Fixed Capital Investment Cost) |
| Premium | No premium for production of green electricity<br>20% premium paid for grain to farmers[23] |
| Farmer participation rates | 85% for grain, 70% for straw[23] |
| Harvesting & transportation | Farmer responsible for harvesting, while the biorefinery responsible for raw material transportation[23] |
| Biomass inventory | 15 days (including one week at the farm at no cost) |
| Product inventory | 3 weeks |
| Depreciation | Linear |
| Harvested straw | 80% (20% of straw is ploughed back into the soils) |

### *2.2.2 Decision Making Using Multi-Criteria Decision Making (MCDM) Approach*

In the second part of the methodology, the results from the techno-economic analysis in Step IV were used to support decision making to screen-out less promising process alternatives. In order to do so, first of all a set of necessary economic criteria was defined by decision making conductor. These defined criteria were then interpreted by a panel of decision makers. As the last step, based on the opinion of panelists, relative importance (weighting factor) of the decision criteria were quantified using which finally the design alternatives could be ranked in terms of their economic performance.

The decision criteria were defined to be practical, interpretable and complete, and to keep the analysis manageable at this early design stage.[32] Table 3 presents a list of the economic criteria (Step V) in two main categories: profitability-oriented and business strategy-oriented criteria. The criteria are defined in such a way that higher values always indicate better performance.

Table 3: Set of techno-economic criteria used for decision making.

| Interpretation* | | | Metric[12] |
|---|---|---|---|
| Profitability Oriented Criteria | IRR: Internal Rate of Return | Measures the profit/risk ratio under normal market conditions. This ratio should normally be greater than 20%, the minimum target for **profitability over the short-term**, before considering probable future technology improvements. | $\mathrm{NPV} = \sum_{t=0}^{22} \frac{\mathrm{CF_t}}{(1+\mathrm{IRR})^t} = 0$ |
| | DIRR: Downside Internal Rate of Return | Measures the viability of the business model or the **robustness** of the biorefinery process, defined as maintaining reasonable profitability (nominally, above 11%) under poor future market conditions (maximum biomass price (182 $/tonne for Triticale grain and 52 $/t for Triticale straw) and minimum product price (1755 $/t for PLA $/t)). | $\mathrm{NPV} = \sum_{t=0}^{22} \frac{\mathrm{CF_t}}{(1+\mathrm{DIRR})^t} = 0$ |
| | ROCE: Return on Capital Employed | Measures the **cash flow that the project generates from its invested capital.** | $\mathrm{ROCE} = \frac{\mathrm{EBIT}}{\mathrm{Capital\ Employed}}$ |
| Business Strategy Oriented Criteria | RD: Revenue Diversification | Measures the ability to improve margins due to product diversity and to **stabilize project revenue** by mitigating the risk of low profit from a single product because of price volatility. More diverse revenue has enhanced benefit if the process has **flexibility** between products in the product portfolio. | $\sum_{i=1}^{\text{Number of byproducts}} \frac{\text{Revenue from byproduct (i)}}{\text{Total revenue}}$ |
| | ARUC: Ability to Respond to Unknown Changes | Measures the ability of a biorefinery alternative to **stay in operation under unknown changes** in the future business environment, by maintaining more free cash flow (FCF) for a longer period of time. | $\sum_{i=\text{first year of construction}}^{i=\text{10th year of production}} \mathrm{FCF_i}$ |
| | RTMU: Resistance to Supply Market Uncertainty | Measures the **sensitivity** of the project **to the market value of the raw materials and energy**. | $\frac{\text{EBIT per tonne of product}}{\text{Cost of (raw materials + Energy) per tonne of product}}$ |

*The interpretation presented for each criterion was obtained as a result of the MCDM panel.

NPV: Net Present Value
CF: Cash Flow
EBIT: Earning before Interest and Tax
FCF: Free Cash Flow

To obtain an aggregated score representing the level of economic performance of each alternative, an importance value is attributed to each criterion by conducting a MCDM panel in which a weighting activity was carried out using the trade-off method[10] (Step VI). Although economic scores in this study are obtained using all six criteria, this number of criteria should be reduced to avoid complexity of decision making in the sustainability assessment in which economic criteria are accompanied by other types of criteria. Therefore, the two objectives of conducting the MCDM analysis were as follows:

(1) To identify the most economically-promising design alternatives using a purely economic perspective (Step VIII), and

(2) To identify a set of important techno-economic criteria (Step VII) by screening out the less important criteria. This refined set of criteria will later be combined with environmental and competitiveness criteria in another MCDM[4] analysis, to assess the sustainability of the process alternatives.

In an MCDM, three main steps are followed including interpretation of the decision criteria, quantifying the criteria weights and ranking the alternatives. As the first step in a decision making activity, panelists interpret the meaning of each criterion and will get consensus on a unique interpretation for each criterion. The second step is the weighting activity, in which the first stage is to select the most important criterion and to choose a target value based on the preferences of the panelists. The target value is the minimum acceptable value for the most importance criterion satisfying investors to invest in a triticale-based biorefinery strategy. As the next step, the importance of each criterion is compared with that of the most important criterion using the trade-off method[10]. In this step, each panelist determine how much he/she would be willing to lose from the target value of the most important criterion to achieve benefit from another criterion by going from its lowest value to its highest value. Using the values that the panelists give to these pair-wise comparisons, the weights of the criteria can be calculated. At the end, to define the overall performance of each alternative, a unique score ($SC_e$) is obtained by combining the weighting factors ($W_i$) and the calculated utility values associated with each criterion ($U_i$: value of each criterion in dimensionless form between zero to one) using the following equation:

$$SC_e = \sum_{i=1}^{N} W_i \, . \, U_i \tag{1}$$

Where N is the number of criteria.

In this study, decision making has been conducted on the PLA platform. However the presented decision making approach can be applied for the other platforms and even for any other context.

# 3 RESULTS AND DISCUSSION

## 3.1 Techno-economic results

The techno-economic evaluation of the base cases and alternatives is presented in Table 4.

Table 4: Summary of results of techno-economic analysis.

| Platform | Alt. | FCI[1] (MM$) | WCI[2] (MM$) | TCI[3] (MM$) | Biomass Cost [4] ($/t[a]) | Energy Cost [5]($/t[a]) | Cost of Product ($/t[a]) | Main Product Revenue [6] ($/t[a]) | Co-Products Revenue ($/t[a]) | Operating Margin[b] ($/t[a]) | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ethanol | **Base** | **219** | **15.3** | **234.3** | **328.6** | **35.7** | **619.6** | **689** | **241.4** | **310.7** | 1,3,7, 23-29 |
| | 1 | 366.9 | 31.3 | 398.1 | 835 | 20.6 | 1261.6 | 689 | 596.2 | 23.5 | |
| | 2 | 221.7 | 16.2 | 237.8 | 351.7 | 46.4 | 657.9 | 689 | 239.6 | 270.6 | |
| | 3 | 249.8 | 22.4 | 272.2 | 515.1 | 59.5 | 915.4 | 689 | 2127.3 | 1900.8 | |
| | 4 | 396.8 | 20 | 416.8 | 344.4 | 33.3 | 778.6 | 689 | 249.2 | 159.51 | |
| | 5 | 229.8 | 16.5 | 246.2 | 368.4 | 35.5 | 667 | 689 | 246.4 | 268.3 | |
| PLA | **Base** | **296.3** | **19.2** | **315.5** | **421.5** | **93.4** | **1496** | **2160** | **374.8** | **1039** | 1,3,7 23-29,c |
| | 1 | 438.2 | 24.4 | 462.6 | 657.9 | 92.4 | 1313.7 | 2160 | 626.4 | 1313.4 | |
| | 2 | 294.1 | 19.2 | 313.2 | 421.5 | 103.3 | 1040.1 | 2160 | 361.3 | 1472.9 | |
| | 3 | 338.2 | 16.3 | 354.5 | 411.7 | 98.3 | 910.9 | 2160 | 390.7 | 1640 | |
| | 4 | 286.5 | 18 | 304.4 | 415.4 | 35.5 | 959 | 2160 | 377.5 | 1578.6 | |
| | 5 | 299.6 | 19.3 | 318.9 | 430.4 | 96.4 | 1041.6 | 2160 | 372 | 1490.4 | |
| TPS | **Base** | **134.8** | **57.7** | **192.4** | **80.2** | **468.2** | **3626.78** | **2970** | **1556** | **899.2** | 1,3,7, 23-26, 29, d,e,f |
| | 1 | 202.6 | 35.2 | 237.7 | 175.4 | 218.1 | 2210 | 2970 | 227.6 | 987.7 | |
| | 2 | 146.4 | 65.7 | 212.1 | 98.5 | 680.7 | 4176.8 | 2970 | 1920.5 | 713.8 | |
| | 3 | 345.6 | 60.7 | 406.3 | 157.1 | 448 | 3804.6 | 2970 | 1770.8 | 936.2 | |

1 FCI: Fixed Capital investment Cost
2 WCI: Working Capital Investment Cost
3 TCI: Total Capital Investment Cost (summation of FCI and WCI)
4 Triticale grain price: 182 $/tonne, Triticale straw price: 34 $/tonne.
5 Electricity price: 0.07 $/kWh, Natural gas price: 6 $/GJ.
6 Ethanol price: 689 $/tonne, PLA price: 2160 $/tonne, TPS/PLA composite: 2970 $/tonne
a Costs are in $/tonne of main product.
b Does not include capital investment cost.
c http://www.powershow.com (2004).
d ucahelps.alberta.ca (2013).
e www.icis.com (2013).
f http://archive.nrc-cnrc.gc.ca/eng/ibp/imi.html (2011).

In this table the estimated total capital investment (TCI) cost, is presented as the summation of the fixed capital investment cost (FCI) and the working capital investment cost (WCI). In this table, total production cost has been presented as the cost of product. It mainly includes cost of raw materials (biomass and chemical), energy and utilities, maintenance and repair, labour, operating supplies, insurance and overhead, administrative, distribution and selling, among which two main components of production cost including biomass cost and energy cost are presented in this table. In the last column of this table, the operating margin is calculated by subtracting the production cost from total revenue (summation of the revenue out of main product and the revenue out of by-products). For ethanol production TCI is approximately 234 MM$ and the annual production cost is approximately 89 MM$ (0.58 $/L of ethanol), while the annual revenue from the product portfolio is 134 MM$ (a generous assumed market price of about 0.9 $/L of ethanol). Although production of PLA in the base-case scenario is more capital-intensive (TCI=316 MM$), it attains higher margins. The TPS/PLA blend base case is the least capital-intensive option (TCI=193 MM$), and generates acceptable margins. Figures 3 and 4 respectively summarize the profitability-oriented and business strategy-oriented criteria for the base case, best-case (highest criterion value), and worst-case (lowest criterion value) scenarios.

Comparing the IRR of the base cases for the 3 platforms shows that producing value-added products, including PLA and a TPS/PLA blend, is more profitable (IRR more than 20%) than the production of a commodity product such as ethanol (IRR of approximately 9%).

To investigate the effect of potential support from government through subsidies, a sensitivity analysis on TCI was conducted by applying 5%, 10% and 20% decrease in TCI as a subsidy. The results of the sensitivity analysis show that a 20% decrease in TCI would lead to increases of approximately 30%, 24%, and 19% respectively in the IRR of the base-case scenarios for the ethanol, PLA, and TPS/PLA blend platforms. Consequently, it can be concluded that government subsidies could lead to a significant increase in the profitability of biorefinery projects and a considerable reduction of the investment risk.

As shown in Figure 3, none of the ethanol production scenarios are adequately profitable (IRR is lower than 20%), except for Alternative 3 that involves the production of a value-added co-product (xylitol) from the $C_5$ stream, which has been extracted using an advanced fractionation technology (PLPW[23]). These results underline the importance of considering value-added co-products as part of a commodity-driven product portfolio to achieve economic profitability. For this platform, any increase in investment cost without an increase in revenue through the production of value-added co-products can lead to negative profitability (e.g., Alternative 1: cogeneration). For the PLA platform, all scenarios are profitable enough except Alternative 1 as cogeneration (IRR=17%), a capital-intensive option with no revenue from value-added co-products. For the TPS/PLA blend platform, all scenarios are profitable enough except Alternative 3 as mechanical pulping (IRR=8%). This scenario may be economically viable only in the context of an integrated biorefinery in which existing mechanical pulping equipment at the mill can be used for the biorefinery process. The DIRR criterion shows that among all the platforms, the PLA platform offers the best business viability under poor market conditions. However, ethanol (except for Alternative 3) and TPS/PLA blend platforms are not robust under the same conditions, mainly because of their dependency on biomass price in the case of ethanol production, and high impact of product market price under the worst market conditions in the case of TPS/PLA blend production (with a large gap between average sale prices assumed under normal market conditions and poor market conditions). The values associated with the ROCE criterion show that value-added product platforms obtain more value from their assets than do commodity platform.

By comparing the values of the Revenue Diversification (RD) criterion for the ethanol and PLA platforms (Figure 4), it can be concluded that co-products play a major role in revenue creation for commodity platforms. A comparison of the PLA and TPS/PLA blend platforms shows that specialty co-products (e.g., biocomposites) can better stabilize revenue, mainly because of their higher market value and lower market volatility compared to commodity co-products. In the same category of criteria, the values of the Ability to Respond to Unknown Changes (ARUC) criterion show that the value-added product platforms considered are better equipped to mitigate risks over the long term by generating more free cash flow than commodity platform. In addition, comparing the Resistance to Supply Market Uncertainty (RTMU) criterion for the three platforms shows that high sensitivity to supply-market uncertainties has a significant impact on the economic viability of the ethanol (to a lesser extent in Alternative 3) and TPS/PLA blend platforms. This is due mainly to the high dependency of production costs on biomass price in the case of ethanol production and the high dependency of production costs on PLA price in the case of TPS/PLA blend production. Although the ethanol platform is sensitive to the supply market, the results of Alternative 3 underline that for the scenarios considered, producing value-added co-products mitigates the impact of the supply market.

Identifying the most and least promising alternatives, especially within a platform, is not straightforward. For instance, in the PLA platform, Alternative 4 (SSCF) shows the best performance on profitability-oriented criteria; however, the results associated with business strategy-oriented criteria are different. Therefore, calculating a unique economic score for each alternative by weighing conflicting criteria using an MCDM tool is crucial for assessing different alternatives.

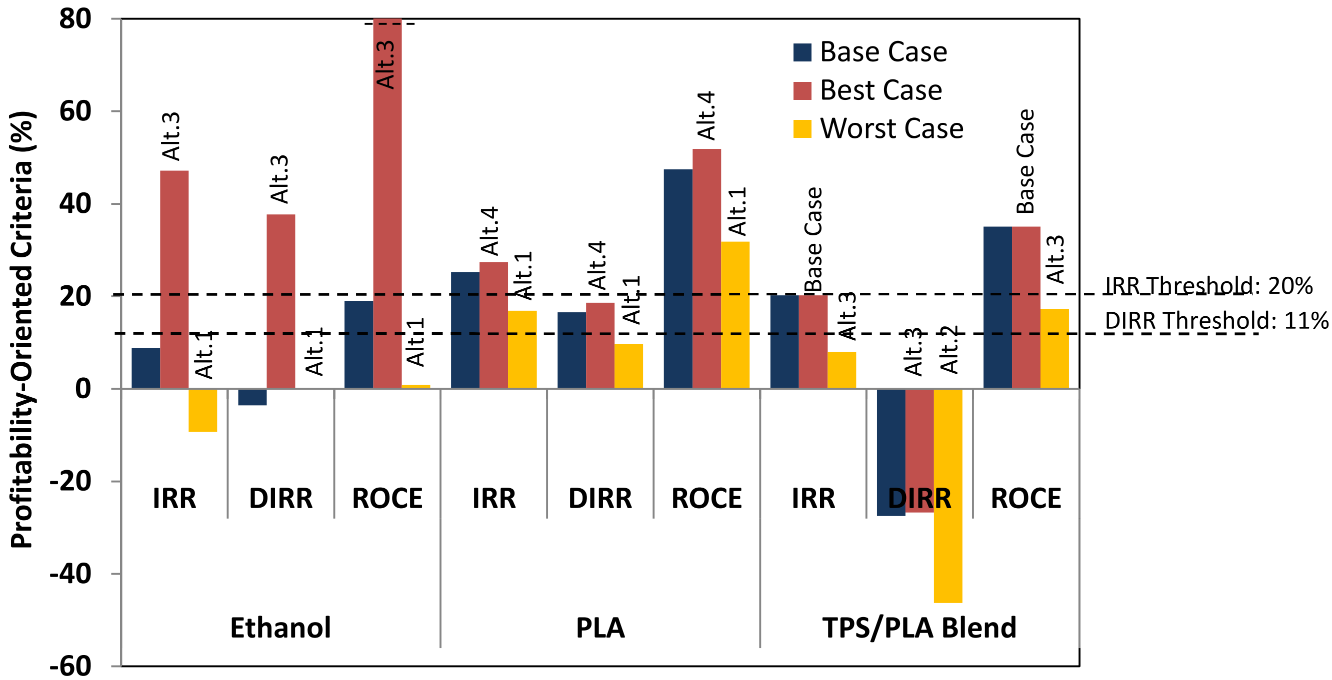


Figure 3: Profitability-oriented criteria.

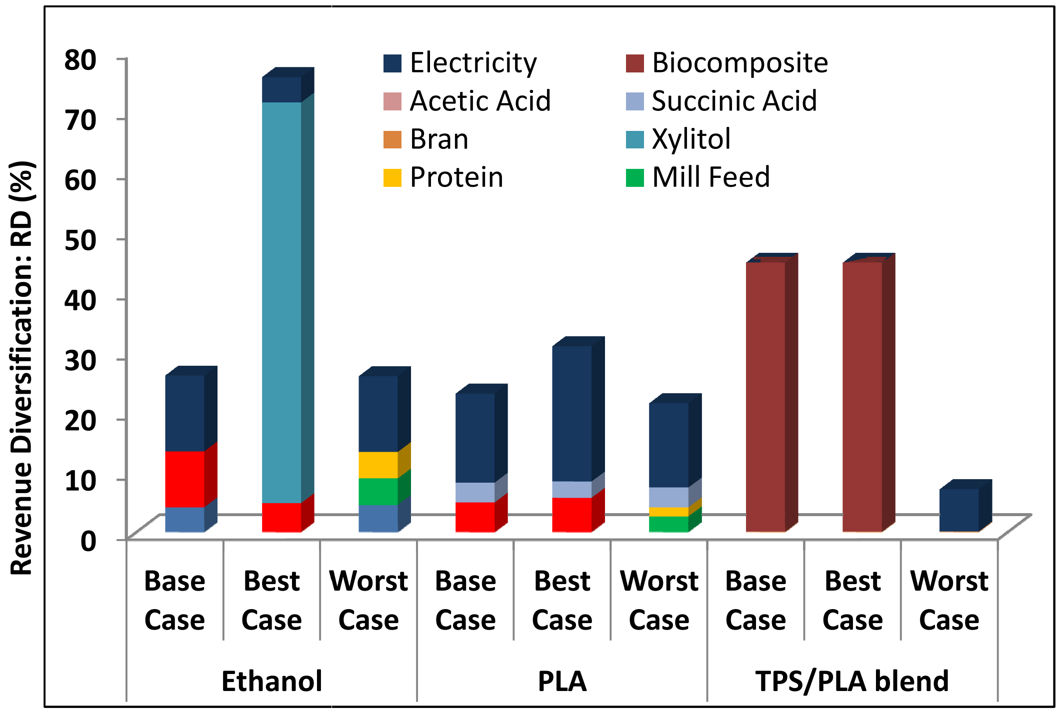


Figure 4: Revenue diversification.

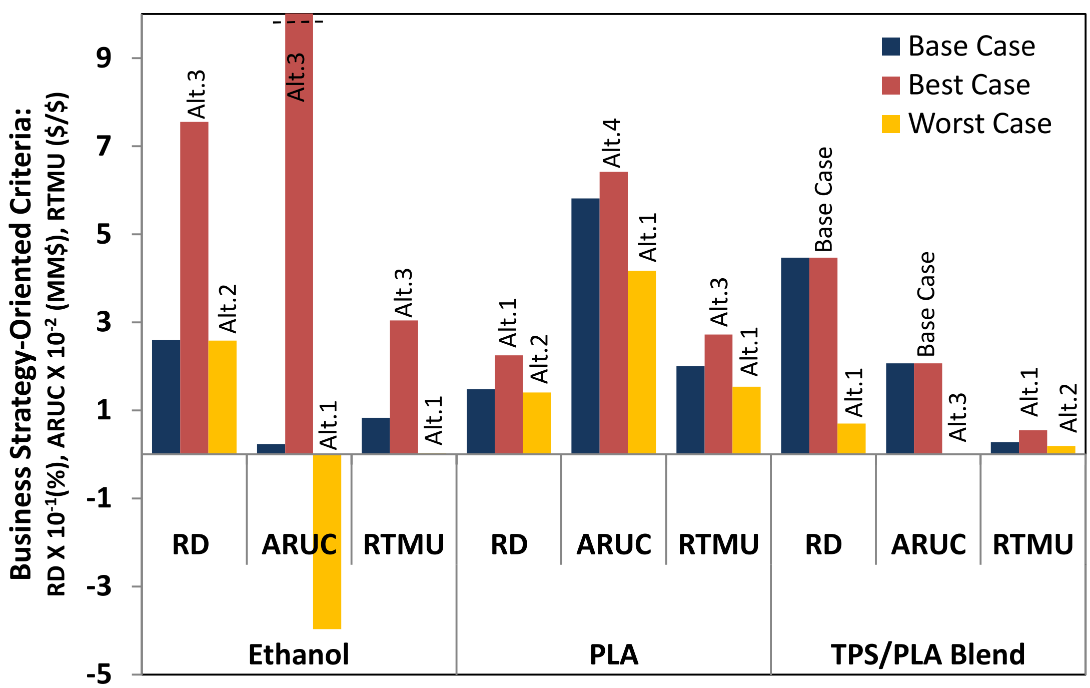


Figure 5: Business strategy-oriented criteria.

## 3.2 MCDM Results

Decision making results depend strongly on the case study context (the results). In this study, decision making was conducted on the PLA platform. The MCDM methodology used can be applied to the other platforms, however the weights for different criteria would undoubtedly be different.

The multi-disciplinary panel in this study consisted of five panelists from industry and academia. They had various backgrounds including biorefinery expertise, energy, economics, market, and environmental sciences, ensuring that all the critical points which should be considered in strategic decision making would be captured.

### *3.2.1 Interpretation of criteria*

As the first step in a decision making activity, panelists interpreted the meaning of each criterion that the conductor had defined, as presented in Table 3.

### *3.2.2 Weighting of criteria*

In weighting activity, the first stage was to select the most important economic criterion and to choose a target value based on the preferences of the panelists. Not surprisingly, the IRR criterion representing short-term profitability was selected as the most important criterion, with a target value of 27%. In the next stage, the importance of each criterion was compared with that of the most important criterion using the trade-off method[10]. Using the values that the panelists gave to the pair-wise comparisons in trade-off activity, the weights of the economic criteria were calculated and are presented in Figure 6.

### *3.2.3 Screening economic criteria*

As shown in Figure 6, similar weights were given to IRR and DIRR (24.8% and 23.6% respectively) and these two criteria were selected as the most important. The standard deviation of the scores that panel gave to one criterion in trade-off activity, can represent the level of consensus among the panel on the relative importance of that criterion. For instance, the low standard deviation associated with DIRR implies a high degree of consensus on selecting this criterion along with IRR as the most important economic criteria. Among the business strategy-oriented criteria, the RTMU criterion was assessed as important for decision making.

The two least important economic criteria were RD and ROCE, with 5.5% and 11.5% importance respectively. The low importance of the RD criterion was associated with a lack of interpretable distinction between competitiveness criteria[15] and the economic concept of RD.

Based on the weighting activity, three criteria, IRR, DIRR, and RTMU, were considered the most important criteria to be used in the sustainability assessment of the PLA platform.[16]

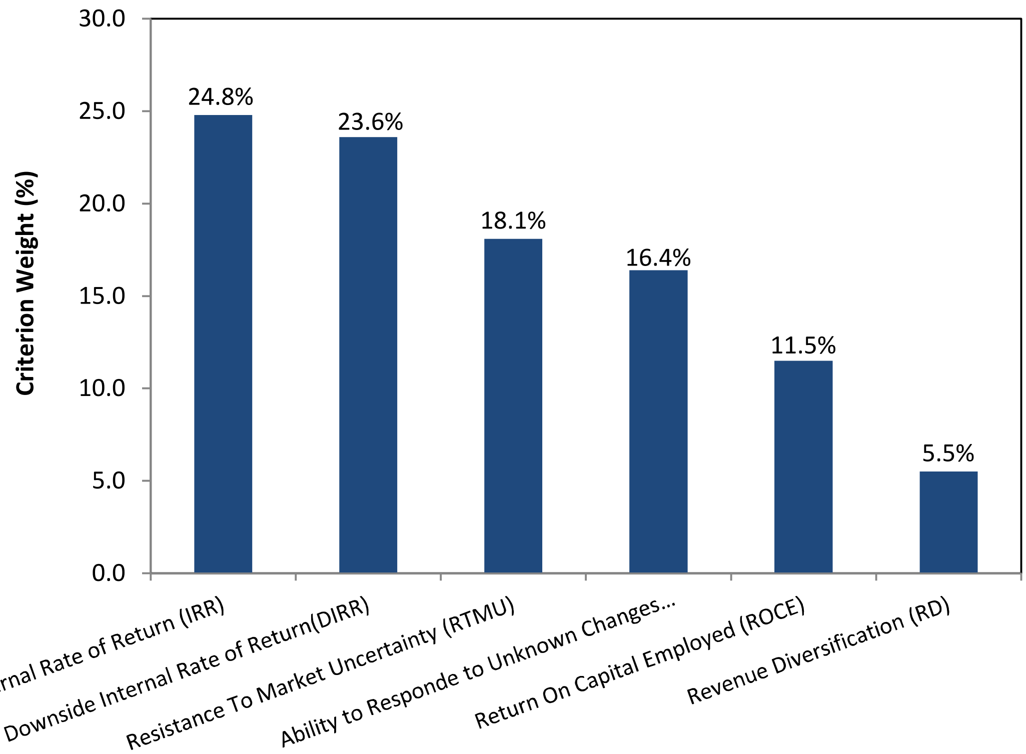


Figure 6: Criteria weights resulting from MCDM.

*3.2.4 Ranking of alternatives based on techno-economic performance*

The alternatives in the PLA platform were ranked using their overall economic scores (Figure 7), with the goal of screening out the economically under-performing alternatives. The least promising alternative in the PLA platform was found to be Alternative 1 (cogeneration). The overall economic scores show that the base case, Alternative 2 (wet milling), and Alternative 5 (pearling) have almost the same economic performance. However, the levels of risk are dissimilar and may play a major role in decision making. Among these options, the base case with minimum level of risk due to its use of existing commercial technologies was favoured.

The two alternatives which show significantly better economic performance are Alternatives 4 (SSCF) and Alternative 3 (ultra filtration) due to their extremely high values of RTMU (Figure 7) justified by low raw material (sulphuric acid) consumption in Alternative 4, and low energy demand in Alternative 3.

The MCDM results show that the alternatives with the best performance on profitability-oriented criteria do not necessarily achieve the highest score. For instance, the base case for the PLA platform is the second-best alternative from a profitability perspective; however, Alternative 3 (ultra filtration) shows better overall economic performance due to its significant advantage on the business strategy-oriented criteria. This result suggests the need to consider both business strategy-oriented criteria and profitability-oriented criteria in decision making, especially in the biorefinery context.

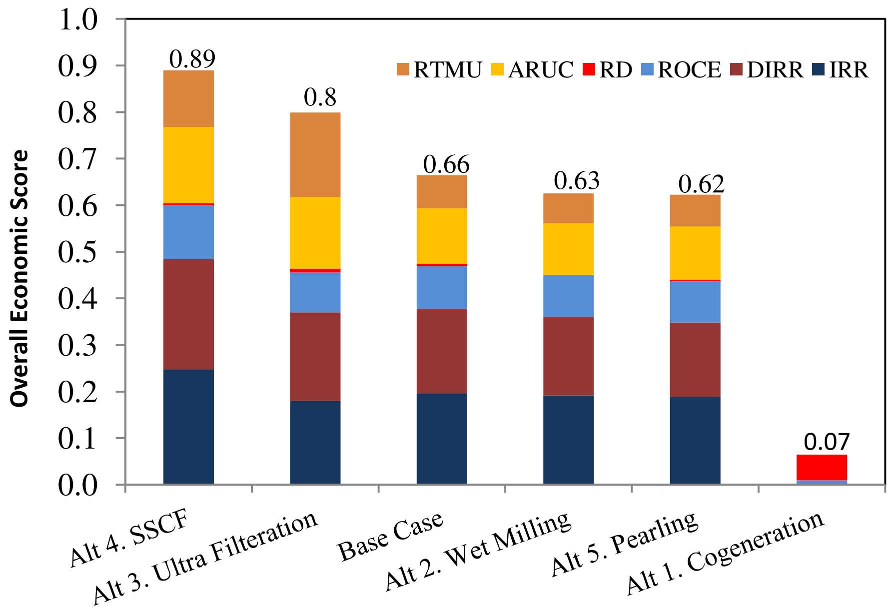


Figure 7: Economic scores of alternatives for the PLA platform resulting from MCDM.

## 4 CONCLUSIONS

The need to identify sustainable strategies in the triticale-based biorefinery context led this study to focus on techno-economic evaluation as one pillar of sustainability assessment. The economic performance of several triticale-based product-process alternatives, ranging from commodity to more value-added product platforms, was assessed by a set of profitability-oriented and business strategy-oriented criteria using the results of a systematic techno-economic analysis. The results show that producing value-added products is more profitable than producing commodity products, except for design alternatives on the commodity platform in which value-added co-products enable improved revenue creation. Moreover, the results show that the commodity product platform is less able to mitigate risk over the longer term, is less resistant to supply market volatility, and is more affected by external sources of uncertainty due to its higher dependence on biomass cost.

In contrast with most of companies that evaluate biorefinery on an ad-hoc basis, one strategy at a time, this study could employ a systematic approach to identify promising biorefinery strategies. In order to identify promising alternatives within a platform, a score was attributed to each design alternative on the PLA platform as a result of conducting an MCDM panel. The MCDM results show that the alternatives with the best performance on profitability-oriented criteria do not necessarily achieve the highest score. This underlines the need to consider both business strategy-oriented criteria and profitability-oriented criteria in strategic decision making, especially for the biorefinery context as a new business. The internal rate of return (representing short-term profitability), the downside internal rate of return (representing project robustness), and the resistance to supply market uncertainty (representing project sensitivity to external sources of uncertainty in the supply market) were the 3 criteria deemed suitable for the sustainability assessment. Moreover, the economic scores attributed to the alternatives show that producing electricity in the straw line through a combined heat and power unit is the least promising design alternative from an economic perspective and should be screened out of the list of promising strategies.

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# APPENDIX B – Article 2:

## Systematic Assessment of Triticale-Based Biorefinery Strategies: Sustainability Assessment using Multi-Criteria Decision Making (MCDM)

Modeling and Analysis

Biofpr
Biofuels Bioproducts & Biorefining

# Systematic assessment of triticale-based biorefinery strategies: sustainability assessment using multi-criteria decision-making (MCDM)*

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Abstract: Triticale – a hybrid of rye and wheat – is a man-made crop that has the potential to be a preferred feedstock for the biorefinery in Canada because of its ability to grow on marginal land, its high yields, and its non-competition with food-based crops. However, it is challenging to identify sustainable investment options among the many possible triticale-based biorefinery pathways. Several product-process combinations for the production of polylactic acid (PLA) were defined in this study, each involving different degrees of technology and market risk. The different biorefinery configurations had conflicting rankings considering different criteria, making a trade-off analysis essential to assess the most sustainable biorefinery strategies. Economic, competitive, and environmental dimensions of the biorefinery alternatives were thus evaluated in a multi-criteria decision-making (MCDM) panel, so that the triticale-based biorefinery strategies could be ranked using a sustainability perspective.

In this study, a set of ten criteria determined as the most important through previously-conducted MCDMs were presented to a decision-making panel. They determined that for PLA production, maximizing electricity production through a straw-dedicated CHP unit was the least sustainable investment option, due to poor economic and competitiveness performance associated with its capital-intensiveness and its failure to include a value-added product portfolio. Therefore, this investment option was screened out from the list of strategies to be further analyzed. On the other hand, options featuring higher technology risk including energy-efficient separation processes (ultra-filtration) and integrated fermentation processes (SSCF) attained significantly better sustainability scores due mainly to their low energy and raw materials consumption values. © 2014 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: biorefinery; triticale; sustainability assessment; sustainability criteria; multi-criteria decision-making (MCDM)



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## Introduction

Recently, there has been increased interest in the implementation of biorefineries that use a variety of biomass residues and non-food crops. Triticale (*X Triticosecale Wittmack*) has attracted much interest because it combines the productivity strengths of both wheat and rye, featuring the high yield potential and grain quality of wheat and the good environmental tolerance of rye.[1,2] The intrinsic properties of triticale, including its ability to grow on marginal land, its higher yield compared to wheat, and its non-competition with food-based crops, represent competitive advantages that are increasingly essential as a feedstock for competitive biorefineries. The Canadian Triticale Biorefinery Initiative (CTBI) network – a research program – has systematically analyzed triticale, targeting the development of this crop as an industrial biorefining crop in AQ1 Canada (http://www.ctbi.ca, (2013)). This body of work has shown that there are various possible triticale-based product-process alternatives involving different levels of technology and market risk, and requiring different amounts of capital investment. However, not all of these are necessarily sustainable, and not all will lead to value creation over the long-term for both farmer and potential industrial investor. A *sustainable* investment option must not only generate a reasonable profit, but should also be environmentally preferred, and remain competitive for the longer-term.

Sacramento-Rivero[3] developed a methodology for sustainability assessment of biorefinery strategies using a framework considering fourteen indicators within five themes: feedstock, process, product, environment, and corporate. This methodology generates a radar plot which can quantify the current distance of a biorefinery project from the ideal sustainability performance for each indicator, depending on how far the criterion value is from zero (representing the highest sustainability level). Although this study introduces an interesting set of normalized sustainability criteria, their integration into a unique sustainability score using an evaluating weighting factor for each criterion has not been addressed. Gnansounou[4] performed a sustainability assessment of two wheat-based bioethanol production strategies using twenty economic, environmental, and social criteria. The various criteria were qualitatively evaluated, leading to a lower level of accuracy compared to employing quantitative criteria which can be completely objective and verifiable. Gheewala *et al.*[5] analyzed the degree of sustainability associated with different scenarios of bioethanol production from sugarcane using five criteria, including three economic criteria and one criterion for each of the social and environmental pillars. In this study, choosing the most promising scenario was not challenging given that one scenario always showed the best performance on each sustainability dimension. However, in some situations, decision making can be more challenging, especially in the case where evaluated criteria are conflicting. In such a case, multi-criteria decision-making (MCDM) methods[6] can be used to deal with multiple conflicting objectives.[7,8] Although some systematic approaches in the literature have used multi-objective optimization methods to assess sustainability performance,[9,10] MCDM offers certain advantages over these, including: (i) reflecting the preferences of decision makers regarding the relative importance of the criteria, (ii) consensus building among project stakeholders, and (iii) a focus on criterion interpretation. The application of MCDM to identify sustainable strategies has been analyzed by Wang *et al.*[11] and Lai *et al.*[12] in energy and urban water systems respectively. Their approach is not limited to specific application and can be applicable in any other context, including the biorefinery.

Posada *et al.*[13] have used sustainability criteria to identify promising bioethanol-based products among twelve candidates. They considered a set of sustainability criteria, addressing economic, environmental, safety and health aspects, with arbitrary weights. The variability of their subjective weighting factors has been examined by changing the weights within a specified range with an upper and lower limit, using Monte Carlo analysis. The upper and lower boundary itself, however, was defined subjectively. The issue of arbitrary attributed weights to sustainability criteria can be seen in other studies in different contexts. For instance Sugiyama *et al.*[14] have arbitrarily attributed equal weighting factor to monetary and nonmonetary sustainability criteria. As a continuation of their work, Patel *et al.*[15] have added some criteria into their criteria list and then categorized them in five main groups of decision criteria with equal weighting factors. Schaidle *et al.*[16] have also assessed the sustainability of three biofuel production scenarios using ten conflicting criteria to identify the most sustainable option. Their criteria have been weighted arbitrary through four scenarios. Their results clearly show that applying different weighting factors can change the final decision dramatically. It proves the necessity of quantifying relative importance of decision criteria through a systematic approach.

Krajnc and Glavi[17] presented a methodology to obtain a sustainable development score for evaluating the sustainability performance of companies by integrating economic, environmental, and social criteria using an MCDM method. The European network, Biosynergy[18] has employed a similar method for considering different pillars of sustainability to assess biorefinery strategies. Othman[19] has also employed an MCDM method using a set of quantitative and qualitative sustainability criteria (economic, environmental, and social criteria) to compare some process design alternatives for biodiesel production. Besides all the values of these studies, it should be noted that they have used an MCDM method (analytical hierarchy process (AHP) method) which performs a quantitative comparison between the criteria and does not trade-off the values quantitatively. In addition, their employed MCDM method needs to deal with a large number of pair-wise comparisons between the criteria that is challenging specifically when decision needs be made using a large number of criteria.

The various lessons that can be extracted from the available studies in literature are summarized in three following points:

- *Objectively assessed criteria weighting factors:* In most of the available sustainability assessment studies arbitrary weights have been attributed to decision criteria. Although some studies have evaluated criteria weighting factors, the MCDM method they have commonly employed does not trade-off values quantitatively between panel members.
- *Criteria pertinent to longer-term biorefinery sustainability:* Conventional economic criteria such as return on investment (ROI) are important, however without business viability in the longer term, and competitive position in both biomass supply and the market, profitability alone cannot guarantee economic viability for a biorefinery project.
- *Social metrics:* On a practical level, social metrics can be closely linked to economic or environmental performance, and should be interpretable so as to result in a reasonable weight in order to impact the panel outcome.

The present study addresses these and other issues related to sustainability assessment, for the case study of assessing triticale-based biorefinery strategies for production of polylactic acid (PLA), involving the convening of a series of MCDMs (multi-attribute utility theory (MAUT)[6] method). Using the risk-based approach presented by Chambost *et al.*,[20] a base case and several product-process alternatives were defined for PLA production, each having different degrees of technology and market risk. These design alternatives were assessed using MCDM for different dimensions of sustainability using economic, environmental, and competitiveness perspectives.[21–23] Sanaei and Stuart[21] used a set of profitability and business-oriented criteria to assess the economic potential of each alternative, while Diffo *et al.*[22] used a set of competitiveness driven criteria to evaluate the competitive position of each option. Finally Liard *et al.*[23] used life cycle assessment (LCA) to quantify the environmental impacts of each alternative. Although social metrics are critical in sustainability assessment, they have not been explicitly considered here. One MCDM was conducted for each of the three sustainability pillars to identify the most promising alternatives from economic, competitiveness and environmental perspectives. The analyses yielded conflicting rankings of the alternatives, which showed the necessity of considering the identified important criteria in these three categories simultaneously to determine the most sustainable biorefinery strategies.

In this study, a sustainability assessment is made considering the most pertinent criteria identified from the MCDM conducted for each pillar.

## Context and previous work

### Scenario definition for PLA production from triticale

The implementation of a Greenfield triticale-based biorefinery near Red Deer in Alberta was considered in this study. A risk-based approach presented by Chambost *et al.*[20] has been used to define PLA production scenarios using both triticale grain and straw. This approach involved the definition of (i) a base case (Fig. 1) involving minimum technology risk while maximizing the production capacity of the main product, and (ii) several alternatives (Table 1) involving different degrees of technology and market risk and which should lead to higher expected



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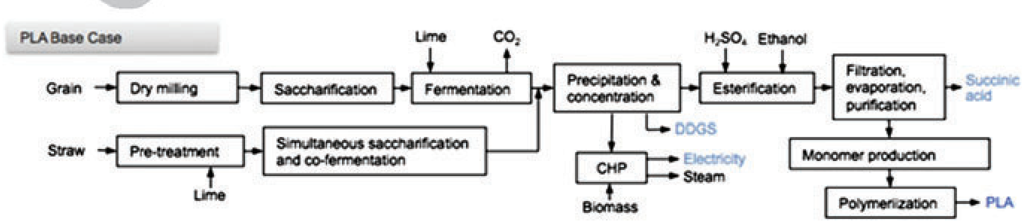


Figure 1. Block flow diagram of the base-case scenario for PLA production.[20]

**Table 1. Definition of PLA production options on the base case.**

| Alt. | Modification to PLA Base Case Process | Justification/Characteristics |
|---|---|---|
| 1 | Send straw to the combined heat and power (CHP) unit. | To investigate the effect of minimizing the risks in the straw line by producing electricity instead of bioproducts. Less capital intensive and also implies less technological risk. |
| 2 | Replace the dry milling unit in the grain line with a wet milling unit. | To investigate the role of producing an extra value-added by-product (protein). Results in purer starch in the main flow and also produces protein as a by-product. |
| 3 | Replace conventional separation in both grain and straw lines with ultra-filtration and electro-dialysis. | To investigate the effect of implementing a more efficient separation unit. Results in less energy consumption and produces acetic acid as a co-product. |
| 4 | Employ simultaneous saccharification and fermentation (SSCF) in the grain line. | To investigate the effect of process integration. Results in energy savings. |
| 5 | Add a pearling unit before milling in the grain line. | To investigate the effect of increased purity in the main flow and reduction in the size of the other units. |

return. The base case was defined based on two assumptions, namely (i) the use of prove commercial technology on the grain processing line (inspired by NatureWorks[24] technology), and (ii) the use of the most advanced process on the straw processing line to decrease the uncertainty in production of second generation bioproducts. The mass and energy balances associated with each alternative have been presented by Chambost *et al.*[20] assuming a production volume of 100 000 t/y for PLA. This production volume has been determined based on a market analysis.[22] Through consideration of different process alternatives, the product portfolio of each option yielded several interesting business opportunities summarized in Table 1, as follows: (i) 'Alt 1. Cogen' involves the production of electricity and steam by burning straw in a CHP unit; (ii) 'Alt 2. Wet Milling' implies the replacement of the dry milling unit in base case scenario by a wet milling unit, leading to the production of proteins; (ii) 'Alt 3. Ultra-filtration' involves the implementation of a more efficient separation process, leading to acetic acid production and elimination of gypsum; (iv) 'Alt 4. SSCF' implies the intensification of the process by the combination of saccharification and fermentation process steps into a single one; and (v) 'Alt 5. Pearling' involves the production of bran and stillage by the addition of a pearling unit to the grain line.

## Overview of key economic, competitiveness, and environmental results for the production of PLA

### Assessment of the PLA platform

Multi-disciplinary assessments, including techno-economic,[21] competitiveness,[22] and environmental[23] analyses, have been conducted to support early stage decision-making for investment strategies by answering the following questions: (i) What is the economic potential associated with each process alternative, taking into account different levels of technology risks? (ii) What is the competitive position associated with each product portfolio that may lead to viable and long-term business models? and (iii) What would be the environmental impacts or benefits associated with each investment option? To identify the most promising alternatives, three MCDM panels were convened that led to economic, competitiveness, and environmental scores for each alternative.

The economic performance of projects is often assessed using a profitability oriented criterion commonly presented by internal rate of return (IRR). From an investor's perspective, biorefinery projects should lead to value creation over the longer term while mitigating risks and ensuring competitiveness, and should guarantee business viability under the probable worst market conditions. Therefore, not only profitability oriented criteria, but also business oriented criteria should be considered to assess the economic viability of each investment opportunity. Sanaei and Stuart[21] developed a set of economic criteria addressing profitability driven as well as business driven issues to provide a better characterization of the economic potential of each alternative. Profitability oriented criteria included (i) IRR to assess the short-term profitability potential of the project, (ii) downside internal rate of return (DIRR) to evaluate the project robustness under the worst market conditions assuming highest biomass and lowest product prices, and (iii) return on capital employed (ROCE) to assess the efficiency of the investment. With regard to the need to measure the impacts of external parameters on margin creation (making profit), three additional criteria were defined including (i) resistance to supply market uncertainty (RTMU) to assess project sensitivity to raw material and energy cost fluctuations, (ii) ability to respond to unknown changes (ARUC) to measure the potential of risk mitigation by generating free cash flow, and (iii) revenue diversification (RD) to evaluate the benefits of margin creation and revenue stabilization associated with a diversified product portfolio.

From a business modelling point of view, a competitive assessment of biorefinery options is of critical importance to identify the most promising alternatives under different product portfolio potentials and to establish robust business strategies for long-term value creation. A market oriented assessment was performed by Diffo *et al.*[22] which considered various competitive market issues related to the context of the triticale-based biorefinery, including (i) competitive access to biomass (CAB) to assess the potential to secure low-cost access to biomass over the long term, (ii) product portfolio positioning (PPP) to evaluate the potential to capture market share and to secure a first-to-market position, (iii) competitiveness on production costs (CPC) to assess the potential to compete on market prices against the best technology available and to create margins, (iv) margins under price volatility (MPV) to evaluate the potential to create margins under the best and worst product price scenarios, and (v) technology strategy related to market competitiveness (TECH) to assess the flexibility potential of the process under market constraints.

From an environmental point of view, quantifying the potential environmental impacts of each alternative is a driver for sustainability assessment. Based on an LCA-based analysis, Liard *et al.*[19] used the most significant end-point impacts, with reference to IMPACT 2002+, as criteria to be considered for evaluating the PLA alternatives, including (i) human health (HH), (ii) ecosystem quality (EQ), (iii) GHG emissions (GHG), and (iv) non-renewable resources (NRR). Taking into account the context of triticale as an energy crop, other criteria, not represented in the end-point category, were considered as well such as (v) land occupation (LO), (vi) aquatic acidification (AA), and (vii) fresh water input (W).

Overall economic, competitiveness, and environmental scores for each alternative were calculated based on a series of three MCDM panels (Fig. 2).

The economic and competitiveness assessments resulted in somewhat similar alternatives ranking, especially for the two most promising alternatives (SSCF and ultra-filtration), as well as for the least promising investment option (cogeneration). The reason for this is that the cost-revenue basis is a common foundation of economic and competitiveness analyses. However, value creation potential is analyzed from two distinct points of view: (i) economic analysis assesses profitability and business viability potential, while (ii) competitiveness analysis evaluates the robustness of the strategy in meeting short and longer term business model objectives. In addition, it should be noted that although there might be some similarities in the parameters used to evaluate the economic and competitiveness criteria, these two types of criteria have completely independent interpretations and thus for decision-making purposes they are considered as independent criteria. The poor competitive performance of the base-case scenario can be attributed to the production of a lower volume of co-products, which weakened the competitive position of the product portfolio. The cogeneration alternative is capital intensive and is sensitive to biomass prices, so offered relatively little economic or competitive potential, although it resulted in considerable environmental benefit.

With the conflicts in rankings, no clear answer was obtained regarding which alternatives are sustainably promising for investment and should be further considered.

## Identifying a set of critical criteria for sustainability assessment

Through the three MCDM activities, a set of necessary criteria was identified for the specific case of PLA production from triticale feedstock.

Aggregating the three sustainability dimensions for decision-making potentially involves a large set of decision-making criteria, increasing drastically the level of inconsistency and making a single panel impractical. Therefore, a refined set of pertinent criteria was identified based on the three MCDM panels covering economic, competitiveness, and environmental perspectives (Fig. 3).

From the economic perspective, among the profitability oriented criteria, IRR, and DIRR were selected as the most important economic criteria due respectively to the importance of short-term profitability in the biorefinery project and the need for project robustness. Moreover, among the business strategy oriented criteria, RTMU was selected as the most important criterion due to the magnitude of project sensitivity to variations in the impacting parameters such as raw material and energy costs.[21] From a competitiveness perspective, CAB, CPC, and MPV were selected as the most important criteria for decision-making, due mainly to (respectively) (i) the competitiveness associated with securing access to feedstock and building

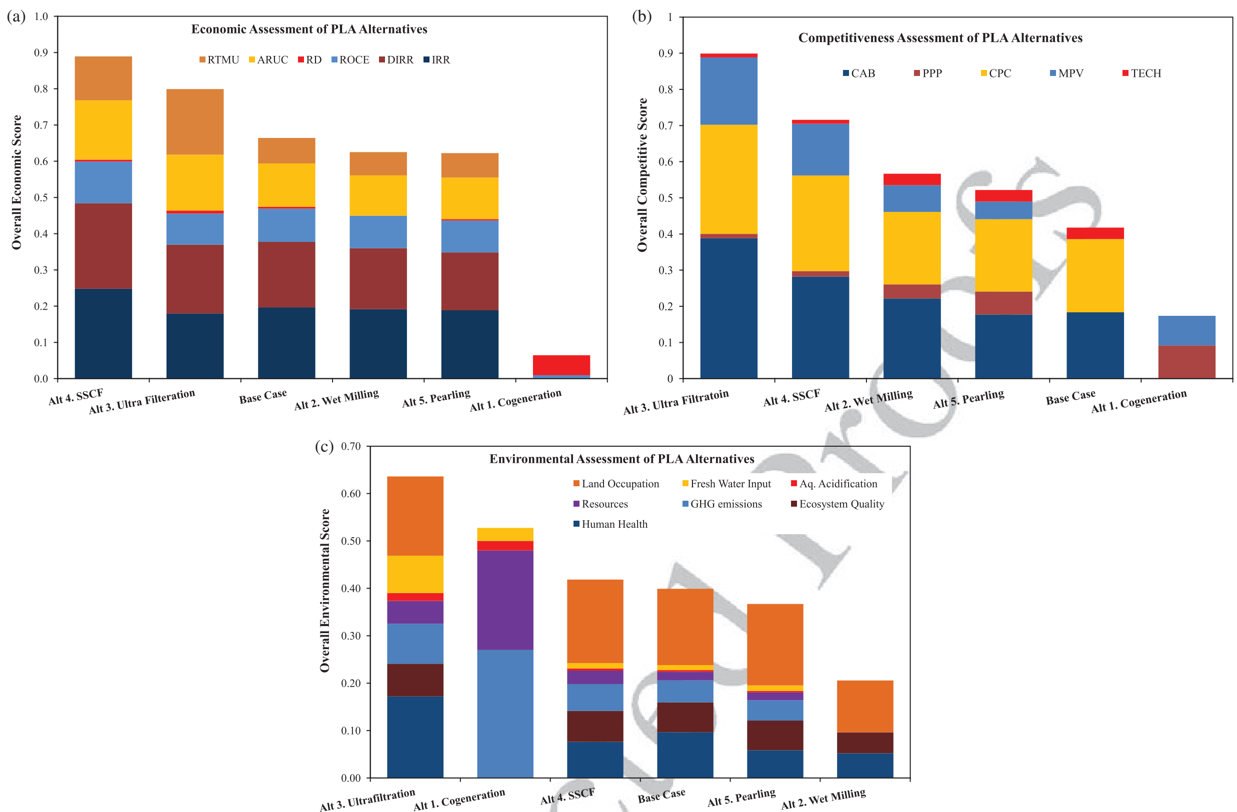


Figure 2. Ranking of PLA production alternatives using (a) economic, (b) competitiveness, and (c) environmental assessments.[21–23]

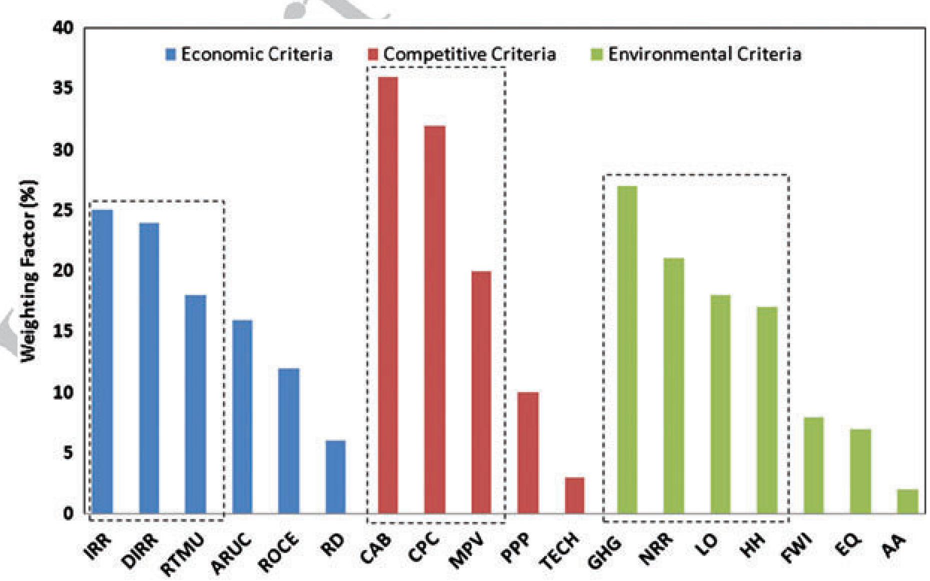


Figure 3. Weighting factors of economic, competitiveness, and environmental criteria according to three MCDM panels.[21–23]

  | *Biofuels, Bioprod. Bioref.* (2014); DOI: 10.1002/bbb

a value proposal for farmers, (ii) the potential to be cost-competitive and to provide a low-cost value proposal to the consumer, and (iii) the potential to generate margins under volatility.[22] Finally from an environmental perspective, GHG, NRR, LO, and HH were selected as the most important criteria for sustainability assessment, taking into account (respectively) that (i) GHG mitigation is a priority in Alberta, with a likelihood of potential future regulations to favor large GHG emission reductions; (ii) energy savings are crucial for biorefinery development considering the limited amount of resources available; (iii) land use is a critically important issue in the context of the food-to-fuel debate; and (iv) human health is a generically important concept when considering environmental impacts on human beings.[23]

This set of refined criteria involving ten sustainability metrics was then used as a basis for conducting an overall MCDM focussed on evaluating the degree of sustainability associated with each investment option.

## Methodology

The overall methodology employed in this study is summarized in Fig. 4 and can be divided into two major parts:

*(1) Part I:* Assessing the competitiveness, economic and environmental performance of the investment options using a set of criteria, and then conducting an MCDM panel for each pillar separately (MCDMs Nos. 1–3) to identify a set of important sustainability criteria.[21–23]

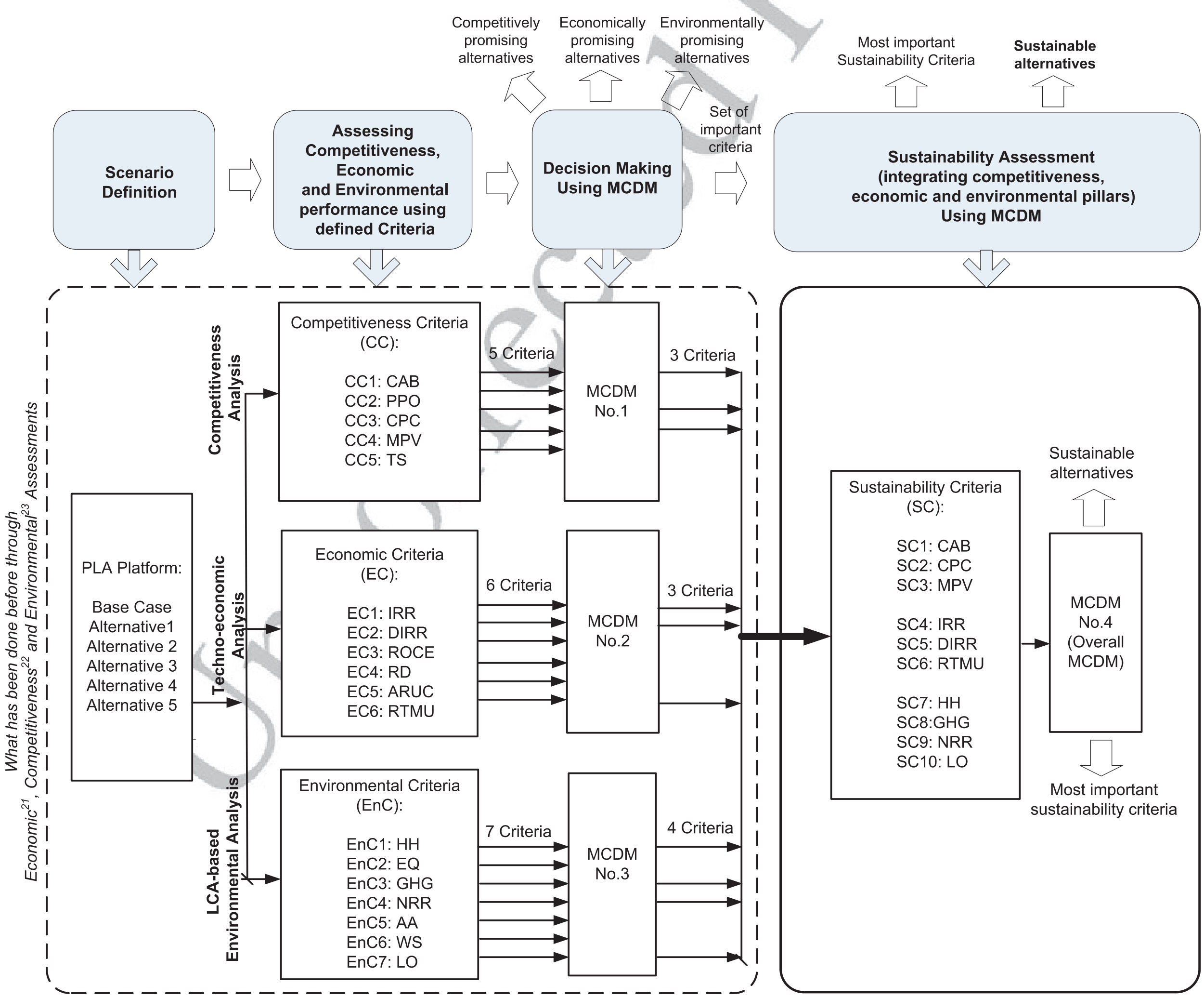


Figure 4. Sustainability assessment methodology.

(2) *Part II:* Integrating these three pillars into an overall MCDM panel (MCDM No. 4) using the refined set of sustainability criteria.

The criteria used for decision-making on the sustainability of each alternative (Part I outcome) are presented in Table 2 along with the interpretation of each criterion. In the case of the economic and competitiveness criteria, a higher value indicates better performance, while for the environmental criteria, the opposite is true. To obtain an aggregated score that reflects the level of sustainability of investment options using these criteria, an importance is attributed to each criterion through a weighting activity using a trade-off method,[6] referred to as MCDM No. 4 in Fig. 4. Based on the weights obtained in the panel activity, a unique sustainability score was attributed to each alternative. Using this score, the most sustainably promising investment options which have the highest sustainability scores were identified.

## Multi attribute utility theory (MAUT) method

Among the available MCDM methods, multi-attribute utility theory (MAUT)[6] has been chosen in this study. In this method, the metrics that quantify the decision criteria are called attributes, for instance if profitability of a design alternative would be a decision criterion, IRR can be considered as the attribute.[25] In the MAUT method, there are two key parameters used to rank the design alternatives which are (i) utility function ($u_i(x_i)$) and (ii) relative importance of each decision criterion ($w_i$). Using these two parameters, the overall utility value ($U(x)$) of each design alternative, that in this study represents the overall sustainability performance of that alternative, is calculated according to the following equation:

$$U(x) = \sum_{i=1}^{N} w_i \cdot u_i(x_i) \qquad (1)$$

where $U(x)$ is the overall utility value or sustainability score, $N$ is the number of criteria, $w_i$ is weighting factor of criterion i such that $0 \leq w_i \leq 1$ and $\sum_{i=1}^{N} w_i = 1$, $u_i(x_i)$ is the utility function of criterion i.

### Utility function

The utility value of each attribute is a value between zero and one that is evaluated using a utility function. In order to develop that function for each criterion, two values are required which include the lower and the upper bound for that criterion.[25] These boundaries would respectively represent the worst criterion value- or the worst attribute value ($x_{i\ Lower\ Bound}$) - at which the utility value would be zero ($u_{x_{i\ Lower\ Bound}} = 0$) and the best criterion value ($x_{i\ Upper\ Bound}$) at which the utility value would be one ($u_{x_{i\ UpperBound}} = 1$). A function between these two boundaries would be called utility function which is commonly assumed to be linear by default. If the criterion value for an alternative is equal to or below the lower bound, its utility value would be zero and if the criterion value is equal to or higher than the upper bound its utility value would be one.[25]

For criteria that higher values are better (e.g. IRR), the minimum criterion value that for any value below it the panel would not have any preference among the alternatives, should be set as the lower bound and similarly maximum criterion value as the upper bound.

### Weighting factors

As mentioned before, the trade-off[6] method is used for weighing the decision criteria. As its first step, after interpreting the decision criteria, all the panelists are asked to select the most important criterion and to determine a target value for it. The target value in this study is the minimum acceptable value for the most importance criterion satisfying investors to invest in a triticale-based biorefinery strategy.

The trade-off method is based on indifference judgment between criteria, evaluated for different alternatives.[25] In this method, each decision-maker determines a criterion value that makes him/her indifferent between two situations A and B. In these designed situations the value of the most important criterion (k) and a criterion that is compared with it (m) is different but the values of the other criteria are assumed to be the same. The indifference in this comparison means that the overall utility value (U) of these situations (A and B) should be the same (Eqn (2)):

$$U_A = U_B \qquad (2)$$

In order to evaluate the relative importance of the criteria, a criterion is compared with the most important criterion one at the time. In each comparison the panelists are asked to determine if in situation A they would have the target value for criterion k and the minimum value for criterion m, this is indifferent for them with which value of criterion k in situation B when criterion m would be at its maximum value. Indifferent judgment between situations A and B for each criterion, and considering that the weights should always add up to one, result in the

**Table 2. Set of sustainability criteria for decision-making.[21–23]**

| Sustainability Criteria (SC) | | | Interpretation | Definition of Metric |
|---|---|---|---|---|
| Economic Criteria[21] | SC1: IRR | Internal Rate of Return | Measures profit/risk ratio under normal market conditions. IRR should be greater than 20% as the minimum risk target for emerging industries to guarantee their **profitability in the short term** before considering any probable future improvement. | $NPV = \sum_{t=0}^{22} \frac{CF_t}{(1+IRR)^t} = 0$ |
| | SC2: DIRR | Downside Internal Rate of Return | Measures the viability of the business model to guarantee the **robustness** of the project by maintaining profitability (pessimistic IRR above 11%) under the worst predicted market conditions (maximum biomass price and minimum product price). It shows that the project can survive and continue production even under the worst predicted market conditions. | $NPV = \sum_{t=0}^{22} \frac{CF_t}{(1+DIRR)^t} = 0$ |
| | SC3: RTMU | Resistance to Supply Market Uncertainty | Measures the **sensitivity** of the project **to the fluctuation in market value of key parameters** in a biorefinery context (raw materials and energy). A project with high RTMU would be less sensitive to any change in raw material and energy prices to minimize its vulnerability to external sources of uncertainty. | $\frac{\text{EBIT per ton of product}}{\textbf{cos}\ t \text{ of (raw materials + Energy) per ton of product}}$ |
| Competitiveness Criteria[22] | SC4: CAB | Competitive Access to Biomass | Represents the **ability to guarantee a supply of biomass** over the long-term while providing a competitive value proposal to farmers. It shows also the **potential to face volatility on biomass prices.** | *EBITDA per ton of biomass* |
| | SC5: CPC | Competitiveness on Production Costs | Shows **how competitive the alternative is** compared to the current benchmarked PLA production, as well as the potential to increase market share through a competitive pricing strategy and the potential to minimize the impacts of volatility due to competitors' pricing strategies to achieve good market share in the long term. | $\frac{\text{production } \textbf{cos}\ t \text{ benchmark} - \text{current production } \textbf{cos}\ t}{\text{production } \textbf{cos}\ t \text{ benchmark}} \times 100$ |
| | SC6: MPV | Margin under Price Volatility | Shows the **potential to generate margins** under the lowest product market prices and to extract benefits from positive price fluctuations in those markets. It demonstrates as well the **potential to achieve an economically sustainable business model over the long term**. | 60% *worst case EBITDA* + 40% *best case EBITDA* |
| Environmental Criteria[23] | SC7: GHG | GHG Emissions | Shows the potential contribution of a biorefinery project to **climate change** through GHG emissions in terms of the number of cars equivalent. | $\frac{\text{GHG emissions (kg } CO_2 \text{ equivalent)}}{\text{Yearly GHG emissions per average Canadiancar (kg } CO_2 \text{ equivalent)}}$ |
| | SC8: NRR | Non-Renewable Resources | Shows **the amount of non-renewable resources consumed or saved** by the project in terms of energy compared to the reference case. | $\frac{\text{Fossil based energy consumption (MJ)}}{\text{Coal based available reserves (MJ)}}$ |
| | SC9: LO | Land Occupation | Shows the proportion (in %) of productive land used for the project compared to the total area used to produce wheat (for food purposes) in the Prairies. It therefore represents the **potential competition with food.** | $\frac{\text{Land occupation } (m^2)}{\text{Land occuption by wheat in the prairies } (m^2)}$ |
| | SC10: HH | Human Health | Shows **the impact contribution (in %) of the biorefinery project on human health** based on increased number of healthy years due to the absence of non-GHG pollution and especially particulate matter equivalent (PMeq) emissions (including PM, Sox, and Nox emissions), compared to other main activities around Red Deer. | Human health impact (DALY)/Human health impact (DALY) incurred by the total emissions of particulate matter (PM), SOx, and NOx in the area of Red Deer |

NPV: Net Present Value.
CF: Cash Flow.
EBIT: Earnings before Interest and Tax.
EBITDA: Earnings before Interest, Tax, Depreciation and Amortization.
DALY: Disability Adjusted Life Year.

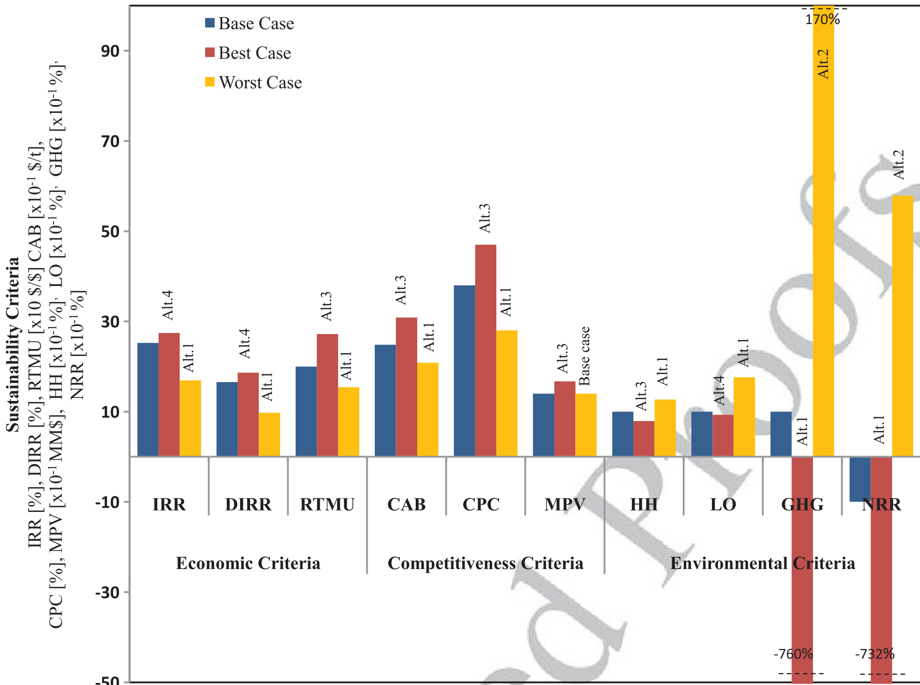


Figure 5. Sustainability criteria evaluation for base case, best case and worst case PLA production alternatives.

following equation by which weighting factors of the decision criteria are obtained.[25]

$$\begin{bmatrix} 1-u_k(x^B_{k,m=1}) & -1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 1-u_k(x^B_{k,m=N}) & 0 & \cdots & -1 \\ 1 & 1 & \cdots & 1 \end{bmatrix} \begin{bmatrix} w_1 \\ \vdots \\ \vdots \\ w_N \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} \quad \forall m \neq k \qquad (3)$$

More information regarding the mathematics of this method can be found in what Janssen has done.[25]

## Results and discussion

### Evaluating sustainability criteria

The sustainability criteria are shown in Fig. 5 for (i) the base case, (ii) the best case represented by the highest values for the economic and competitiveness criteria and the lowest value for the environmental criteria, and (iii) the worst case represented by the lowest value for the economic and competitiveness criteria and the highest value for the environmental criteria. Consideration of the information in Fig. 5 highlights the complexity involved in decision-making regarding which PLA production alternatives to favor from a sustainability perspective.

This set of ten criteria and their outcomes were used in the final MCDM panel to evaluate sustainability of different PLA production alternatives. The multi-disciplinary panel involved five panellists from industry and academia, and was the same panel that participated in the three previously convened MCDMs. The panellists had various backgrounds, including biorefinery, energy, economics, market, and environmental expertise, which ensured that expertise in the critical dimensions that should be considered in strategic decision-making would be captured.

### Decision-making

#### Criteria weighting

The first step in conducting the MCDM panel is the weighting activity, for which the first stage requires selecting the most important criterion, and choosing a target value for that criterion based on the preferences of the panellists. The IRR criterion was selected as the most important criterion by the panel, with an average target value of 28.8%. Using the trade-off method, the panelists determined how much of the 28.8% they would agree to lose, in order to increase the value of another criterion from its lowest value among the alternatives to its highest

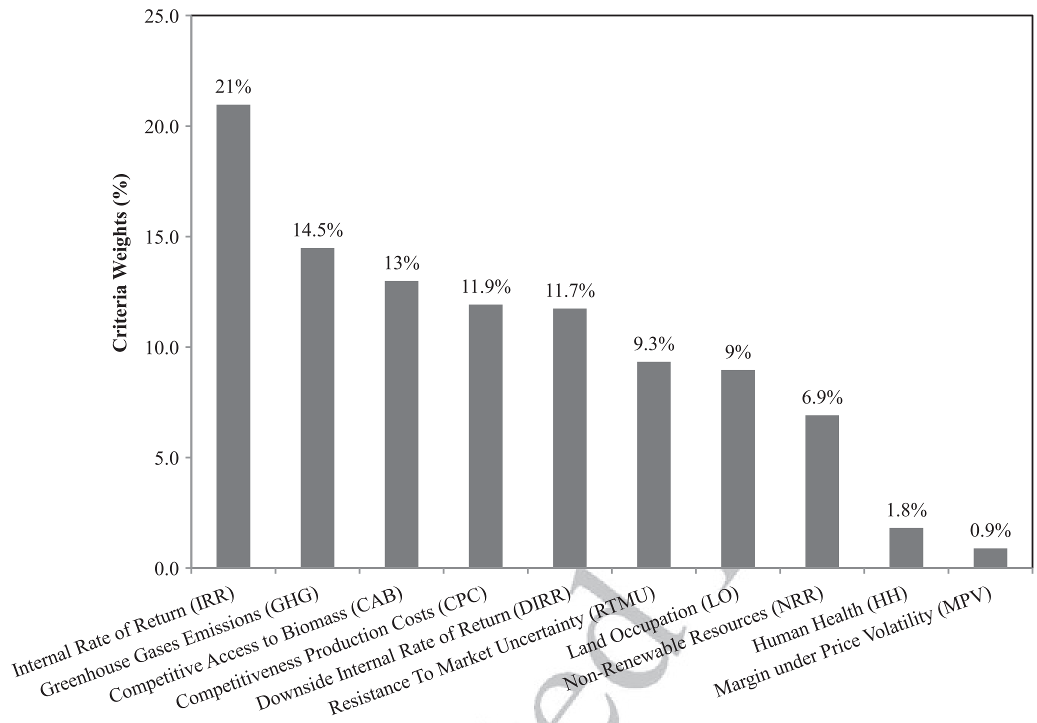


Figure 6. Weights of sustainability criteria obtained in the overall MCDM.



value. For instance, the amount that a panellist would agree to lose from the 28.8% value of IRR to increase DIRR from 9.8% (its lowest value) to 18.7% (its highest value) determines the relative importance of DIRR compared to IRR. The average values of the numbers given by panel members to this comparison for each criterion were used to calculate weighting factors of the criteria according to Eqn (3). The calculated weights are presented in Fig. 6.

Interestingly, the three first-ranked criteria had already been selected as the most important criterion in its own category through previously performed MCDMs: IRR in the economic driven MCDM, GHG in the environmentally driven MCDM, and CAB in the competitiveness driven MCDM. This sustainability MCDM exercise demonstrated that despite the conventional mentality about making decisions based only on economic criteria, both environmental and market competitiveness criteria are important, and can be more important than other economic criteria such as DIRR and RTMU in the context of this study.

The two least important sustainability criteria were HH and MPV. The low importance of the HH criterion can be explained by its associated scale, which is local opposite of the other defined environmental criteria. MPV has been recognized as an important criterion in concept, to consider in decision-making; however in this case it did not help to differentiate among alternatives because the MPV values of all the alternatives were similar.

The standard deviation of the scores that panel gave to one criterion in trade-off activity, can represent the level of consensus among the panel on the relative importance of that criterion. For instance, the low standard deviation associated with given numbers to HH criterion, implies a high degree of consensus on selecting this criterion as one of the least important sustainability criteria. The lowest level of consensus among the panellists occurred for the NRR criterion due to disagreement among the panellists about the scale of the effect of this criterion: some panellists looked at this criterion on a regional scale and believed that in Alberta it could not be considered as an important issue. However, another group of panellists believed that it could have a high impact if viewed on a universal scale through an overall vision.

## Utility function

In this study, for each of economic and competitiveness criteria, the utility value of minimum criterion value among the alternatives has been set to zero (lower bound). Whereas environmental criteria for which the maximum criterion value among the alternatives represents the lower bound. Similarly the utility value of the best criterion value among the alternatives has been set to one (upper bound). For any criterion value in between the lower bound and the upper bound, the utility value has been calculated according to a linear function that links these two boundaries.

Exceptionally for IRR as the most important criterion, in which target value (28.8%) is higher than the maximum criterion value among the alternatives, target value has been set as the upper bound with utility value equal to one.

## Ranking of alternatives

To define the overall sustainability performance associated with each alternative, a unique score ($SC_e$) was obtained using the weighting factors ($w_i$) and the calculated utility values associated with each sustainability criterion ($u_i$) using the following formula:

$$SC_e = \sum_{i=SC_1}^{i=SC_{10}} w_i . u_i \qquad (4)$$

In Fig. 7, all alternatives have been ranked using their overall sustainability scores. These scores indicate that the least promising alternative for PLA production from triticale is alternative 1 – cogeneration. In this alternative, GHG, NRR, and MPV were the most strongly contributing criteria, with GHG playing a major role in the overall score, because the values of the other criteria were the smallest among all the alternatives, and consequently their associated utility values were set to zero. Despite the promising environmental performance of this alternative, it remains a capital intensive investment option with a high level of sensitivity to biomass price because of the large quantity of biomass required. Moreover, it does not involve a value-added product portfolio, resulting in poor economic and market-competitive performance.

The overall sustainability scores show that the base case, alternative 2, and alternative 5 were ranked similarly. However the levels of technology and market risk are dissimilar and could play a major role in decision making, favoring the base case that involves existing commercial technologies and therefore a lowest level of risk.

It was concluded that the PLA production scenario maximizing electricity as a co-product through a straw-dedicated CHP unit was the least sustainable investment option and therefore it was screened out by the panel from the list of promising triticale-based biorefinery strategies to be further analyzed. On the other hand, the options featuring higher technology risk, which involve energy efficient separation processes (ultra-filtration) or more integrated processes (SSCF), obtained significantly better sustainability scores, due mainly to their low energy and raw

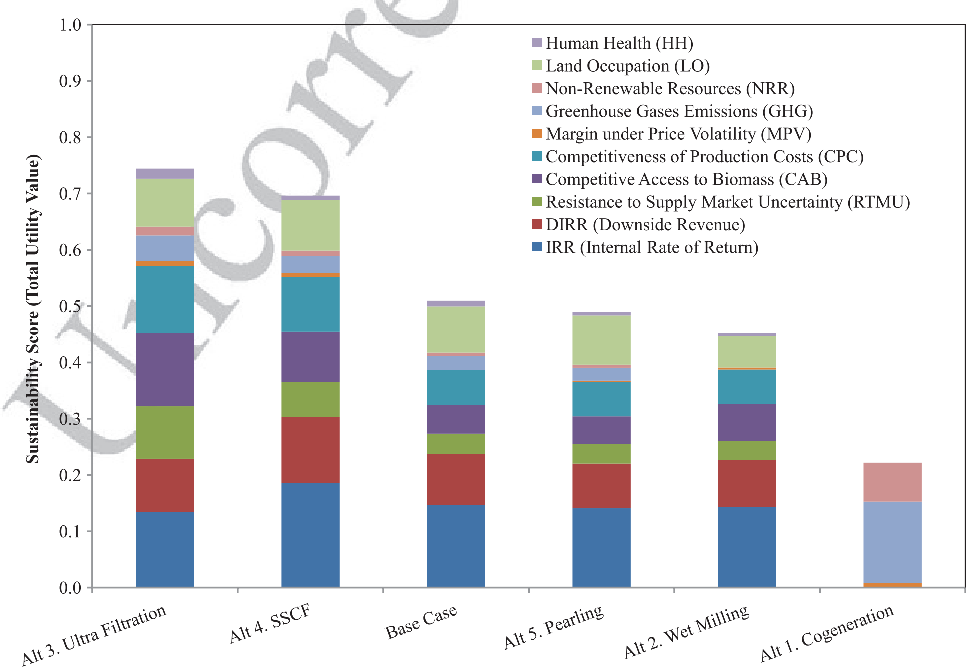


Figure 7. Sustainability Scores of PLA Production Alternatives.





*Biofuels, Bioprod. Bioref.* (2014); DOI: 10.1002/bbb

materials consumption values. The MCDM results show that without considering environmental contributions to the sustainability score, two promising alternatives (SSCF and ultra-filtration) could not be distinguished. SSCF was favored from an economic perspective, due mainly to its cost reduction because of process intensification, while ultra-filtration was favored from a competitiveness perspective, due mainly to the competitive market position of its product portfolio. However, the better environmental performance of ultra-filtration, due mainly to reductions in lime and sulfuric acid consumption, did result in a slightly higher overall sustainability score for this alternative compared to SSCF. This confirms the importance of environmental contributions in differentiating among investment options from a sustainability point of view. These two alternatives are not distinguishable in terms of associated risk with them.

## Conclusions

The sustainability of several investment options for PLA production from triticale has been assessed in this study using an MCDM tool with a set of ten multi-disciplinary criteria. In contrast to conventional analyses which often consider short-term profitability metrics for decision making, this work takes into account complementary criteria representing business oriented performance, potential environmental footprint, and market competitiveness as critical indicators of the sustainability of the biorefinery strategies using a longer term vision. These conflicting sustainability criteria were simultaneously considered in an MCDM panel, to attribute a unique sustainability score to each investment option and ranked them by their sustainability performance.

The MCDM results showed that profitability (IRR), potential contribution to reduction of GHG emissions (GHG), and competitive access to biomass (CAB) were the most important sustainability criteria for distinguishing the PLA production alternatives. It was also concluded that the PLA production scenario (Alt.1 cogen) maximizing electricity as a co-product through a straw-dedicated CHP unit was the least sustainable investment option. As a result, this investment option was screened out by the panel from the list of promising triticale-based biorefinery strategies to be further analyzed. On the other hand, the options featuring higher technology risk, which involve energy efficient separation processes (Alt.3 ultra-filtration) and more integrated processes (Alt.4 SSCF), with very close sustainability performance were identified as the most sustainable investment options among the candidate triticale-based biorefinery strategies. The base case, Alternative 2, and Alternative 5 show almost the same sustainability performance. However, the levels of risk are dissimilar and may play a major role in decision making. Among these options, base case with minimum level of risk due to its use of existing commercial technologies is favored.

The overall methodology used in this study illustrates the strength of the trade-off MCDM method for distinguishing between product-process options using a sustainability perspective in a number of ways such as (i) the transfer of knowledge on a range of sustainability criteria to decision-makers having diverse backgrounds, (ii) the systematic approach raises awareness and respect of the panel members for the interpretation of the sustainability criteria, (iii) the diverse criteria are compared and weighed on a comparable basis, taking into account the outcomes of each alternative, and (iv) the results of preferred and less preferred production alternatives can be systematically explained.

## Acknowledgements

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# APPENDIX C – Article 3:

# Systematic Retrofit Design Methodology for Evaluation of Integrated Forest Biorefinery Strategies

## Systematic Retrofit Design Methodology for Evaluation of Integrated Forest Biorefinery Strategies

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**ABSTRACT**

North American forest product companies are considering the transformation of their businesses through biorefinery integration into their existing pulp and paper facilities. However not all biorefinery strategies are sustainable and not imply the same level of risk. In order to assess biorefinery strategies, it is essential to first identify the potential integrations between biorefinery candidates and the existing mill, and then to evaluate the cost synergies associated with these potential integrations. This article describes it as retrofit design methodology. Considering the unique characteristics of the studied kraft pulp mill, four biorefinery technologies were identified as transformation strategies. It was found that the main cost savings belong to integration potentials at the energy island and waste water treatment unit. The results of retrofit design that are used in economic analysis in this study can then be used to further analyze the candidate biorefinery strategies in terms of their sustainability performance.

Key words: Integrated Forest Biorefinery, Retrofit Design, Techno-economic assessment, Multi-Criteria Decision-making (MCDM)

## 1 INTRODUCTION

Although the North American forestry industry can survive in the short term by cost reductions, for the longer term forest products companies are increasingly considering business transformation in order to improve their financial position. One of these transformation strategies is integration of biorefinery technology into the existing pulp and paper facilities of forest products companies. However, all biorefinery strategies are not necessarily promising in terms of sustainability and financial performance. Thus screening out unsustainable strategies from the list of possible solutions at the early stage strategic design is essential to arrive at promising biorefinery strategies. However a systematic approach is essential to achieve this efficiently. In this regard a systematic retrofit design methodology followed by economic evaluation is presented in this paper.

There are several studies in the literature focusing on process integration in existing pulp and paper facilities with the objective of cost minimization. In order to minimize the operating cost, many studies have considered energy and mass integration mostly employing pinch, advanced pinch and water pinch analysis methods and optimization techniques (Atkins, Walmsley et al. 2011; Jönsson, Ruohonen et al. 2011; Moshkelani, Marinova et al. 2013). These integration methods have been described in detail by El-Halwagi (El-Halwagi 2006). A second group of studies considers capital cost reduction by property integration and the possible synergies at the mill (Stuart and El-Halwagi 2013). Both of these cost reduction approaches have been applied mostly for the existing process units at the mill with the objective of profitability improvement by yield enhancement, resource conservation (mass and energy), waste minimization and quality enhancement (El-Halwagi 2006). Although these methods, along with revenue maximization by finding the best product combination, have been also applied in the retrofit context, it has been done always for a single biorefinery technology (Mateos-Espejel, Moshkelani et al. 2011; Moshkelani, Marinova et al. 2013). This implies that before any probable cost minimization analysis at the tactical or operational level of design, promising biorefinery technologies for being integrated into the mill should be identified at the strategic level of design. In order to meet this objective, candidate biorefinery technologies should ideally be compared in terms of performance using an overall sustainability context. As a first step, potential synergies between the mill and biorefinery options should be identified. Some of these synergies have been addressed in literature, but not systematically. For instance, Hytönen et al. (Hytonen and Stuart 2009) have analyzed integration of biorefinery technologies into a kraft pulp mill considering capital cost savings, operating cost synergies and revenue diversification for bioethanol production. They have considered three main integration opportunities including energy, feed water and wastewater systems. However their work makes no mention of cost synergies in the materials handling system, nor incremental costs caused by the additional operating labor to handle biorefinery plant. Moreover, it is unclear whether associated costs for modifications of existing equipments at the mill being to be used above their current capacity to cover biorefinery utility demand have been addressed.

Selecting sustainable biorefinery strategies for a company is not a straightforward task especially when considering sustainability criteria which are conflicting between options, in which case multi-objective decision-making must be used (Othman 2011). This approach enables stakeholders and decision-makers to compare different biorefinery strategies for their core business transformation, that has been employed by Sanaei and Stuart (Sanaei and Stuart 201X) to assess the same studied technologies in this work.

The overall objective of this study is to present a systematic approach for retrofit design and economic analysis of integrated forest biorefinery strategies at the early stage of design, using the investor perspective.

## 2 METHODS OF RETROFT BIOREFINERY DESIGN

In a retrofit biorefinery context, there are several integration potentials between the existing facilities in pulp production line(s) at the mill and the biorefinery plant. In order to quantify these potential synergies, and to maximize the benefits of transformation strategy, the unique characteristics of the mill and integration potential should be identified. The potential integration opportunities can be categorized in three sectors including process, biomass and product.

**2.1. Biorefinery Integration Potential with Existing Mill Processes**

The first integration with existing pulp production process can be using the residual streams from the mill in the biorefinery process. For the case study mill, mass balances show that there are some potentially available streams including knots, turpentine, fines and reject oversize chips that may have potential to be used in biorefinery processes. Other potential integrations with the process can be process units that have the capability to be integrated into the biorefinery process. These major process units include (1) boilers and turbines at the energy island (energy integration), (2) wastewater treatment plant, (3) landfill area for solid wastes and (4) unused existing equipment.

In order to evaluate energy integration potential, the existing energy island at the mill and its operation must be characterized, and the energy sinks and sources should be identified by the mill energy balances. This indicates whether the case study mill is energy demanding, or whether it has excess steam or electricity that can be used in the biorefinery. The next step involves the identification of the types and working capacities of the boilers and turbines comprising the energy island. This helps identify how much of the energy in the biorefinery process can be supplied by existing energy island, and consequently how much incremental fuel would be needed to produce total estimated energy consumed by biorefinery process. In the case that existing nominal capacities of the boilers and turbines are adequate to support the energy demand of both biorefinery and pulp processes, then simply the cost of excess fuel fed to the boilers must be considered in the economic analysis. Cases where new boilers are required to support high energy demands of biorefinery processes must consider the cost of additional fuels and also the cost of new steam generation capacity in the most practical manner.

Another process integration consideration involves evaluating whether the liquid discharge emanating from the biorefinery process can be treated in the existing facilities at the mill. In order to evaluate this in a preliminary manner, the Biochemical Oxygen Demand (BOD) load and hydraulic load increases should be considered, as well as additional biosolids generation – and compared to spare capacity to determine capital investment needs. As well, the associated operating cost from increased aerator power consumption as well as solids management costs should be addressed in the economic analysis. Moreover, the composition of liquid wastes from the biorefinery process should be estimated, which can be challenging. As an example, when liquid wastes have a low pH, the cost of neutralization should be addressed in the economic analysis. Besides liquid wastes, biorefinery process may have solid wastes likewise. Sometimes existing landfills or other facilities may have enough capacity to handle these, and otherwise the solid wastes may need to be sent to the landfill of other facilities close to the mill.

At many mills there can be unused equipments that can potentially be used to reduce biorefinery capital costs. In these cases, the cost of bringing these equipment items to specification for incorporating into the biorefinery process should be carefully assessed.

**2.2. Biorefinery Integration Potentials with Biomass Harvesting and Handling**

One of first questions for examining the potential of biorefinery processes concerns the type and quantity of biomass required for the strategy, and the price that this can be supplied at from the woodlands around the mill. In order to estimate the available biomass, the existing and potential future demand of other mills in the area should be considered. In evaluating the delivered biomass price for the biorefinery the annual allowable cut should be taken into account, along with the estimated biomass harvesting, loading and transportation costs as well as stumpage fees, when integrated into the pre-existing harvesting operations.

Another potential integration opportunity related to biomass concerns synergies in material handling systems. When using different types of biomass feedstock for the new biorefinery process compared to those used for the pulp and power production processes, we should consider whether new material handling equipments are needed to avoid biomass contamination.

### 2.3. Biorefinery Integration Potential with Product

One of the most important potential synergies between the mill and biorefinery process concerns product portfolio diversification and supply chain synergies. The potential benefits of margin creation and revenue stabilization associated with diversifying the product portfolio should be carefully addressed by adding the revenue from biorefinery products to the existing products at the mill, considering the delivered costs to the customer. To do this at the early stage of design is difficult since it requires a careful evaluation of the affected supply chains, not only at the strategic level but also at the tactical-operational levels. Supply chain design of integrated forest biorefinery has been addressed in literature through several studies such as Mansoornejad et al (Mansoornejad, Pistikopoulous et al. 2013) and Dansereau et al. (Dansereau, El-Halwagi et al. 2012). However even considering its importance, this analysis is beyond the scope of this study. The economic analysis in this study covers costs associated with business transformation from the delivered biomass at the mill gate to the final products excluding transportation considerations to the target markets.

Considering these potential integration opportunities and taking into account the specific characteristics of the case study mill, some biorefinery technologies can be selected to be integrated into the mill as candidate transformation strategies. These technologies should be assessed in terms of economic performance as a sustainability pillar enabling decision-makers to identify the preferred strategies.

## 3 RESULTS AND DISCUSSION

### 3.1. Existing mill

The case study mill is a kraft pulp mill with pulp production capacity of about 1000 bdt/d, from about 2000 bdt/d of softwood chips. A simplified process flow diagram of the pulp production processes at the mill is presented in Figure 1.

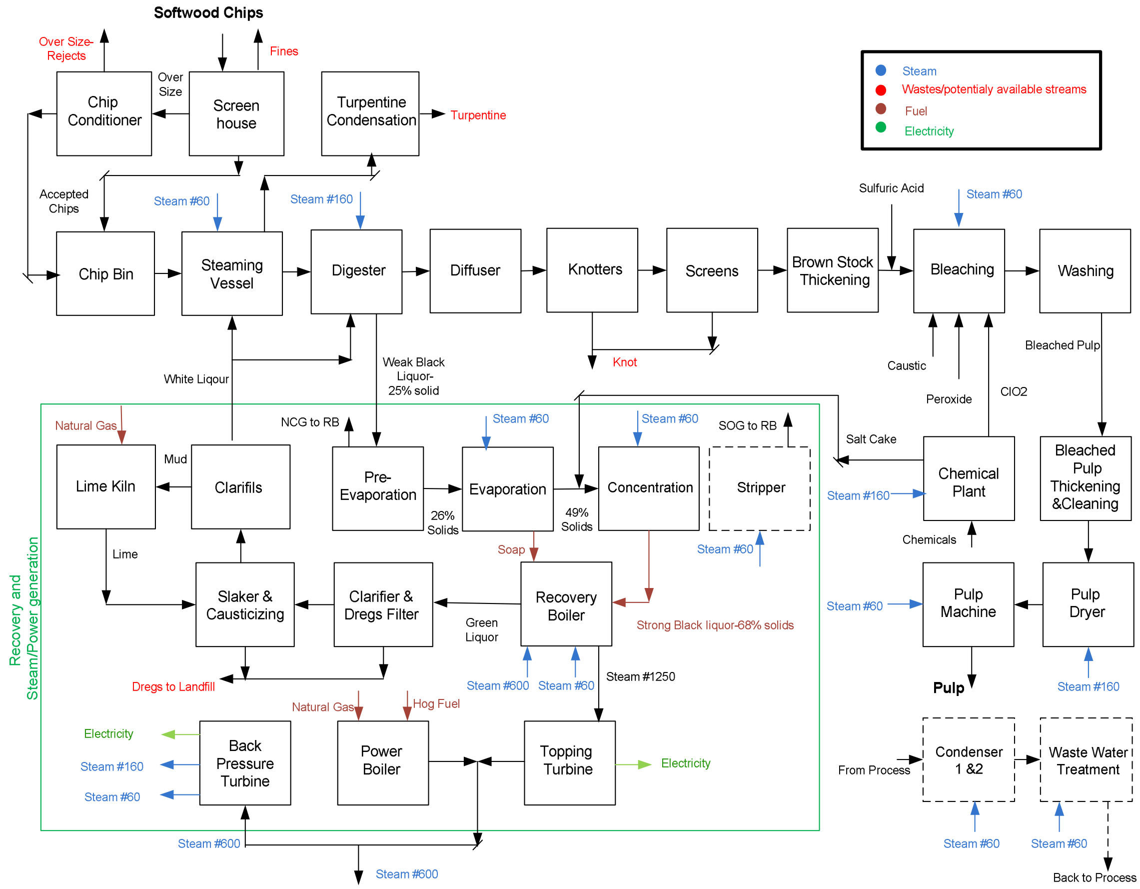


**Figure 1. Simplified process flow diagram of the case study mill**

## 3.2. Candidate Biorefinery Technologies

In order to identify biorefinery technologies having good potential for the case study mill, certain unique characteristics of the mill were identified and matched with the list of emerging strategies having good potential. In order to mitigate technology and market risks associated with their implementation, a phased approach is considered for each biorefinery scenario. Phase I ideally involves minimum technology and market risks, while Phase II involves technology that when implemented, results in manufacturing of value-added products ending with higher revenues but having higher technology and market risk that should be resolved in a few years time. In this study it is assumed that Phase I would be constructed within two years and will be in production for about five years. In the sixth year of production while Phase I is running, Phase II is constructed and then operated beginning in the seventh year of production

The unique characteristics of the case study mill considered in order to target biorefinery technologies included the following:

- Considering that the case study mill is energy self sufficient and connected to a saturated power grid, it would be difficult to accrue large energy-related benefits with green electricity production via combined heat and power (CHP) unit.
- Considering the changing production bottleneck in the case study mill, ie not due to recovery boiler capacity, limits the opportunity to increase pulp production capacity by lignin precipitation or other similar strategies.
- Considering that nearby market opportunities are limited and access to markets further away is costly, when a local market cannot be identified it would be better to target low volume/high value products (added-value products) with biorefinery strategy compared to large volume/low value products (commodity products).
- Access to large volume of hardwood chips potentially provides a competitive advantage over mills having access only to forest residuals. Targeting organosolv and biochemical processes that produce added-value lignin-based products seems more promising.

Considering these, four biorefinery technologies were identified for the case study mill including (1) lignin precipitation (Alt.1), (2) organosolv treatment (Alt.2), (3) fast pyrolysis (Alt.3), and (4) concentrated acid hydrolysis (Alt.4).

In the product portfolio of the candidate technologies, lignin is the only co-product that exists in all alternatives. In phase I this stream will be sold into low value applications having a low level of technology and market risks. For organosolv treatment and concentrated acid hydrolysis, being energy demanding options, lignin is burnt in phase I in order to produce additional steam and electricity. For lignin precipitation which is a very low energy demanding option, lignin is sold as carbon black. In fast pyrolysis, as an energy self sufficient technology, for phase I the bio oil is sold to the local market.

In phase II the lignin in all biorefinery candidates would be converted into lignin-based value-added products. There is a wide range of value-added applications from lignin including replacing phenol in phenol formaldehyde (PF) resins, polyols in polyurethane foams, polyacrylonitrile (PAN) in carbon fiber, dispersants, polymer (thermoplastic) blends and composites, and activated carbon as some of the important ones. Among these applications, two of them were considered in this study depending on the type of lignin produced by the biorefinery strategy. Phenol substitution in PF resins production was considered for lignin precipitation, fast pyrolysis and concentrated acid hydrolysis, whereas PAN replacement for carbon fiber production which was considered for organosolv treatment. The limiting factor when using lignin in these applications concerns the relative reactivity of lignin because of its chemical structure. Thus lignin needs to be modified to enhance its reactivity to an acceptable level for certain products (Hu, Pan et al. 2011). Enhancing lignin reactivity can be done by chemical, enzymatic or genetic modification processes, among which chemical modifications are the most advanced processes. These modification processes would vary based on the type of lignin (kraft lignin, organosolv lignin, pyrolitic lignin) and the application requirements.

Phenol substitution in PF resins production is the most considered application from lignin over the last decades (Malutan, Nicu et al. 2008). Phenol and phenol derivatives are increasingly being considered due to an increase in the forecasted demand of PF resins, and also an increase in the cost of petroleum-based phenol (Tymchyshyn and Xu 2010). In addition to cost reduction as an important advantage of using lignin in PF resins, it would result in reduction of the carcinogenic formaldehyde due to presence of a resin component which is already cross-linked (Gosselink 2011). There are several methods to modify lignin to increase its phenolic content for this specific application such as phenolation, methylolation, demethylation, glyoxaltion, oxidation and reduction among which phenolation and methylolation are the most case study ones (Hu, Pan et al. 2011).

Considering this, for the lignin precipitation and concentrated acid hydrolysis processes where lignin is targeted for phenol substitution in PF resins production, lignin is first reacted with phenol to be modified through the phenolation process, and then sold as modified lignin to PF resin producers. Although in fast pyrolysis the value-added application is the same as lignin precipitation and concentrated acid hydrolysis, there is a difference. Bio oil is a mixture of about 400 types of chemicals which 20% to 30% of it is the phenolic fraction that has the potential to be extracted from bio oil (Sukhbaatar, Steele et al. 2009). Although bio oil can be directly modified and then be used for phenol substitution (Cheng, Yuan et al. 2012), extracting the phenolic fraction and then modifying that fraction seems more efficient. There are several methods in literature for this extraction among which solvent extraction presented by Sukhbaatar et al. (Sukhbaatar, Steele et al. 2009) has been considered in this study due to its cost advantages. In this process, water and methanol are used in two steps to obtain water-insoluable pyrolytic lignin with between 20% to 25% yield based on bio oil weight.

Phenol substitution by lignin at different levels as high as 75%, has been successfully tested and can be found in several publications in the literature. However as discussed by Pizzi (Pizzi 2006), these studies have not considered that the cost advantage could be lost due to lengthening of panel press time when we use lignin-phenol-formaldehyde resin as a wood adhesive at over a 30% substitution rate. Thus for the purposes of this study, a 30% phenol substitution rate has been considered as the maximum rate. This rate is applied on total consumed phenol including the phenol used for modification of lignin itself and the phenol that is mixed with modified lignin to react with formaldehyde in order to produce PF resin. Assuming this, the phenolation process would end with producing about 2.1 tonnes phenolated lignin from each tonne of lignin (Cetin and Ozmen 2002).

The unique nature of produced lignin from the organosolv process, and its advantages compared to the other types of lignin, leads us to target lignin in this alternative for textile PAN replacement in carbon fiber production which needs high quality lignin.

The schematic of the phases for the biorefinery alternatives and a simplified process flow diagram of each considering the capacity of available biomass (discussed in section 3.4) are presented respectively in Figures 2 and 3.

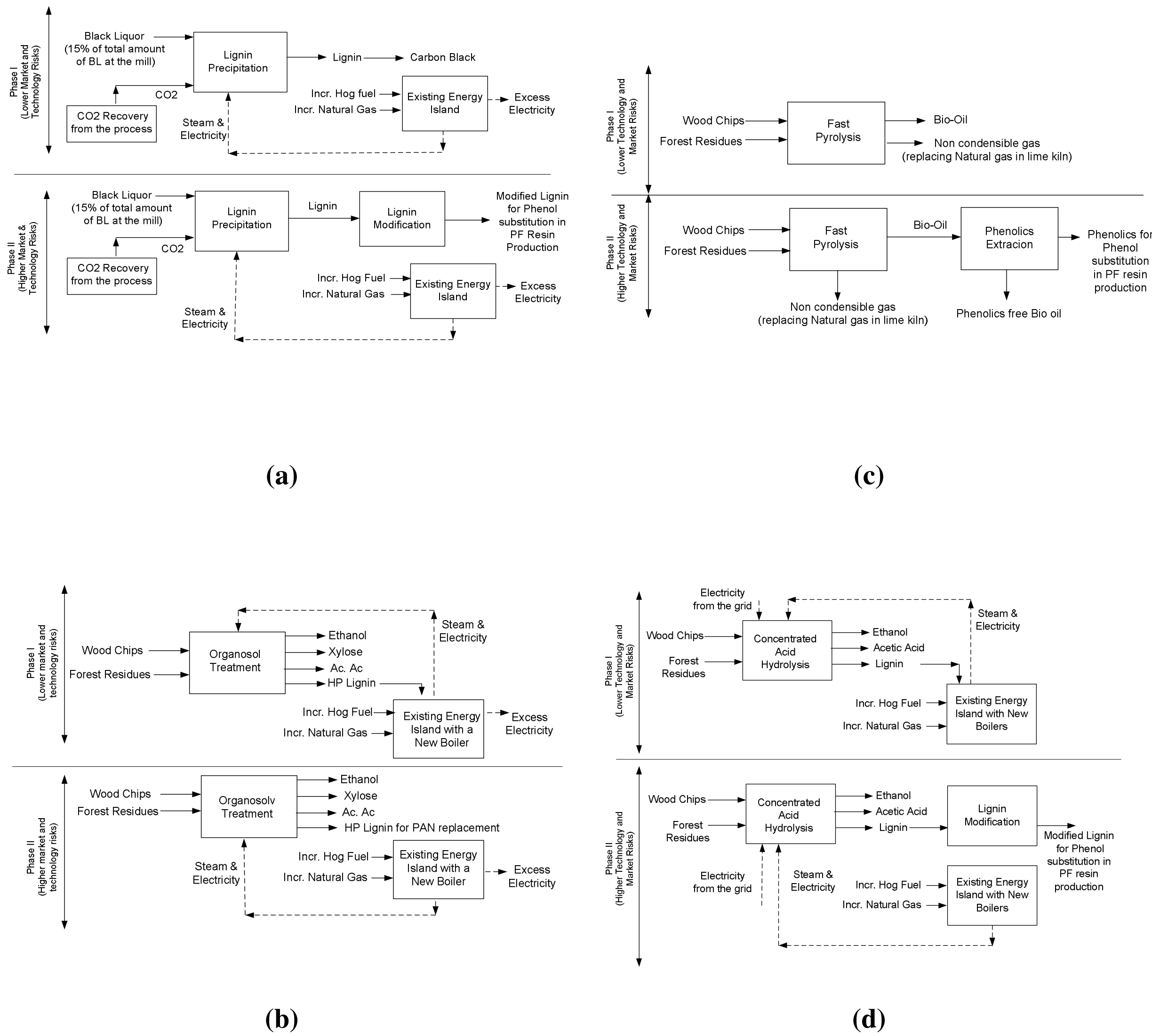


**Figure 2. Phase I and Phase II for each biorefinery candidate: (a) Lignin Precipitation (b) Organosolv Treatment, (c) Fast Pyrolysis (d) High Concentrated Acid Hydrolysis**

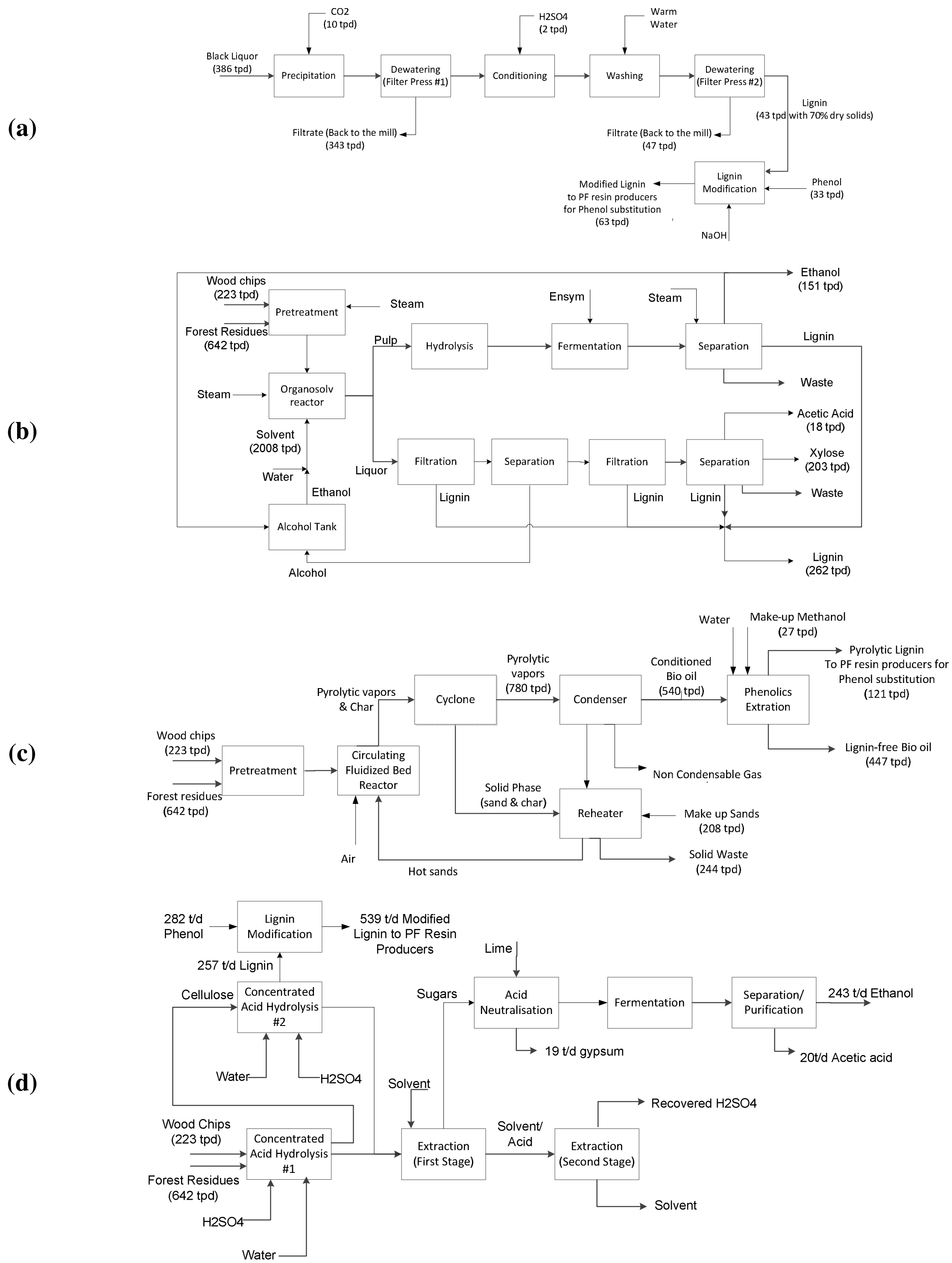


**Figure 3. Simplified process flow diagram for the Phase II of (a) Lignin precipitation, (b) Organosolv Treatment, (c) Fast Pyrolysis, (d) Concentrated acid Hydrolysis.**

**3.3. Biorefinery Integration Potential with Existing Mill Processes**

The mass balances of the mill indicated that there are certain available streams including knots, turpentine, black liquor, fines and reject oversize chips that may have a potential to be used at biorefinery processes. Among these, both the quality and quantity of the knots stream were inadequate, turpentine is already sold to the market as a byproduct, and fines are currently burnt to provide energy at the energy island of the mill. Considering this, the only stream that potentially can be used at the biorefinery plant would be reject oversize chips, and black liquor.

In order to identify the volumes of raw materials including oversize chips, fiber balances were performed and are presented in Figure 4. This figure shows that the amount of oversize chips at the mill is 2-4 bdt/d.

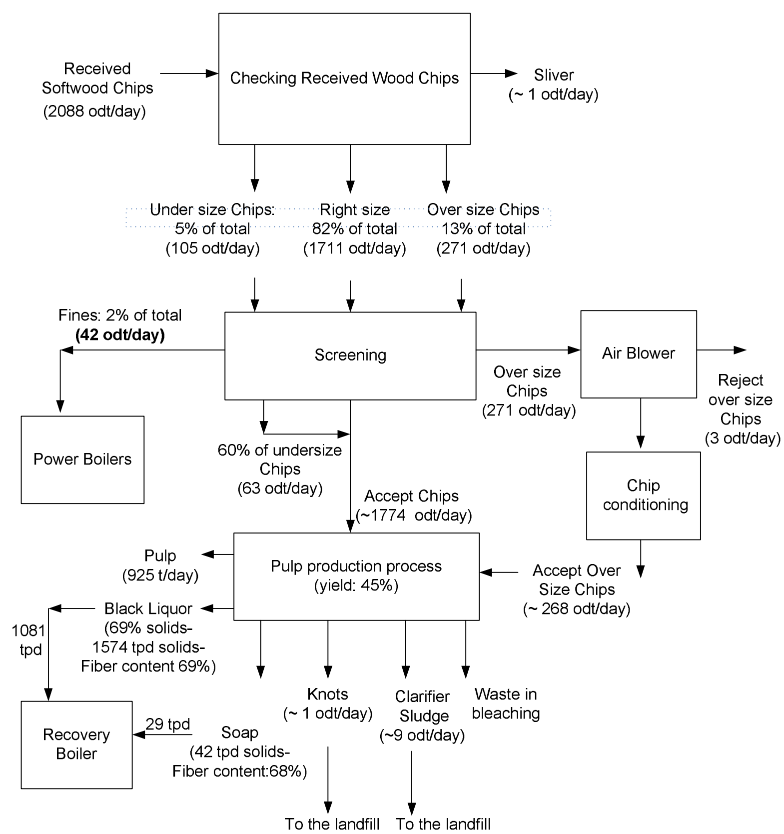


**Figure 4. Fiber balance at the case study mill**

*Energy Island*

The energy balance of the pulp production line shows that in winter, the consumptions of high, medium and low pressure steam are respectively about 15, 91 and 215 t/h provided by the existing energy island at the mill. Moreover, electricity consumption at the mill is about 30 MW while the energy island supplies more than this. Depending on the season, the amount of excess electricity would be in the range of 2.5 MW to 7 MW. Thus the mill is energy self-sufficient.

In order to identify how to consider integrating the biorefinery plant with the energy island at the early design stage, the types and the capacities of existing boilers were identified. The boilers at the mill include: (1) a recent recovery boiler which is currently working at 75% of its nominal capacity and produces 290 tph steam, (2) two power boilers (90% of their energy is provided by hog fuel and the rest by natural gas) which have a total nominal capacity of about 120 tph steam, and are used mainly in winter time with 50% of their nominal capacity, and (3) two natural gas boilers with a total nominal capacity of about 140 tph which are currently unused. In addition to these boilers, there are two turbines including a back pressure turbine with maximum capacity of 36 MW, and a condensing turbine with maximum capacity of 15 MW. As an example, the configuration of the integrated energy island has been illustrated for the organosolv process in Figure 5. As can be seen in this figure, in Phase I lignin produced through organosolv treatment process, is sent to the existing power boilers in energy isaland at the mill in order to be burnt. This stream will provide a portion of energy which is required to produce steam and electricity for both the pulp mill and biorefinery plant. Taking into account the energy of this stream, the amount of hog fuel and natural gas that should be burnt in order to supply the total required energy can be estimated (~ 50 tph hog fuel and 1600 m3/h natural gas). However in Phase II, since the produced lignin in organsolv treatment is not sent to the power boilers but is converted into added value products, the consumption of hog fuel and natural gas is increase to 71.4 tph and 2283 m3/hr.

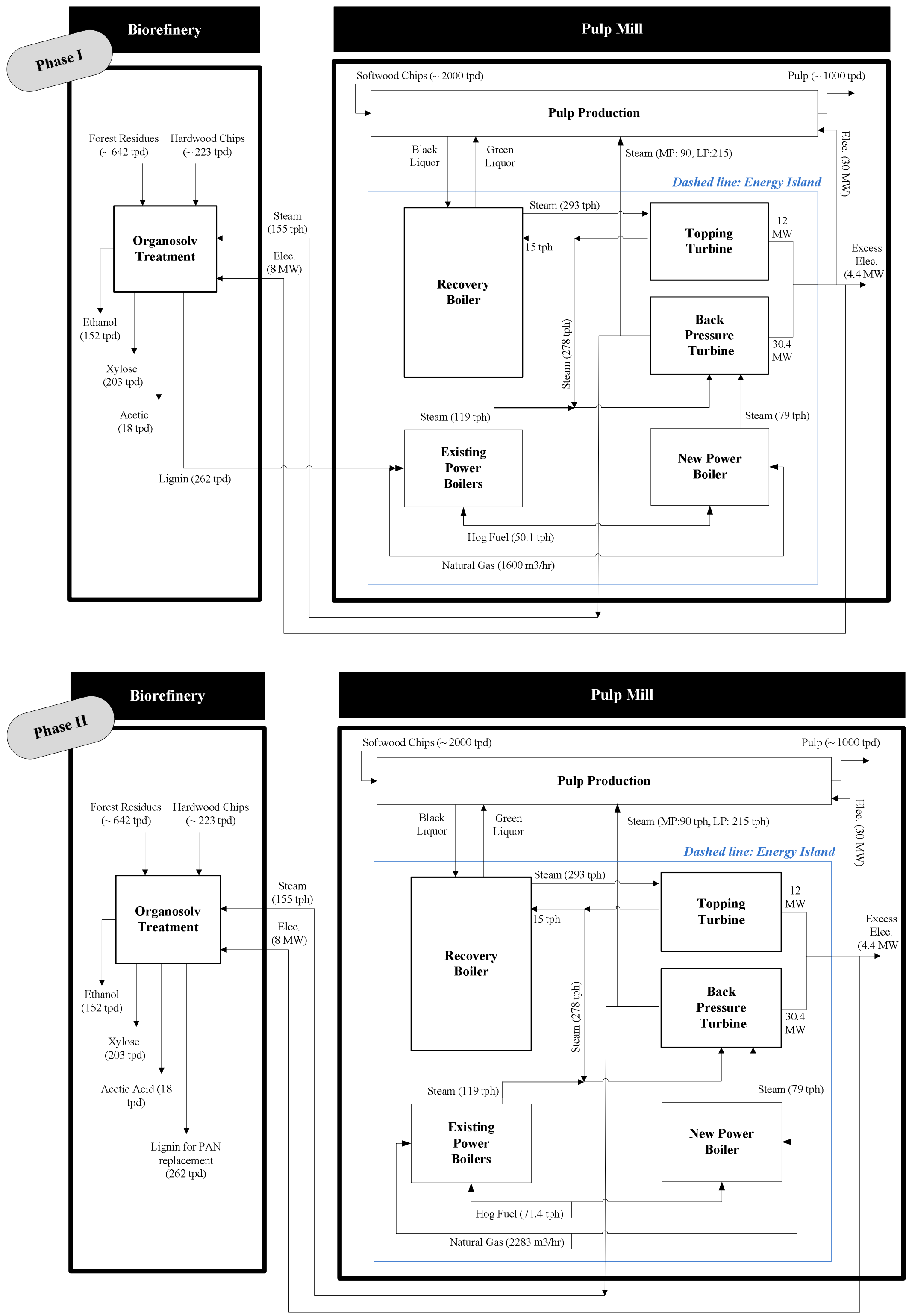


**Figure 5. Energy integration between the organosolv treatment process and the mill**

Based on the designed integrated energy island, the amount of incremental fuel that should be fed to the boilers has been estimated considering summer and winter operating conditions. The results of energy integration for all the alternatives can be found in Table 1.

**Table 1. Energy and fuel consumption of biorefinery alternatives**

| | Biorefinery Electricity Cons. (MW) | Biorefinery Steam Cons.[a] (tph) | Additional Hog Fuel Required (t/h)[c] | Additional Nat Gas Required (m3/h)[c] | Burnt Lignin (t/h) | Excess Elec. (MW)[c] | New boiler /Quantity |
|---|---|---|---|---|---|---|---|
| **Phase I** | | | | | | | |
| **Alt.1** | 1.2 | 0 | 19.4 | 880 | 0 | 3.5 | No |
| **Alt.2** | 8 | LP:10, MP:145 | 42 | 1600 | 11 | 4.4 | Yes/1 |
| **Alt.3** | 3.8 | 0 | 8.1 | 0 | 0 | 3 | No |
| **Alt.4** | 12.6 | LP:19, MP:110, HP: 62 | 54.2 | 1992 | 11 | -0.2[b] | Yes/2 |
| **Phase II** | | | | | | | |
| | Biorefinery Elec. Cons. (MW) | Biorefinery Steam Cons.* (tph) | Additional Hog Fuel Required (t/h)[c] | Additional Nat Gas Required (m3/h)[c] | Burnt Lignin (t/h) | Excess. Elec. (MW) | New boiler /Quantity. |
| **Alt.1** | 2.2 | 0 | 19.4 | 880 | 0 | 2.5 | No |
| **Alt.2** | 8 | LP:10, MP:145 | 63.3 | 2383 | 0 | 4.4 | Yes/1 |
| **Alt.3** | 4.8 | 0 | 8.1 | 0 | 0 | 2 | No |
| **Alt.4** | 13.2 | LP:19, MP:110, HP: 62 | 75.6 | 2676 | 0 | -0.8[b] | Yes/2 |

a: Energy consumption has been estimated by process simulation.
b: Negative value shows the amount of needed electricity which cannot be provided at the mill and should be bought.
c: The cost of hog fuel, natural gas and electricity are respectively about 30 $/t, 0.017 $/m3 and 68.6 $/MWh

As can be seen in this table, for alternatives 2 and 4, the additional hog fuel and natural gas required in Phase II is more than Phase I since in this phase (Phase I) a part of required energy is supplied by burning lignin. The decrease in excess electricity in Pahse II is mainly because of increase in electricity consumption of the process due to considering lignin modification unit in Phase II. The only alternative in which excess electricity is unchanged is Alternative 2, in which the produced lignin does not need to be modified for being used to produce added value products. The reason is that organosolv lignin has higher quality compared to the kraft lignin in lignin precipitation process, pyrolysis lignin in fast pyrolysis technology and precipitated lignin in concentrated acid hydrolysis process.

*Waste Water Treatment Plant*

The raw BOD load from the existing mill is about 18 t/day, however the wastewater treatment plant is designed to handle BOD loads of up to 22 t/d. In addition, the current hydraulic loading to the wastewater treatment plant is 115,000 m3/day, however larger amounts up to 120,000-125,000 m3/day can accommodated considering average and peak flows. Preliminary estimates of the BOD load in the biorefinery options considered in this study were about 3.4 to 4.8 t/d (16,300 mg/L cellulosic ethanol (Brault, Kouakou et al. 2009)) of easily biodegradable organics. According to the design capacities of the biorefinery options, the hydraulic loading would be between 4,200 to 6,000 m3/day (0.02 m3 effluent/L ethanol (Brault, Kouakou et al. 2009)). Thus treating biorefinery wastes, in terms of both BOD content and hydraulic loading would be manageable in the existing wastewater treatment plant at the mill. The cost for additional power consumption due to using more aerators, as well as additional nutrient requirements for the increase in BOD content has been included in the economic analysis.

*Landfilling*

Among the biorefinery strategies, fast pyrolysis and concentrated acid hydrolysis are the two alternatives that would have solid waste about to manage. The solid waste in fast pyrolysis is estimated at 244 tpd including sands and ash, and in concentrated acid hydrolysis is estimated at 19 tpd which include mainly gypsum. They have been assumed to be sent to the mill landfill with the associated cost of 35 $/t.

*Unused Equipment*

Whereas several tanks and other equipment items could potentially be incorporated into the biorefinery designs for capital offset, after closer examination it was found that for lay-out considerations or due to the state of equipment disrepair, this was not practical.

### 3.4. Biorefinery Integration Potential with Biomass Harvesting and Handling

The available biomass as biorefinery feedstock to the case study mill which can be supplied from woodlands around the mill to a 240 km radius includes hard wood chips and forest residues. Forest residues consist of softwood waste (chipper bark and limbs), hardwood waste (chipper bark and limbs) and hardwood roundwood waste (roundwood limbs and tops). The availability of each type of biomass along with their delivered costs at the mill gate are summarized in Table 2.

**Table 2. Biomass availability supplied by woodlands around the case study kraft mill**

| Biomass Type | Capacity (gmt/day) | Annual bone dry | Capacity (odt/day) | Average price ($/gmt) |
|---|---|---|---|---|
| | *Wet basis* | | *Dry Basis* | |
| **1. Wood Chips** | | | | |
| 1.1. Hardwood Chips | 396 | 55.6% | 220 | 53 |
| 1.2. Reject oversize softwood chips (existing at the mill) | ~ 5 | 61.4% | ~ 3 | Hog fuel equivalent cost (currently burned at the mill) |
| **2. Forest residues** | | | | |
| 2.1. Hardwood waste | 99 | 55.6 % | 55 | 44 |
| 2.2. Softwood waste | 835 | 61.4 % | 513 | 51 |
| 2.3. Hardwood roundwood waste | 133 | 55.7 % | 74 | 49 |
| **Total** | **1468** | - | **865** | - |

The alternatives are designed to use all this available biomass, except lignin precipitation (alternative 1) which just uses 15% of the existing black liquor at the mill.

The existing materials handling system at the mill includes scales, two dumpers, two stackers and conveyor system. Due to the risk of mixing softwood used for pulp production and hardwood which will be fed to the biorefinery plant, their materials handling systems should be separate. In alternatives 2 to 4 which use hardwood chips and forest residues, the existing scales can be shared, while just one more dumper should be added to the two existing dumpers at the mill, in addition to a new stacker and a new conveyor feed system to the biorefinery. Taking this into account, about 11 MM$ as the cost of new dumper, new stacker and also new feeding system has been considered in the economic analysis.

### 3.5. Biorefinery Integration Potential with Product

The product portfolio in each biorefinery strategy option along with the incremental revenue at the mill has been summarized in Table 3. Some ideas as possible integration potential of biorefinery products with the existing facilities outside the mill for secondary transformation have been suggested as future opportunities. For instance the bio-oil from fast pyrolysis can be transported to existing refinery facilities located not far from the mill, for upgrading to transportation fuels.

**Table 3. Product portfolio and the associated revenue**

| Products | Price ($/t) | Capacity (Phase II) tpd | Revenue (Phase II) MM$/y | Capacity (Phase I) tpd | Revenue (Phase I) MM$/y |
|---|---|---|---|---|---|
| **Alt.1: Lignin Precipitation** | | | | | |
| Modified lignin for phenol substitution | 1270 [a] | 63 | 26.7 | 0 | 0 |
| Carbon black | 945 | 0 | - | 22 | 6.8 |
| Excess electricity | 68.8 [b] $/MWh | 2 MW | 1.3 | 3.5 MW | 1.9 |
| Total | - | - | **28** | - | **8.7** |
| **Alt.2. Organosolv Tretment** | | | | | |
| Lignin for PAN replacement | 1556 [c] | 262 | 135.9 | 262 | - |
| Ethanol | 689 [d] | 152 | 34.9 | 152 | 34.9 |
| Xylose | 200 | 203 | 13.5 | 203 | 13.5 |
| Acetic Acid | 568 [e] | 18 | 3.4 | 18 | 3.4 |
| Excess electricity | 68.6 $/MWh | 4.4 MW | 2.4 | 4.4 MW | 2.4 |
| Total | - | - | **190.1** | - | **54.3** |
| **Alt.3: Fast Pyrolysis** | | | | | |
| Bio oil | 308 [f] | 0 | 0 | 540 | 55.5 |
| Phenolics free bio oil | 240 [g] | 446.4 | 35.8 | 0 | - |
| Phenolics | 1270 | 121 | 51 | 0 | - |
| Non condensable gas | 0.0172 [h] $/m3 | 204 | 1.6 | 204 | 1.6 |
| Excess electricity | 68.6 $/MWh | 2.1 | 1.1 | 3 | 1.7 |
| Total | - | - | **89.5** | - | **58.8** |
| **Alt.4: High concentrated acid hydrolysis** | | | | | |
| Modified lignin for phenol substitution | 1270 | 539.4 | 228.3 | 0 | - |
| Ethanol | 689 | 220 | 50.5 | 220 | 50.5 |
| Acetic acid | 568 | 20 | 3.7 | 20 | 3.8 |
| Total | - | - | **282.5** | **-** | **54.3** |

a: Assuming 10% discount on the most recent price of fossil based Phenol (1411 $/t) [Petrochemicals eTrack, Global data, 2013]
b: Provided by the host mill
c: 0.4-0.7 $/lb (Naskar 2011)
d: Average historical price of ethanol which has a volatile market
e: Recent acetic acid price [Petrochemicals eTrack, Global data, 2013]
f: 10% discount on reference fuel (fossil fuel) energy equivalent price of bio oil
g: Energy equivalent price of bio oil after separating its phenolics content
h: Provided by the host mill

## 3.6. Techno-economic Analysis

Applying the estimated cost synergies between the mill and the biorefinery process, investment and production cost of each alternative in both phases have been estimated which can be found in Table 4.

**Table 4. Summary of techno-economic results**

| Alternatives | Fixed Capital Investment Cost in Phase I (MM$) | Fixed Capital Investment Cost in Phase II (MM$) | Working Capital Investment Cost in Phase I (MM$) | Working Capital Investment Cost in Phase II (MM$) | Production Cost in Phase I (MM$/y) | Production Cost in Phase II (MM$/y) | Revenue in Phase I (MM$/y) | Revenue in Phase II (MM$/y) | Internal Rate of Return, (%) |
|---|---|---|---|---|---|---|---|---|---|
| Alt.1: Lignin Precipitation | 12 | 10[a] | 1.1 | 4.3 | 6.9 | 23.7 | 8.7 | 28 | 8% |
| Alt.2: Organosolv Treatment | 216 | 0[b] | 7.6 | 20.2 | 45.6 | 56.2 | 54.3 | 190.1 | 14.2% |
| Alt.3: Fast Pyrolyiss | 155.5 | 10[c] | 7.2 | 10.4 | 37.6 | 43.4 | 58.8 | 89.5 | 11% |
| Alt.4: High Concnetrated Acid Hydrolysis | 193.6 | 11[d] | 7.3 | 26.4 | 92.2 | 239.2 | 282.5 | 54.3 | Negative Net Present Value |

a: The cost of CO2 capturing facilities and lignin modification unit
b: There is no need for lignin modification unit (no additional investment cost in Phase II)
c: The cost of lignin extraction and modification unit
d: The cost of lignin modification unit

Using this information along with the estimated revenue in each Phase (Table 3), economic performance of each alternative was assessed using techno-economic analysis model. The results of estimated profitability of each alternative (in terms of Internal Rate of Return) show that , lignin precipitation and concentrated acid hydrolysis technologies are the two least-preferred options in terms of economic profitability in the context of the studied mill. However despite of the conventional methods, decision should not be made based on profitability only. There are several other parameters that should be taken into account to determine the economic success of the biorefinery strategies.

Considering that most of forest products companies currently have financial limitations for investing in capital intensive biorefinery strategies, the investment cost of the biorefinery alternatives would determine whether the forest products companies can integrate these technologies into their existing facilities or not. For instance, although organosolv treatment shows better profitability than lignin precipitation technology, in the context of this study its required fixed capital investment cost (216 MM$) is almost ten times higher than total investment cost (both Phase I and II) of the lignin precipitation technology (22 MM$). Considering that, in addition to profitability, the total capital investment cost of these alternatives and more importantly their investment efficiency should be also taken into account in decision making for the companies with this constraint.

In Table 4 IRR represents long-term profitability applying a phased implementation approach in which it is assumed that in Phase II, targeted value-added products can be produced. However there is possibility that in a worst case scenario, switching into Phase II can not be pursued due to either technology or market risk. Therefore, profitability of Phase I needs to be guaranteed as a pre-requisite to implement the biorefinery strategy. Given techno-economic results for organosolv treatment technology, it is clearly seen that the estimated revenue of this alternative in Phase II (190.1 MM$/y) becomes about 3.5 times higher than its revenue in Phase I (54.3 MM$/y), while the production costs in this phase (Phase II) is just 20% increased. This confirms that the economic success of the organosolv treatment option belongs mainly to the Phase II strategy. Thus, although this alternative is a most promising option in terms of the long-term profitability, it may not be as promising as the other alternatives in terms of short-term profitability. Therefore in order to make a wise decision, along with IRR, short-term profitability of Phase I should also be taken into account to compare the economic performance of the candidate biorefinery strategies.

The biorefinery options with the higher profitability generally have higher created margin. However a factor that can determine their future success is the capability to maintain this created margin and to stabilize their revenue. This should be taken into consideration in order to investigate whether a biorefinery alternative can be maintained economically promising in long-term vision. In this regard, more diversified product portfolio in which a considerable portion of the revenue comes from value-added products (with less volatile market), is more promising. As can be seen in Table 3, although concentrated acid hydrolysis technology was the least promising option in terms of profitability, 80% of its revenue is coming from the value-added product, and thus in this perspective shows better performance than the identified promising alternatives in terms of profitability.

In addition to the factors explained above, the level of technology risk associated with each of these strategies can play a main role in capability of implementing each technology. For instance, in spite of lower profitability of fast pyrolysis alternative compared to the organosolv treatment, less technology risk is associated with it as a commercialized technology, compared to the organosolv treatment technology which is currently available at pilot scale. It shows that the technology and market risks associated with these biorefinery technologies along with the other aspects of economic performance is crucial to be considered for making a wise decision.

It can be concluded that a set of economic criteria (that normally are conflicting) representing different aspects of the project, is required to be defined and evaluated using which the economic performance of the biorefinery alternatives can be well compared. In addition to these economic criteria, the biorefinery strategies should also be assessed from competitiveness and environmental perspective.

## 4 CONCLUSIONS

The overall systematic methodology developed in this study illustrates the strength of the retrofit design for distinguishing between biorefinery technologies.

Applying the estimated cost synergies as a result of retrofit design, economic performance of each alternative was assessed through techno-economic analysis. The results show that, lignin precipitation and concentrated acid hydrolysis were the two least-preferred options in terms of economic profitability in the context of the studied mill. However in order to make a final decision, the alternatives need to be analyzed in terms of other economic aspects, and also from a competitiveness and environmental perspective which is presented by Sanaei and Stuart (Sanaei and Stuart 201X).

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## APPENDIX D – Article 4:

## Sustainability Assessment and Strategic Decision Making of Integrated Forest Biorefinery Strategies

**Sustainability Assessment and Strategic Decision Making of Integrated Forest Biorefinery Strategies**

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## ABSTRACT

The integration of biorefinery technologies into existing pulp and paper facilities is a promising transformational strategy for forest product companies. However identifying sustainable biorefinery strategies at the early stage of design is a complex task. In this study, four biorefinery technologies have been assessed in the retrofit context to a kraft pulp mill. In order to assess them, a set of economic and competitiveness criteria are defined and evaluated which then along with a set of environmental criteria are aggregated into a unique sustainability score for each biorefinery strategy through a multi-criteria decision making (MCDM) panel. The results show that lignin precipitation and concentrated acid hydrolysis alternatives were not sustainable in the context of this case study. The overall methodology in this study can potentially assist forest products mills to target their preferred biorefinery strategy at the early design stage, using a perspective of sustainability.

Key words: Integrated Forest Biorefinery, Economic Criteria, Competitiveness Criteria, Sustainability Assessment, Multi-Criteria Decision-Making (MCDM)

## 1 INTRODUCTION

A systematic framework is needed for forest product companies considering the integration and implementation of biorefinery technologies into their mills, in the context of identifying sustainable strategies – especially at the early design stage. The design process fundamentally implies that possible design options be assembled, and then based on a systematic evaluation, those that are less-preferred are eliminated. A systematic methodology was presented by Sanaei and Stuart (Sanaei and Stuart 201X) for evaluating critical issues related to biorefinery implementation in retrofit to an existing kraft pulp mill. In this paper, the four biorefinery options being considered are evaluated using "smart" criteria, and using a multi-criteria decision-making (MCDM) panel, the less-preferred biorefinery options are identified and eliminated from the list of investment options.

Identifying sustainable transformation strategies is not a straightforward task using a sustainability perspective when outcomes are conflicting. For example, how important is return on investment, compared to how fast the new market for your products is expected to grow in the coming years, or how much greenhouse gas reduction the process implies? Resolving this dilemma implies a multi-objective problem in decision-making (Othman 2011). This approach enables company stakeholders and decision-makers to compare the performance of different biorefinery strategies for their core business transformation, and identify less-preferred options.

There are several studies in the literature that address sustainability assessment at different levels of design. In some studies, sustainability has been addressed by a detailed analysis based on conceptual process design in which all processes are simulated and then they are assessed in terms of economic and environmental performance (Posada, Rincon et al. 2012; Posada, Patel et al. 2013). For instance, a method has been presented by Hung et al. (Huang, Lin et al. 2009) as a modeling of integrated forest biorefinery options to assess them in terms of economic and environmental perspective, in which two simulation software packages (Aspen Plus for biorefinery process, and WinGims for pulp production process) are linked. While there are advantages with this classical approach to conceptual design, it should be noted that they are not practical at the strategic level of design due to being time-intensive and data demanding. At the early design stage, it is desirable to use a less-rigorous and time-consuming but systematic methodology to triage biorefinery options.

Many sustainability assessment studies in the literature regarding the biorefinery consider a superstructure of biorefinery options, evaluated using process systems engineering (PSE) tools and mathematical optimization methods for multi-objective problems (Buping, Ng et al. 2011; Sharma, Sarker et al. 2011; Gebreslassie, Waymire et al. 2013; Santibanez-Aguilar, Gonzalez-

Campos et al. 2013; Wang, Gebreslassie et al. 2013). These methods have been applied to a wide range of applications including selection of most appropriate feedstock, determination of optimal production capacity, identification of optimal process stages, and figuring out the optimal supply chain design and etc.

However, surveys clearly show that the most common decision-making problems that companies regularly face are product-process pathway selection at the strategic level of design (Hodgett 2013). At that level, decision-makers are not looking for the optimal solution but interested in identifying non-promising options to screen them out from the list of investment possibilities. Commonly these types of problems are solved by rationalization taking into account several assumptions, however this can possibly end with inaccurate results (Othman 2011). Therefore, it is critical to employ a systematic approach for comparing strategies at the strategic level of design.

There are some exceptional cases in literature where the results from assessing sustainability pillars in their context were consistent, and so decision-making was obvious. For instance Pourhashem et al. (Pourhashem, Adler et al. 2013) have assessed three lignin-based biorefinery strategies separately in terms of economic and environmental performance. In their study, one of the three options showed the best performance for both economic and environmental aspects and so decision-making for the most sustainable strategy was straightforward. However, more frequently the results of assessing sustainability pillars are conflicting, making decision-making complex. In such cases, the Multi-Criteria Decision-Making (MCDM) approach would help decision-makers to aggregate conflicting criteria into an index or sustainability score, by quantifying the relative importance of each sustainability criterion. There are currently numerous applications of MCDM approaches in general, and for the forestry sector in particular regarding which Balteiro and Romero (Diaz-Balteiro and Romero 2008) have completed a good review. In some studies, MCDM has been accompanied with multi-objective optimization methods through which a set of promising strategies is first computed via a Pareto multi-objective optimization, and then MCDM is used to identify the preferred options (Perera, Attalage et al. 2013).

Few studies have employed MCDM to identify sustainable biorefinery strategies at the early-stage, strategic level of design. The drawback of most of these studies is that in order to calculate an integrated score for each alternative, often an arbitrary relative importance (weighting factor) is attributed to evaluation criteria. These weights have been pre-set generically, without considering the context of the results for the different options being considered. Although some criteria can be very important in concept, in the context of results they may not help decision-makers to differentiate between the candidate alternatives. For example, if we have the same internal rate of return for several options, then despite the importance of this criterion, we must use others to distinguish between the most- and least-preferred options.

Posada et al. (Posada, Patel et al. 2013) have used MCDM to identify promising bioethanol-based products among twelve candidates. They defined a set of sustainability criteria with arbitrary weights, addressing economic, environmental, safety and health aspects - and then normalized them using the impacts of comparative petrochemical-based pathways. The variability of their weighting factors was examined using Monte Carlo analysis whereby the criteria weights were varied within a specified range considering an upper and a lower limit. The issue of arbitrary attributed weights without considering the context of the results can be seen in other studies as well. For instance in the context of chemical design for methyl methacrylate (MMA) production, Sugiyama et al. (Sugiyama, Fischer et al. 2008) have applied MCDM using a set of sustainability criteria including economic, environment, health and safety. An equal weighting factor was attributed to financial and non-financial criteria. As a continuation of their work, Patel et al. (Patel, Meesters et al. 2012; Patel, Meesters et al. 2013) added some criteria into their list and employed them to assess laboratory experiments. They defined five main groups of decision criteria each including sub-criteria, however they also assumed equal weighting factors. Schaidle et al. (Schaidle, Moline et al. 2011) compared three biorefinery options producing fuels considering a set of economic, environmental and social criteria. Their criteria were weighed arbitrary for four scenarios. In the base case, they were weighed equally, and in other scenarios, one criterion was given twice importance of the other two. Their results clearly show that applying different weighting factors changes the final decision dramatically, demonstrating the importance of quantifying criteria weights systematically – one method being by conducting an MCDM panel.

Most studies that have quantified weighting factors for decision criteria have used the Analytical Hierarchy Process (AHP) panel method. However AHP's validity has always been a subject of debate because of semi-qualitative comparison between the criteria instead of measuring their relative importance quantitatively. In addition, rank reversal is arguably the main drawback of AHP method. Furthermore, decision makers' preference and the criteria importance can not be well considered separately in AHP method. Othman (Othman 2011) has employed the AHP method using a set of quantitative and qualitative criteria including economic, environmental and social criteria for process design of biodiesel. However attributed scores to the decision criteria were not obtained from conducting a multidisciplinary panel.

One study where the values of panel decision-makers were well-reflected in measuring weighting factors of the decision criteria can be found in Cohen and Stuart and Quintero-Bermudez et al (Cohen and Stuart 2012; Quintero-Bermudez, Janssen et al. 2012). They used the Multi Attribute Utility Theory (MAUT) method to assess a set of conflicting criteria for identifying preferred biorefinery technologies to produce lignocellulosic bioethanol. In order to quantify the weighting factor for 8 criteria, they conducted a multidisciplinary panel using MAUT. In order to demonstrate the method, the authors employed literature-based data. This issue has been addressed by Hytönen and Stuart (Hytonen and Stuart 2011) who used MCDM in the retrofit biorefinery context in order to first quantify the relative importance of decision criteria, and then accordingly to identify promising bioethanol production pathways at a case study mill. However the main gap in their work is that the set of decision criteria employed only addressed economic performance. However considering environmental and other criteria would increase the number of criteria which is not practical. This issue lead Sanaei et al. (Sanaei, Chambost et al. 201X) to use MCDM not only to quantify the criteria weights, but also to refine a set of necessary and sufficient sustainability criteria into a refined set of important criteria, determined in the context of the specific results of the case study. They presented a systematic approach, where several MCDMs are employed for sustainability assessment for greenfield agricultural-based biorefinery strategies. A series of initial MCDMs was employed employing the MAUT method, to refine criteria in each "dimension" of sustainability value to a small set of "important" criteria. The current study improves on this last method, considering modifications including (1) retrofit design for integrated forest biorefinery context (2) implying a phased approach of implementation of biorefinery strategies and (3) defining more representative decision criteria that can address concepts of technology and market risks.

The overall objective of this article is to present a systematic approach for sustainability assessment of integrated forest biorefinery strategies at the early design stage considering the investor perspective, and employing a set of "smart" criteria that address economic, competitiveness and environmental performance, as well as technology and market risks.

## 2. METHOD FOR SUSTAINABILITY ASSESSMENT

The overall methodology consists of two main steps including (1) retrofit design and techno-economic analysis, and (2) sustainability assessment employing the multi-criteria decision-making (MCDM) panel approach. The first step for this case study is presented by Sanaei and Stuart (Sanaei and Stuart 201X).

### 2.1. Summary of retrofit design and techno-economic analysis

Four biorefinery technologies were selected as candidates to be integrated into the case study mill. In order to mitigate technology and market risks associated with their implementation, a phased approach was applied to each technology. Through a retrofit design activity, the integration potential between the case study mill and the candidate biorefineries were evaluated. These estimated cost synergies were considered in the techno-economic assessment.

Using the results of techno-economic analysis, the economic and competitiveness attributes of each process alternative is assessed in this study using a set of "smart" criteria. More information about the scenario definition, retrofit design basis and techno-economic analysis can be found in Sanaet and Stuart (Sanaei and Stuart 201X).

### 2.2. Sustainability Assessment and Decision-making

Although there are different definitions for sustainability, most commonly it is defined as "… *development that meets the needs of current generations without compromising the ability of future generations to meet their needs and aspirations*", which was presented in Brundtland Commision report in 1987 (Davidson 2005). There are different interpretations of this definition, among which that an industrial process should be able to create maximum profit while providing minimum environmental impact and maximum social benefits (Piluso, Huang et al. 2008). According to the classical definition, aggregation of the economic, environmental and social pillars is a measure of sustainability. Incorporation of these pillars in evaluating industrial projects has also been called sustainable engineering, green engineering, design for the environment, eco-efficiency and other terms (Allen and Shonnard 2012).

Although the social pillar of sustainability is conceptually important, on a practical level it is linked to economic and environmental performance. On the other hand, since technology and business plans must serve market needs, the performance of a strategy in terms of its success in the market (market competitiveness) is critical for long-term business sustainability. However this concept is often missed in sustainability assessments. In a practical way, competitiveness analysis is another pillar of sustainability. Diffo et al. (Diffo, Chambost et al. 201X) have defined a set of competitiveness criteria, with which they assessed different greenfield agricultural-based biorefinery strategies. As a continuation of that work, Sanaei et al. (Sanaei, Chambost et al. 201X) aggregated the most important competitiveness criteria with a set of economic and environmental criteria, and evaluated biorefinery strategies in terms of sustainability performance. Similarly, in the current study sustainability has been defined as an aggregate of economic, environmental and competitiveness performance criteria.

*2.2.1. Economic Criteria*

Economic performance of capital projects is often assessed using short-term profitability criteria, for example Internal Rate of Return (IRR) or Net Present Value (NPV). However, from the investor perspective, biorefinery projects should not only be profitable in the short-term, but also should have robust business model that enables value creation over the long-term, while mitigating risks. For example, the strategy should be viable under poor market conditions. Considering this, a set of "smart" criteria should be defined and evaluated using which biorefinery strategies can be well distinguished.

Considering the economic perspective, three conventional economic criteria have been considered in this study including Internal Rate of Return (IRR) representing project profitability, Return on Capital Employed (ROCE) showing investment efficiency, and Total Capital Investment (TCI) representing the magnitude of capital investment for the project. Moreover, four unconventional criteria were added to this list including Downside Economic Performance (DEP) representing project robustness under poor market conditions, Short-term Business Viability (SBV) representing the near-term profitability of Phase I, Phase I Implementation Capability (PIC) representing Phase I technology risk, and Resistance to Supply Market Uncertainty (RTMU) representing the project sensitivity to market prices for energy and chemicals. Among these criteria, RTMU was introduced earlier by Sanaei and Stuart (Sanaei and Stuart 201X). The new criteria including DEP, SBV and PIC are described in greater detail below.

Given the risk associated with volatility in the market price of bioproducts, a minimum level of economic viability of the project is acceptable under poor market conditions assuming that the condition lasts only for a finite time in the order of months. Investors should consider their ability to sustain small or even negative cash flows for that finite period of time. This concept has been introduced through the DEP criterion, in which poor market condition is defined as the lowest annual product portfolio value over the last five years, expressed on a monthly basis. It has been assumed that this poor market condition would last for one third a year (four months).

Taking into account the risk associated with emerging biorefinery strategies, profitability of Phase I as the short term strategy is a pre-requisite for investment in a biorefinery strategy. However a reduced short-term profitability may be acceptable to investors relative to strategic objectives, especially in light of more lucrative returns in the longer term. This is addressed by the SBV criterion which is defined as the profitability of Phase I assuming the worst case scenario in which switching into Phase II is not pursued due to either technology or market risk.

Another new criterion which is defined in this study is PIC, which addresses the capability of Phase I technologies to be implemented at the full-scale. The PIC criterion is a combination of three sub-components, including (1) the level of technology maturity (in terms of largest operating plant scale – pilot, demonstration, or commercial), (2) process scalability (in terms of how much the targeted scale of Phase I is far from the largest operating scale of the candidate technology), and (3) the ability of implementing Phase 1 (is the technology supplier willing to implement in the next 24 months). In order to aggregate these three sub-components, a weighting factor ($W_j$) has been attributed to each: 50% for technology maturity, and 25% to each of the second and the third sub-components. This qualitative criterion has been quantified by attributing three possible numbers to each sub-component representing different levels of their performance. These numbers are 1, 3 and 5 that are respectively showing low, medium and high performance ($A_j$). For instance, for the first sub-component concerning technology maturity, if the candidate technology has been commercialized, it's score is 5, if it is at demonstration scale it is 3 and if it is only implemented at the pilot plant it scores 1. Applying this scoring approach and taking into account the attributed weights, a single aggregated score ($PIC_i$) according to the following equation is obtained as the value of PIC criterion.

$$PIC_i = \sum_{j=1}^{3} W_j \,.\, A_j \tag{1}$$

*2.2.2. Competitiveness Criteria*

In addition to economic performance, competitiveness of the biorefinery strategies has been also evaluated through three criteria including Competitive Access to Biomass (CAB), Competitiveness on Production Costs (CPC) and Quality Revenue (QR). The CAB was defined by Diffo et al. (Diffo, Chambost et al. 201X) which represents the potential to secure low-cost access to biomass over the long-term. The CPC represents the potential to compete on market prices against the existing producers (Diffo, Chambost et al. 201X), defined in this study as a maximum amount of discount that can be applied on the minimum product sales price in last five years, resulting in minimum possible margin. The QR criterion is an indication of the benefits due to margin creation associated with added value products in a diversified product portfolio. This criterion is defined as the proportion of total revenue that comes from added value products in the biorefinery product portfolio.

*2.2.3. Environmental Criteria*

Besides the ten economic and competitiveness criteria considered in this study, eight life cycle assessment (LCA) based environmental criteria were evaluated for the same integrated forest biorefinery strategies by Batsy et al. (Batsy, Lesage et al. 2013). Adding these environmental criteria into the list of decision criteria would result in eighteen sustainability criteria, so that employing all of them would make the decision-making panel unmanageable. The remedy is to screen-out less important criteria in the context of this study that cannot help decision-makers to distinguish between the biorefinery alternatives. This is done through criteria refinement procedure by a cascade of MCDM panels.

*2.2.4. Criteria refinement*

The economic and competitiveness criteria refinement was accomplished by performing an MCDM panel (MCDM I) in which the relative importance of criteria are evaluated, in the specific context of the biorefinery options being considered. A similar procedure was followed for the environmental criteria by conducting a second MCDM panel (MCDM II). These two MCDMs resulted in a manageable list of sustainability criteria for the final decision-making panel.

*2.2.5. Multi-criteria Decision-making (MCDM) Panel*

Given the relative importance of the criteria in two first MCDMs, the alternatives can be ranked considering economic, competitiveness and environmental criteria. This has been done by conducting the final MCDM with the same panelists. In this study, multi attribute utility theory (MAUT) (Keeney and Raiffa 1976) has been used as the decision-making methodology.

Each MCDM includes a pre-panel and a panel activity. The pre-panel activity is a short meeting with the decision-makers during which the context of the study and the objectives of decision-making are reviewed, and the set of decision criteria is introduced. The panel activity is performed during a full day meeting with the decision-makers with the objective of interpreting the sustainability criteria, and evaluating their relative importance.

## 3. RESULTS and DISCUSSION

### 3.1. Retrofit Design

The case study mill is a kraft pulp mill with pulp production capacity of about 1000 bdt/d from about 2000 bdt/d softwood chips. The integration of four biorefinery technologies was considered including lignin precipitation (Alt.1), organosolv treatment (Alt.2), fast pyrolysis

(Alt.3) and concentrated acid hydrolysis (Alt.4). Figure 1 summarizes Phases I & II for each technology, and Figure 2 represents a simplified process flow diagram of each biorefinery alternative assuming that available biomass at the mill including up to 223 bdt/d hardwood chips and 660 bdt/d forest residues can be fed to the biorefinery processes.

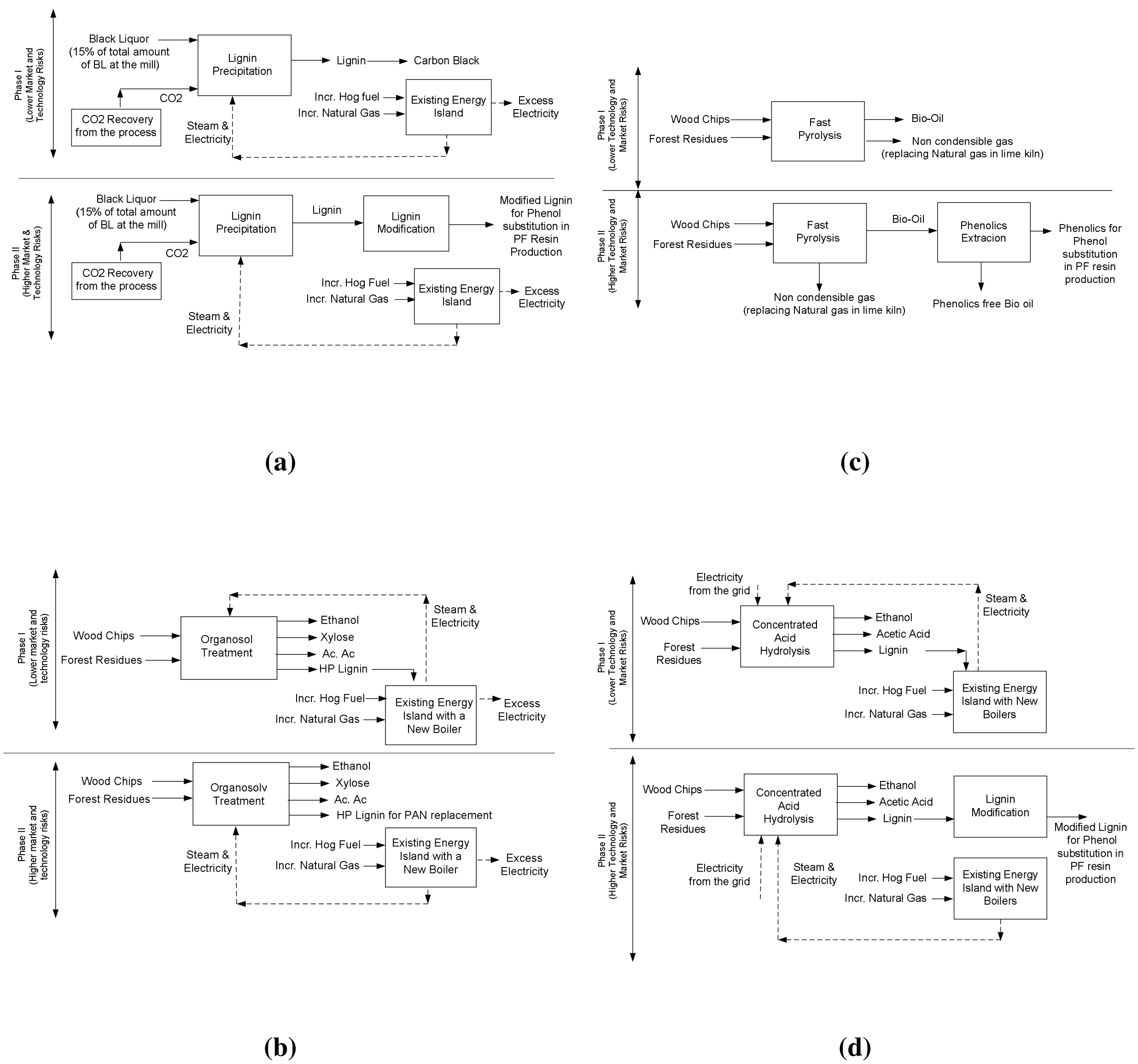
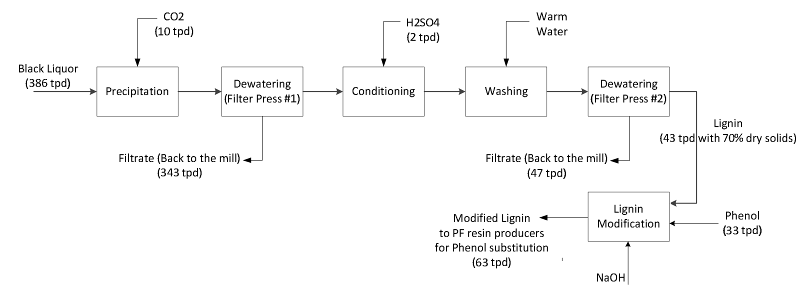
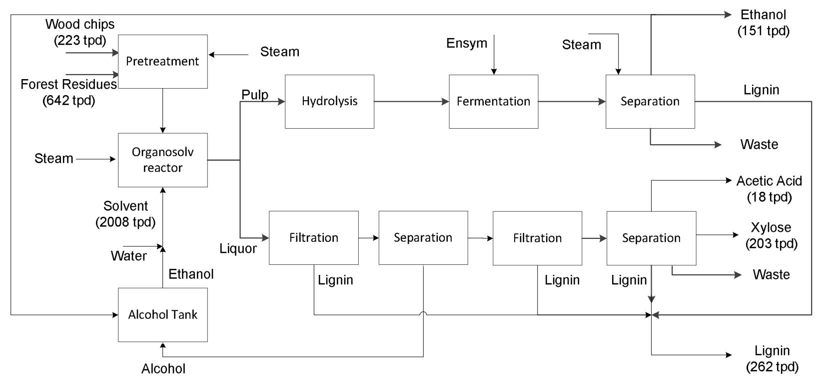



**Figure 1. Phase I and Phase II for each biorefinery candidate: (a) Lignin Precipitation (b) Organosolv Treatment, (c) Fast Pyrolysis (d) High Concentrated Acid Hydrolysis**

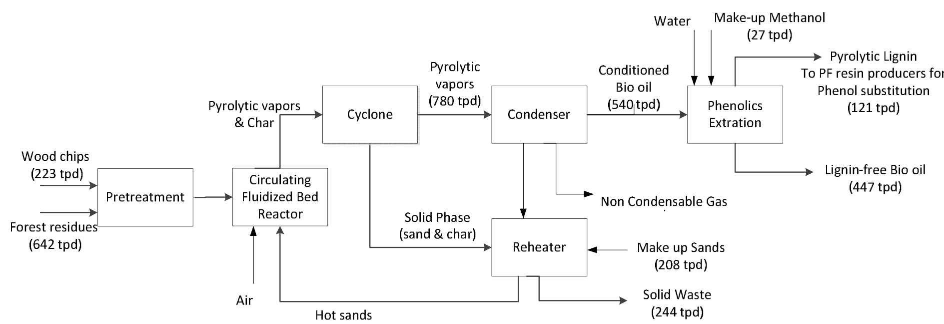
s(a)




(b)




(c)

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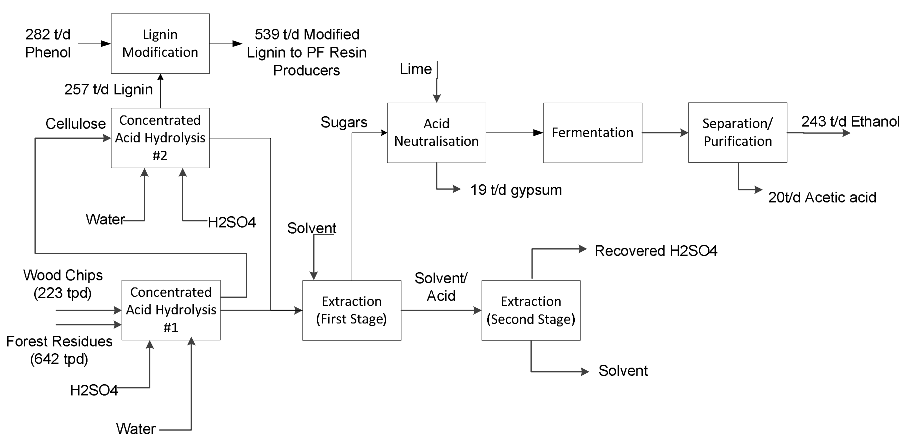



**Figure 2. Simplified process flow diagram for the Phase II of (a) Lignin precipitation, (b) Organosolv Treatment, (c) Fast Pyrolysis, (d) Concentrated acid Hydrolysis.**

## 3.2. Sustainability Assessment

### *3.2.1. Economic and competitiveness assessment*

The economic and competitiveness criteria defined in sections 2.2.1 and 2.2.2 are summarized in Table 1, and the values of these criteria for the four biorefinery technologies are in Figure 3. As can be seen in this figure, these criteria are conflicting and thus making decisions using them in order to identify the most preferred process alternatives in terms of economic and competitiveness performance is not obvious. For instance some criteria such as IRR, ROCE, CPC, DEP and RTMU indicate that lignin precipitation is one of least promising options while based on PIC, TCI, SBV and QR, this alternative is the most preferred investment option.

The multi-disciplinary panel for the MCDMs involved six panelists from industry and academia with various backgrounds including biorefinery, energy, economics, market, and environmental expertise.

The first activity in any MCDM panel is interpreting the criteria. The interpretations of the criteria as a result of this activity have been presented in Table 1, and are critical so that each panel member considers the same understanding of the criteria. The next step involves the weighting activity. In this MCDM, the IRR criterion was selected as the most important criterion, with an average target value of 30%. Using the trade-off method, the panellists then expressed how much from the target value of IRR they would agree to lose, in order to increase the value of each criterion from its lowest value among the alternatives to its highest value. The weights assessed by the panel are summarized in Figure 4-a. As can be seen in this figure, the highest-ranked criteria in the context of this study were Internal Rate of Return (IRR), Competitiveness on Production Costs (CPC), Phase I Implementation Capability (PIC), Downside Economic Performance (DEP) and Return on Capital Employed (ROCE) respectively in the range of 18% to 10% relative importance. Moreover the two least important criteria in this category are Quality Revenue (QR) and Total Capital Investment Cost (TCI). The low importance of QR criterion can be explained: all the alternatives show an equally good performance, so that this criterion did not help the panelists to differentiate between the alternatives.

To define the economic and competitiveness performance associated with each alternative, according to the following equation, a unique economic score ($E_i$) was obtained using the weighting factors ($W_i$) and the calculated utility value associated with each criterion ($U_i$). The utility value of each criterion is a dimensionless value between zero and one, representing the worst and the best performance among the alternatives for each criterion.

$$E_i = \sum_{i=1}^{10} W_i \, . \, U_i \qquad (2)$$

In Figure 4-b, the alternatives have been ranked according to this equation. These scores indicate that the least preferred alternatives in terms of economic and competitiveness performance are lignin precipitation and concentrated acid hydrolysis. On the other hand, the scores show that organosolv treatment and fast pyrolysis are the most preferred technologies. For the organosolv process, this is mainly due to the scores from the CPC, DEP and ROCE criteria. The high values of CPC and DEP criteria in this alternative occurred because even low end market conditions cannot dramatically lower margins due to the high revenue to production cost ratio. In organosolv and fast pyrolysis, the annual revenue considering poor market conditions for one third of the year would be respectively 88% and 32% more than the production costs. Whereas for lignin precipitation and concentrated acid hydrolysis, revenue fell to 3% and 1% less than the production costs for poor market conditions. In addition, although the organosolv process is capital intensive, the investment efficiently represented by ROCE is considerably high due to the margin created because of high revenue coming from lignin stream targeted for PAN replacement in carbon fiber production.

# Table 1. Economic and competitiveness criteria

| Criteria Interpretation (result of conducted MCDM I) | | Metric |
|---|---|---|
| IRR: Internal Rate of Return | IRR measures overall **project profitability under normal market conditions**. It should preferably be greater than a minimum target value for long-term investments and further increased relative to the riskiness of the option -Higher IRR is preferred as this represents a higher profitability. | $\mathrm{NPV} = \sum_{t=0}^{22} \frac{\mathrm{CF_t}}{(1+\mathrm{IRR})^{t}} = 0$ |
| DEP: Downside Economic Performance | DEP measures the financial performance of the biorefinery strategy during poor market conditions. Higher DEP is preferred as a measure of **project robustness**, ie that the project can survive even under unfavourable market conditions. | $DEP = \left(\frac{4*\left(\frac{EBIT}{Revenue}\right)_{@Poor\ market} + 8*\left(\frac{EBIT}{Revenue}\right)_{@Normal\ market}}{12}\right) * 100$ |
| ROCE: Return On Capital Employed | ROCE measures the cash generated relative to the invested capital for a biorefinery strategy and is widely used as a measure by the investment community. It expresses the **efficiency of the investment** measured by how much the biorefinery strategy generates cash flow from investments. Higher ROCE is preferred because it indicates better return on invested capital. | $ROCE = \frac{EBIT}{TCI}$ |
| RTMU: Resistance to Supply Market Uncertainty | This criterion measures **sensitivity of the biorefinery margin to the cost of energy and chemicals**. More robust biorefinery strategies are less sensitive to changes in energy and chemicals price and are less affected by these external sources of uncertainty. | $\frac{\mathrm{EBIT}}{\mathrm{Cost\ of\ Chemiclas + Cost\ of\ ENergy}}$ |
| TCI: Total Capital Investment Costs | TCI is the amount of **capital** that must be raised in order to execute the project. There is a larger challenge to assemble larger capital amounts. | $TCI = FCI + WCI$ |
| SBV: Short term Business Viability | SBV measures **project profitability as IRR in the short-term under normal market conditions** which supports longer term corporate transformation. Larger SBV values is preferred representing greater margin in short term which accordingly supports Phase II implementation. | $NPV = \sum_{t=0}^{22} \frac{\mathrm{CF_t}}{(1+\mathrm{SBV})^{t}} = 0$ |
| PIC: Phase I Implementation Capability | PIC is an aggregated measure of **technology risk** that considers technology maturity (pilot demonstration etc), scale-up requirement to commercial scale, and ability to execute the Phase I technology in 24 months. Higher value of PIC is preferred because it represents lower technology risk in Phase I, and represents an **opportunity to be faster to the market** in Phase II. | $PIC = 0.5 * Maturity\ score + 0.25 * scalability\ score + 0.25 * imlementation\ capability\ score$ |
| CAB: Competitive Access to Biomass | CAB represents the **ability to guarantee supply of biomass** in competitive environment. The margin on biomass is a fundamental competitive factor related to securing feedstock over the longer-term, since it is a measure of capacity to pay more to retain cutting rights and to be competitive against other proponents seeking to use the same type of biomass. | EBITDA per ton of biomass |
| CPC: Competitiveness on Production Costs | CPC shows how competitive the biorefinery product portfolio production costs are relative to market prices (and thus pre-existing producers), and is **an indication of the project to penetrate existing markets and achieve market share** in the short term, to guaranty market position in the longer term. A higher value of CPC is preferred as it shows that products can be manufactured below market prices, and thus the investor can better negotiate take-off agreements to penetrate the market and gain market share. | $CPC = 100\% - \frac{Production\ Costs}{Revenue_{@Poor\ market\ condition}} * 100$ |
| QR: Quality Revenue | QR measures the **ability of biorefinery strategy to maintain strong margins** due to added value products in the product portfolio. The greater the value of QR as a percentage of total revenue, the stronger the biorefinery strategy. | $\frac{\mathrm{Revenue\ from\ value\ added\ products}}{\mathrm{Total\ revenue}}$ |

NPV: Net Present Value
CF: Cash Flow
EBIT: Earnings before Interest and Tax
FCI: Fixed Capital Investment Cost
WCI: Working Capital Investment Cost
EBITDA: Earnings before Interest, Tax, Depreciation and Amortization

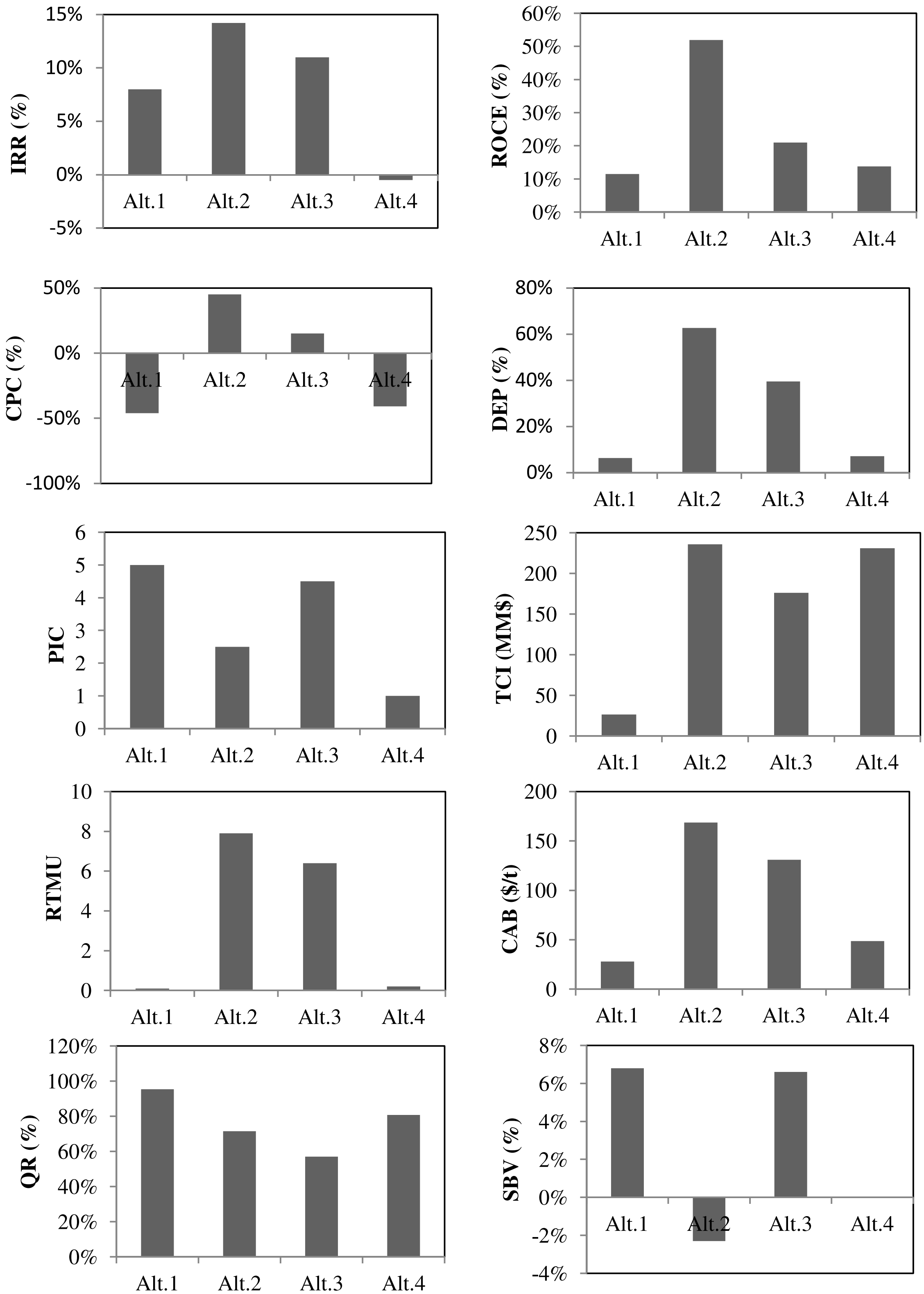
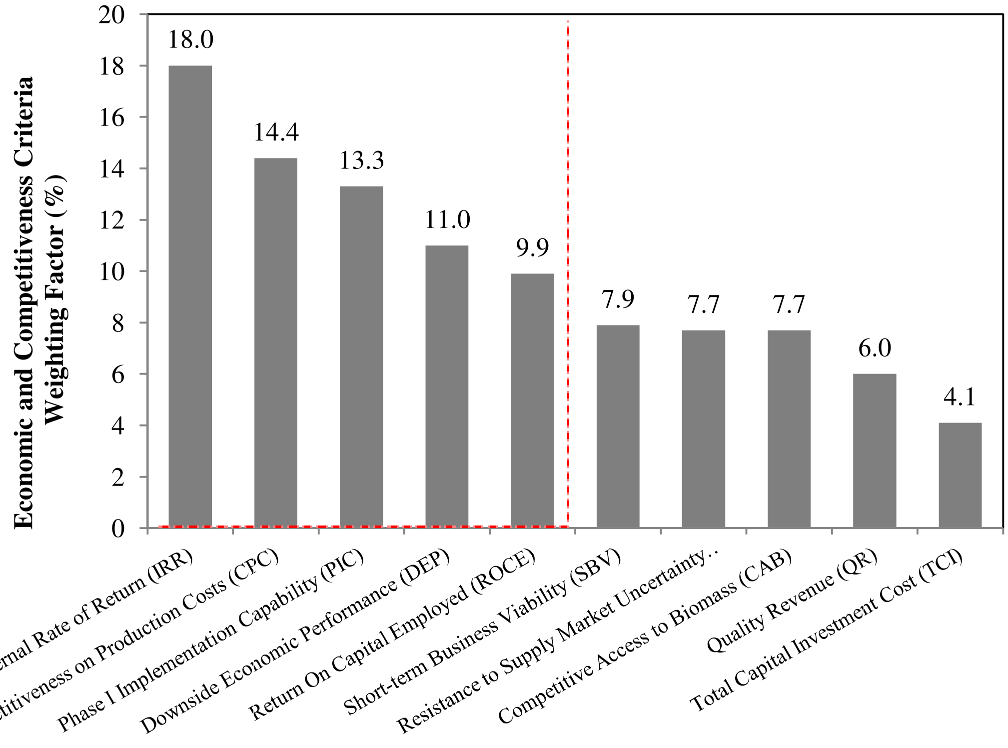
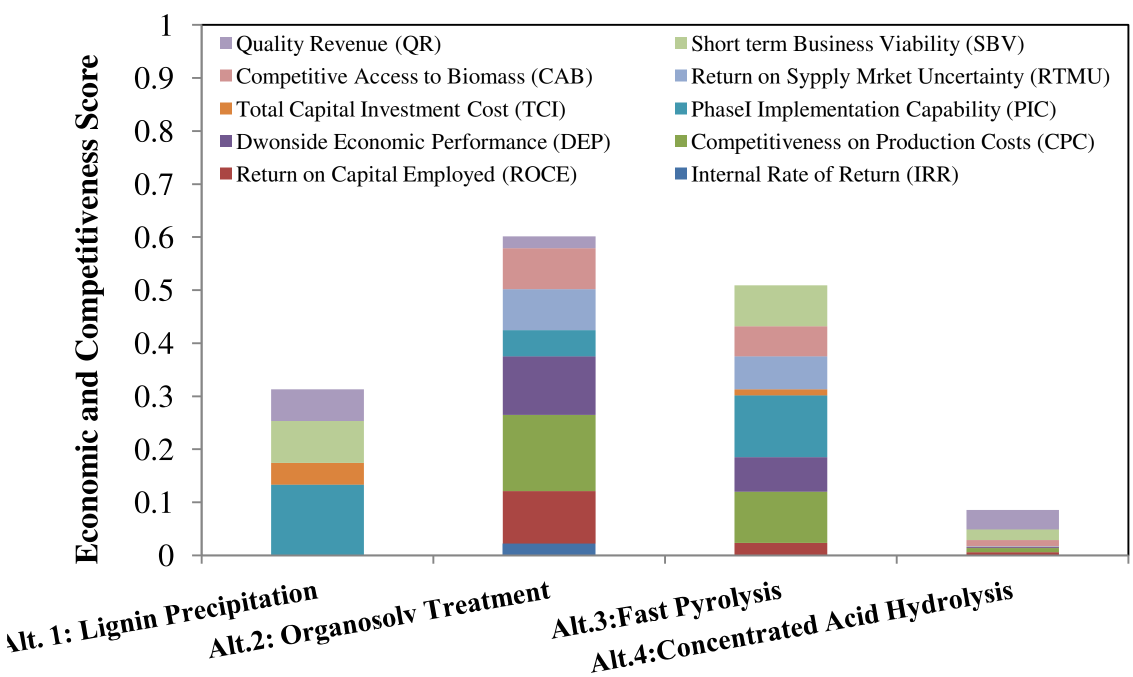



**Figure 3. Economic and competitiveness criteria for the four biorefinery alternatives**




(a)




(b)

**Figure 4: (a): Weighting factor of economic and competitiveness criteria (b) Economic and competitiveness score of biorefinery alternatives**

*3.2.2. Environmental assessment*

The environmental performance of the biorefinery strategies has been assessed by Batsy et al. (Batsy, Lesage et al. 2013) using a similar approach. Eight LCA-based environmental criteria were considered including Greenhouse Gas emission (GHG), Non-Renewable Energy Consumption (NRE), Respiratory Organics (RO), Carcinogens (C), Ionizing (I), Respiratory Inorganics (RI) and Water Turbined (WT). The MCDM results show that among these criteria, three of them were selected by panelists as the most important environmental criteria in the context of the results for the 4 biorefinery options, including Greenhouse Gas Emissions (GHG), Non-Renewable Energy (NRE) and Respiratory Organics (RO) respectively with 33%, 24% and 16% relative importance. The interpretation of this set of important environmental criteria and their values for four case study alternatives are respectively presented in Table 2 and Figure 5.

**Table 2. Selected environmental criteria for sustainability assessment (Batsy et al. 2013)**

| **Criteria Interpretation (result of conducted MCDM II)** | | **Metric** |
|---|---|---|
| GHG: Greenhouse Gas Emissions | GHG represents **carbon footprint** of the alternative in terms of CO2 equivalent compared to the established competitive existing product portfolio. It also represents **competitiveness on "greenness"** in terms of potential for meeting GHG Emissions target (eg. 20% reduction compared to competitive fossil-based product portfolio). Lower values represent better environmental performance. | Absolute value: CO2 equivalent<br><br>Relative value compared to a competitive product portfolio: % |
| NRE:<br>Non Renewable Energy | This criterion shows **the level of stress on NRE** consumption compared to the competitive product portfolio. It also represents the **level of dependency of the candidate biorefinery alternatives on fossil-based energy** which is a limited energy source. Lower values show more independency on fossil-based resources which can be considered as an advantage especially in long-term vision. | Absolute value: KJ<br><br>Relative value compared to a competitive product portfolio: % |
| RO: Respiratory Organics | This criterion shows the potential impact of VOCs and other contaminants emissions into air, having an effect on human health, specifically respiratory, compared to the competitive product portfolio. Lower value of this criterion is preferred due to less risk on human health. | Absolute value: kg ethylene<br><br>Relative value compared to a competitive product portfolio: % |

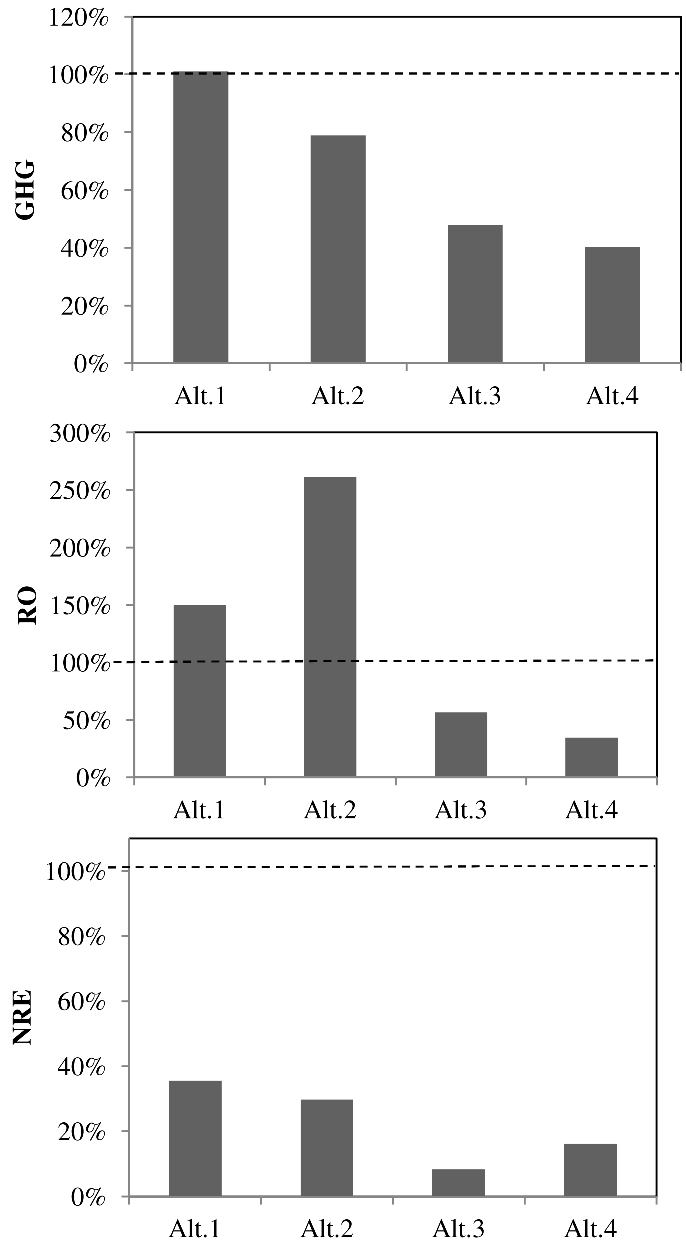



**Figure 5. Selected environmental criteria for the four biorefinery alternatives**

*3.2.3. Decision-making*

The five selected most important economic and competitiveness criteria as a result of MCDM I plus three selected most important environmental criteria as a result of MCDM II were employed for sustainability assessment of the 4 biorefinery strategies. This set of eight sustainability criteria were used in a third MCDM with the same panelists. The trade-off activity in this panel resulted in relative importance of the sustainability criteria (Figure 6-a), and the ranking of biorefinery alternatives in terms of their sustainability performance (Figure 6-b).

The two first-ranked criteria had already been selected as the most important criterion in the earlier MCDMs: IRR as an economic measure, and GHG as an environmental measure. It is interesting that environmental criteria (e.g GHG), competitiveness criteria (e.g CPC) and also risk-based economic criteria (e.g PIC and DEP) were considered important in addition to strictly economic criteria often used for investments in the core pulp and paper business.

The overall sustainability scores show that by considering the environmental criteria, the score of the fast pyrolysis alternative is increased in a way that it would be almost equally preferred as organosolv treatment. In the case of concentrated acid hydrolysis, despite of its promising environmental performance, it is a less-preferred option in terms of sustainability due to its poor economic and competitiveness performance. Thus, lignin precipitation and concentrated acid hydrolysis were screened out from the list of promising transformational strategies for the case study mill.

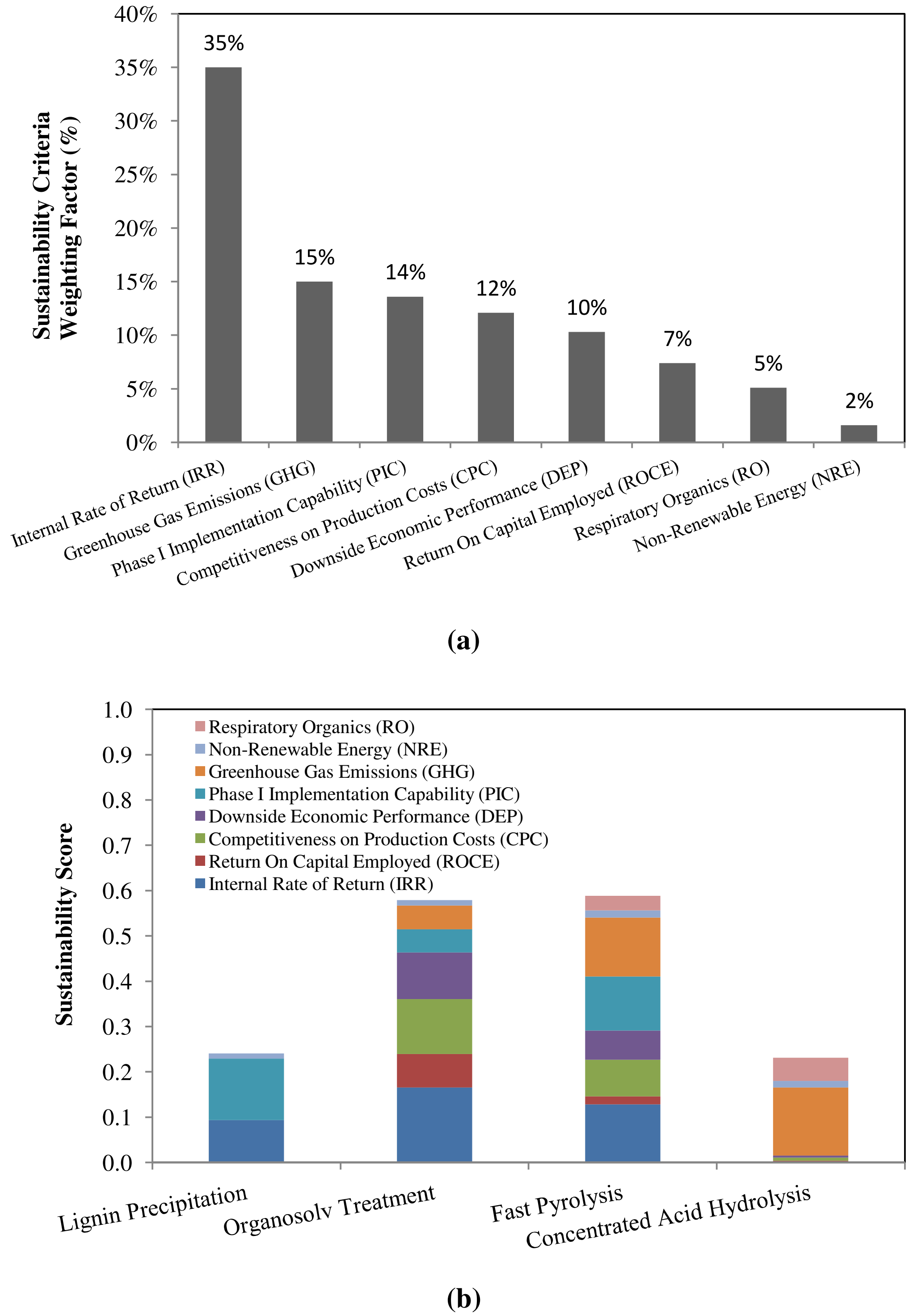



**Figure 6: (a) Weighting factors of sustainability criteria (b) Sustainability score of biorefinery alternatives**

## 4. CONCLUSIONS

From the overall sustainability scores, it was concluded that two alternatives should be screened out from the list of promising biorefinery strategies. Despite of better economic and competitiveness performance of the organosolv treatment, when environmental performance is taken into account, this alternative becomes equally preferred compared to fast pyrolysis technology.

The developed systematic methodology illustrates the strength of MCDM method for distinguishing between integrated forest biorefinery strategies using a sustainability perspective. This practical method can potentially assist forest products companies to identify promising transformational strategies, to transfer knowledge of risk and other key issues to decision-makers, and to build consensus between decision-makers.

## ACKNOWLEDGEMENT

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# APPENDIX E– Article 5:

## Strategic Decision-Making under Uncertainty to Identify Sustainable Biorefinery Strategies, Part I: Uncertainty Analysis

**Strategic Decision-making under Uncertainty to Identify Sustainable Biorefinery Strategies, Part I: Uncertainty Analysis**

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**ABSTRACT**

The biorefinery is a potential game-changer in the forest products sector, being considered by many companies in light of several drivers. However only certain biorefinery strategies will be sustainable and each of them has its own uncertainties and risk. Considering the investor's perspective, it is critical that unsustainable strategies are screened out at the early design stage. In this study four biorefinery technologies, have been assessed in terms of sustainability performance under uncertainty for retrofit in a kraft pulp mill in which uncertainty is quantified by a stochastic risk analysis method (Monte Carlo analysis) resulting in probability distribution functions of sustainability criteria. The conflicting sustainability criteria are then aggregated into a unique index through a multi-criteria decision-making (MCDM) panel. The results show that considering uncertainty in the panel changed the basis of decision-making, and made the decision more objective to better distinguish between the biorefinery alternatives.

**Keywords:** biorefinery design, sustainability assessment, multi-criteria decision-making (MCDM), uncertainty analysis, Monte Carlo analysis

## 1 INTRODUCTION

Increasingly, North American forest product companies are seeking to transform their business through the integration of biorefinery technologies into their existing pulp and paper mills, for the manufacture of an expanded product portfolio. The biorefinery strategy is a potential game-changing solution to current financial challenges the forestry industry is facing. Only certain biorefinery strategies will be sustainable for the long-term, and they each imply different levels of risk. Moreover, the particular biorefinery strategy is unique to every forest products company, ie the existing manufacturing sites, degree of vertical integration, access to biomass feedstock, existing customers and other factors are pertinent to the partnerships that could be formed for successful biorefinery transformation and competitive advantage. Thus, a systematic approach for transformation strategic decision-making is required in order to identify the most-preferred sustainable biorefinery strategies.

At the early design stage, a high level of uncertainty is associated with technology and market data for each product-process biorefinery strategy, and this should be considered in decision-making. Hoffman et al (Hoffmann et al. 2004) introduced three reasons why companies should carefully select project at the strategic level of decision-making: (1) financial resources are limited and among numerous potential emerging technologies, these resources should be allocated to promising long-term strategies, (2) despite that typical project selection procedures are mainly driven by economic objectives, decision-makers should consider environmental and competitiveness objectives, and (3) most information at the early design stage is uncertain and if this uncertainty is not addressed in decision-making, wrong decisions may be taken (Shakhsi-Niaei et al. 2011).

At the strategic level of design, investors seek to efficiently screen out non-promising strategies in order to limit the number of possibilities to be further analyzed at the tactical and operational levels of design where a unique optimal solution is sought. Several studies in the literature address uncertainty in decision-making at the more detailed levels, for example Gebreslas et al. (Gebreslassie et al. 2013) and Hugo et al. (Hugo et al. 2003). Most of these studies are related to supply chain optimization, where this approach has been summarized by Gloria et al. (Giarola et al. 2013). Good Reviews of uncertainty in optimization can be found in the work done by Sahinidis and Verderame et al. (Sahinidis 2004; Verderame et al. 2010). In the context of integrated forest biorefinery, uncertainty analysis has been assessed by Svensson (Svensson 2012).

Despite the importance of involving uncertainty in strategic decision-making in the context of emerging biorefinery technologies, decisions have mainly been made considering deterministic conditions (no uncertainty) (Dorini et al. 2011) and little attention has been paid to decision-making under uncertainty (Shakhsi-Niaei et al. 2011). This is for many reasons but from an industrial perspective, a practical methodology is needed that can at the same time address risk and uncertainty, but also, be understood by decision-makers. A set of sustainability decision criteria covering economic, environmental and competitiveness aspects of a biorefinery project should be evaluated under uncertainty and be employed in a systematic decision-making process.

Some researchers (Medaglia et al. 2007) have tried to consider uncertainty in project selection in a comprehensive way leading to less practical and more complex methods (Shakhsi-Niaei et al. 2011). In contrast to these complex methods, techniques such as multi-criteria decision-making (MCDM) seem more appropriate for the strategic level of decision-making in industry (Keeney and Raiffa 1976). Although there are some studies using MCDM for sustainability assessment of biorefinery technologies, most of them have been done considering deterministic considerations (Sugiyama, Fischer et al. 2008; Othman 2011; Schaidle et al. 2011; Posada et al. 2013).

There are different sources of uncertainty associated with biorefinery project selection using MCDM, including (1) uncertainty in the inputs to the evaluation model, called data uncertainty, (2) uncertainty in evaluation model itself, called model uncertainty, and (3) decision-making uncertainty in attributing relative importance to decision criteria, called MCDM panel uncertainty. Several mathematical and computational methods exist for uncertainty analysis such as statistical methods, fuzzy mathematics and artificial intelligence (Liu and Huang 2012). Among these methods, the statistical method, and especially Monte Carlo analysis method, is the most commonly used method.

Some studies have focused on involving one type of uncertainty (mentioned above) in decision-making. For instance, Liu and Huang (Liu and Huang 2012) have presented a methodology to measure sustainability of biodiesel manufacturing systems using uncertain data, and employ an MCDM method. They used the interval-parameter (IP) method for uncertainty analysis. Although they have mentioned that the relative importance of the decision criteria has been determined by the organization, a systematic approach for quantifying these weights is missing in the study. Cheali et al (Cheali et al. 2014) have considered data uncertainty (uncertainty in biomass and product price) in a superstructure assessment of biorefinery technologies for both biochemical and thermochemical pathways. Their study focused on comparing the economic performance of biorefinery options, however the other sustainability pillars are missing. Madani and Lund (Madani and Lund 2013) used the Monte Carlo method as an uncertainty analysis tool in order to convert an uncertain problem into several deterministic problems, and combined this with game theory. They addressed uncertainty in input data to evaluate the decision criteria, which were aggregated into a sustainability index employing MCDM.

Dealing with conflicting decision criteria requires decision-maker judgment about the relative importance of each criterion, increasing uncertainty in results. For example, Chou et al. (Chou and Ongkowijoyo 2014) have compared the sustainability performance of different renewable energy systems for policy making using MCDM. They addressed the uncertainty associated with relative weighting factors in order to investigate the dependency of the final decision and weighting factors. Their study proposes a risk-based MCDM that uses graphical matrix modeling along with Monte Carlo simulation. In order to address uncertainty in the relative criteria importance, they applied a triangular distribution for the scores given by each decision-maker to each criterion. These triangular distribution functions are developed using three numbers considering the pessimistic, most likely, and optimistic values that a panel member can give to each pair-wise criteria comparison. However attributing a distribution function to the scores for pair-wise comparison does not impact the subjectivity associated with the criteria weighting factors.

Some studies have addressed different sources of uncertainty - including data and panel uncertainty - in decision-making. For instance, Flores-Alsina et al. (Flores-Alsina et al. 2008) assessed sustainability under uncertainty for wastewater treatment systems employing MCDM. They developed a probability distribution function for sustainability criteria by applying uncertain parameters and employing Monte Carlo analysis, in order to investigate the effect of involving data uncertainty in decision-making. They categorized uncertain parameters in three groups, being (1) low uncertain parameters with 5% variation compared to deterministic values, (2) medium and (3) highly uncertain parameters with 25% and 50% variation, respectively. In addition to data uncertainty, these authors also addressed uncertainty in the relative importance of the decision criteria in MCDM. Considering deterministic evaluations, the same weighting factors were assumed for decision instead of quantifying them with decision-makers (stakeholders) using the trade-off method. In addition, in order to address uncertainty in the weighting factors, scenarios were analyzed considering different combinations of criteria weights. Although the effect of uncertainty in data and criteria weight on the final decision was considered separately, the two sources of uncertainty were not applied simultaneously in decision-making. Doroni et al (Dorini et al. 2011) have compared bio-based energy with coal-based electricity generation in terms of sustainability performance, by quantifying uncertainty using Monte Carlo analysis and aggregating uncertain decision criteria using MCDM. The impact of considering all types of uncertainty on the final decision was demonstrated by presenting the results for three cases including (1) assuming no uncertainty, (2) involving uncertainty in data, and (3) involving uncertainty in data and decision-maker preferences. In order to address uncertainty in criteria weights, instead of attributing a deterministic value to each pair-wise comparison, a probability distribution function was used. For instance, instead of defining an average value for the weights of each criterion based on the 6 panelists, a 1/6 probability to each weight was considered to represent the opinion of each panelist. Patel et al. (Patel et al. 2012) assessed sustainability performance of buta-1,3-diene production through bio-based process compared to the conventional process, using MCDM under uncertainty. A set of quantitative and qualitative sustainability criteria was used, considering Monte Carlo uncertainty. In addition to data uncertainty, uncertainty was also addressed in the relative importance of each criterion. However the attributed weighting factors are arbitrarily defined in both deterministic and uncertain conditions, instead of reflecting decision-maker opinions by quantifying weights in the panel. Shakhsi-Niaei et al. (Shakhsi-Niaei et al. 2011) have presented a unique framework for project selection under uncertainty which addressed two phases of project selection: (1) screening out non-promising options (strategic level), and (2) selecting the final promising project. In the first phase, Monte Carlo analysis linked with MCDM was used, whereas in the second phase, Monte Carlo analysis was linked with integer programming considering budget and other logical constraints to find the optimal solution.

Although several studies in the literature have addressed uncertainty in project sustainability assessment and decision-making, a method for identifying sustainable biorefinery strategies for project selection at the strategic level of design considering different sources of uncertainty is missing. In addition, decision-maker attitude toward risk should be determined. Uncertainty and risk should both be addressed at the strategic level of design to increase the quality and efficiency of decision-making. The objective of this study is to develop a systematic approach in order to consider uncertainty and the risk attitude of decision-makers in strategic decision-making, while employing the MCDM approach using a set of sustainability criteria. This article is presented in two parts: (1) Part I focuses on uncertainty analysis, and (2) Part II focuses on the risk attitude assessment of decision-makers.

## 2 METHODOLOGY

The current study presents a new methodology for sustainability assessment of biorefinery strategies for uncertain conditions taking into account uncertainty and risk in decision-making.

In multi-criteria decision-making (MCDM), two determining parameters are used in order to rank alternatives in terms of their sustainability performance, including (1) a "weighting factor" representing the relative importance of the criteria, and (2) a "utility value" , normalized from of the criteria values that the way they are normalized is determined by preference of decision-makers for each criterion. More specifically, utility is a function that converts the criterion value to a dimensionless number between zero to one, representing decision-maker preferences, e.g. the utility value of the best (highest) IRR value is set to one and the utility value of the worst IRR value is set to zero.

When uncertainty and risk are taken into consideration, the weighting factor and utility function can be affected. After involving uncertainty in criteria evaluation, each criterion would be expressed as a range of possible values, which can impact how panel decision-makers consider the criterion and assess weights. Decision-makers face risks in MCDM panels, and in order to deal with it, the combination of attitude toward risk by individual decision-makers may affect the final decision. Taking this into account, decision-maker attitude toward risk should be quantified and accounted for in decision-making. The attitude toward risk can be addressed in the utility function of the decision criteria.

The overall methodology presented in this study is summarized in Figure 1. The methodology for uncertainty analysis, and consequently re-calculating the weighting factors is addressed in the first step of the methodology. Utility reformulation considering decision-maker attitude toward risk, is addressed the second step. Finally, using the new weighting factors and applying the new utility functions, decision-making can be done in the last step of the methodology. For simplicity and practicality purpose, there is necessity that the decision making process can be clearly explained and well understood by the panel members. In this regard, the main contribution of this work is developing the overall methodology, and not necessarily the type of mathematical tools employed.

Part I of this publication focuses on the role of data uncertainty analysis in decision-making, while Part II focuses on measuring the risk attitude of decision-makers and the impact of panel uncertainty in decision-making.

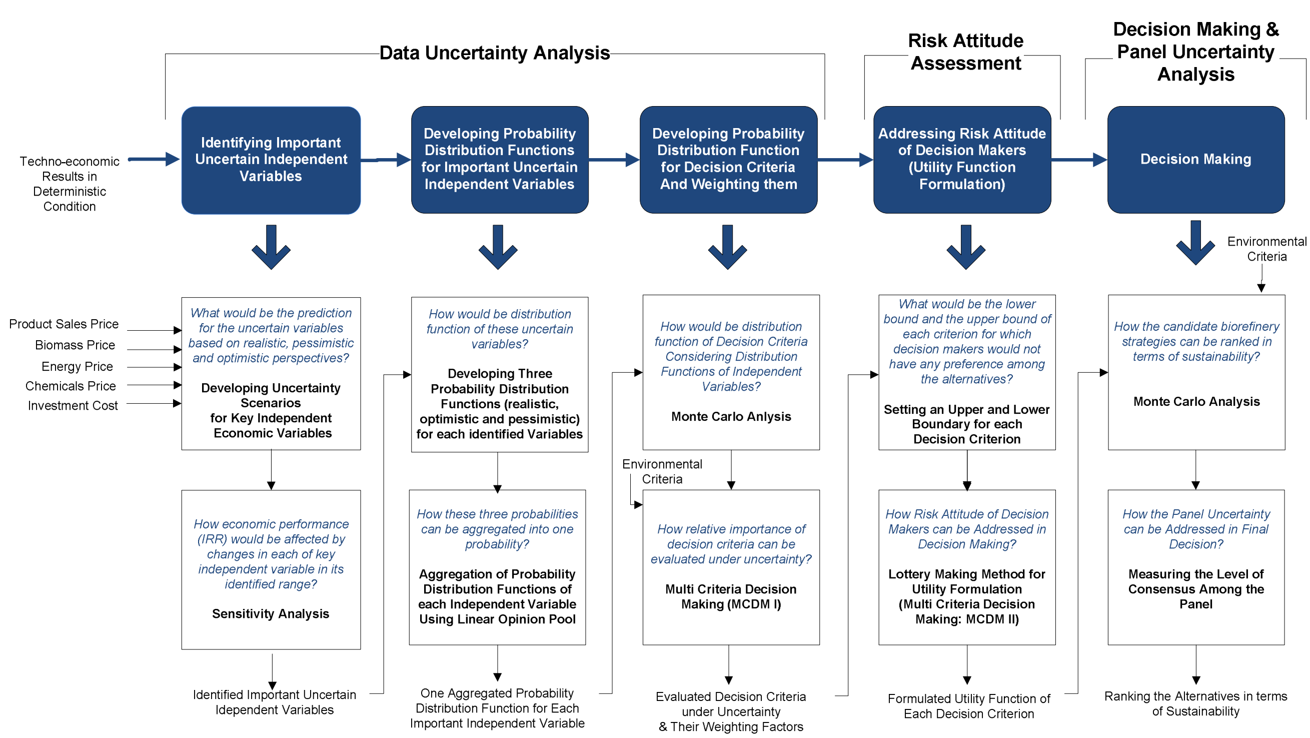


**Figure 1. Overall methodology for addressing uncertainty and risk in decision making for Sustainability assessment of biorefinery strategies**

### 2.1.Data uncertainty assessment

Uncertainty analysis has three main steps comprising (1) classification of sources of uncertainty, (2) identification of an important set of uncertain variables and their associated uncertainty and (3) quantification of uncertainty (Kim and Augenbroe 2013).

Different sources of uncertainty are generally involved in sustainability assessment consisting of (1) data uncertainty representing uncertainty in input data in economic and environmental analysis models, (2) model uncertainty representing uncertainty in the evaluation models such as techno-economic and life cycle assessment (LCA), and (3) panel uncertainty in terms of the level of consensus among the panel members for the final decision.

The objective of "data uncertainty assessment" is to evaluate weighting factors considering data uncertainty, leading to a distribution function for each decision criterion. Criteria are a function of several variables, for example biomass price, product sale price, estimated capital investment costs as input data to techno-economic and LCA models.

This study focuses on recognizing uncertainty, quantifying it, and presenting the results for facilitating the interpretation by decision-makers. For this reason, data uncertainty in this study has been considered using the Monte Carlo analysis method. This method converts a stochastic problem into a number of deterministic problems through the generation of random samples from data distribution functions. Using Monte Carlo, data uncertainty analysis is achieved through (1) the identification of important uncertain variables, (2) the development of distribution functions for the important uncertain variables, and (3) the generation of probability distribution functions (PDF) for calculated criteria as a result of uncertainty in the data.

#### *2.1.1. Identification of important uncertain variables*

In order to identify important uncertain variables, the minimum and maximum possible value for each input variable should be identified in order to identify the impact of changes in variables on the results. Considering data scarcity, a methodology is required in order to consider possible events for each input variable. A survey can be done using available information in open sources and interviews with stakeholders that may imply subjectivity and lead to the definition of extreme events. Three possible perspectives have been used in order to forecast each input variable: pessimistic, optimistic and realistic perspectives. For each perspective, minimum and maximum possible values are attributed to each variable using a triangular distribution function. A sensitivity analysis was performed in order to investigate IRR (as the most important criterion in deterministic condition) sensitivity to each variable change. A variation of +/- 2% of IRR leads to the identification of the most important uncertain variables.

### *2.1.2. Developing probability distribution function for the identified important uncertain variables*

For each variable three triangular distribution functions were developed representing pessimistic, realistic and optimistic perspectives. These PDFs were aggregated into one distribution function for each variable in order to provide a unique representation of decision-maker opinions. Different methods exist for aggregating probability distribution functions: (1) mathematical methods, and (2) behavioral approaches. Although each of these methods has their own advantages and disadvantages, mathematical methods seem more applicable, easy to apply and are defendable (Clemen and Winkler 2007). Mathematical methods can be categorized into three main techniques including (1) axiomatic, (2) linear opinion pool and (3) Bayesian methods (Clemen and Winkler 2007). Linear opinion pool by Stone (Stone 1961) is the simplest and most easily understandable method,  and was selected for this study:

$$p(\theta) = \sum_{i=1}^{n} w_i p_i(\theta) \tag{1}$$

Where *n* is the number of experts (perspectives), $p_i$ is probability distribution of variable θ based on the opinion of expert i (perspective i), *p*(θ) is the aggregated probability distribution, and *wi* are the weights in a way that their summation would be equal to one. The review of different aggregation methods in other studies shows that generally simpler mathematical aggregation methods perform as well as more complex methods (Clemen and Winkler 2007).

*2.1.3. Developing probability distribution function for decision criteria and weighing them*

Distribution functions for important variables are employed in Monte Carlo analysis. In order to facilitate knowledge transfer to decision-makers, three numbers are extracted from each distribution and used in MCDM: (1) modal value (most probably value), (2) minimum value (10th percentile) and (3) maximum value (90th percentile). In this panel a trade-off activity is performed in order to attribute a relative importance (weighting factor) to each criterion considering the evaluated uncertainty associated with each criterion.

**2.2. Multi-Criteria Decision-Making (MCDM) panel**

Among the common methods of MCDM (Chou and Ongkowijoyo 2014), Multi-Attribute Utility Theory (MAUT) (Keeney and Raiffa 1976) has been chosen for this study. With this method, the metrics quantifying criteria are called attributes (Janssen 2007). Two critical parameters are used to rank the design option: (1) utility function $(u_i(x_i))$ and (2) relative importance of each decision criterion $(w_i)$. Using these two parameters, the overall utility value $(U(x))$ of each design alternative, representing the overall sustainability performance of each option, is calculated according to the following equation:

$$U(x) = \sum_{i=1}^{N} w_i \cdot u_i(x_i) \tag{2}$$

Where U(x) is the overall utility value or sustainability score, N is the number of criteria, $w_i$ is weighting factor of criterion i such that $0 \le w_i \le 1$ and $\sum_{i=1}^{N} w_i = 1$ , $u_i(x_i)$ is the utility function of criterion i.

*2.2.1. Utility Function*

The utility value of each attribute is a value between zero and one and is evaluated using a utility function. The lower bound of each criterion is used to represent the worst criterion or attribute value $(x_{i_{LowerBound}})$ at which the utility value would be zero $(u_{x_{i_{LowerBound}}} = 0)$. Similarly the upper bound of each criterion is defined as the best criterion value $(x_{i_{UpperBound}})$ at which the utility value would be one $(u_{x_{i_{UpperBound}}} = 1)$ (Janssen 2007). A function between these two boundaries is called the utility function and is commonly assumed to be linear. If the criterion value for an alternative is equal to or below the lower bound, its utility value would be zero and if the criterion value is equal to or higher than the upper bound its utility value would be one (Janssen 2007).

### *2.2.2. Weighting Factors*

The trade-off method has been used for weighing the decision criteria in this study, and considers: (1) the selection of the most important criterion, and (2) the definition of its target value by the decision-makers. The target value in this study is the minimum acceptable value for the most importance criterion for which the decision-makers would be ready to invest.

In the trade-off method, each decision-maker determines a criterion value which makes his opinion indifferent between two situations A and B (Janssen 2007). The indifference in the comparison of each criterion to the most important criterion means that the overall utility value (U) of these situations (A and B) should be the same (equation 3):

$$U_A = U_B \tag{3}$$

In order to evaluate relative importance, each criterion is compared to the most important criterion one at the time. In each comparison, the panelists are asked to determine if in situation A they would have the target value for criterion k and the minimum value for criterion m, whether this is indifferent for them with which value of criterion k in situation B when criterion m would be at its maximum value. For an indifferent judgment between situations A and B for each criterion, and considering that the weights should add up to unity, results in the following equation by which weighting factors of the decision criteria are calculated (Janssen 2007):

$$\begin{bmatrix} 1-u_k(x^B_{k,m=1}) & -1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 1-u_k(x^B_{k,m=N}) & 0 & \cdots & -1 \\ 1 & 1 & \cdots & 1 \end{bmatrix} \begin{bmatrix} w_1 \\ \vdots \\ \vdots \\ w_N \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} \quad \forall m \neq k \tag{4}$$

# 3 RESULTS

## 3.1. Decision-making for the deterministic case

The authors considered sustainability assessment of integrated forest biorefinery strategies for the deterministic case evaluated here, ie without considering risk and uncertainty – summarized here for completeness.

Four biorefinery technologies - lignin precipitation (Alt.1), organosolv treatment (Alt.2), fast pyrolyis (Alt.3) and concentrated acid hydrolysis (Alt.4) - were assessed in terms of their sustainability performance considering uncertainty and risk. A phased approach for technology and market risk mitigation was defined for the implementation of each biorefinery alternative, in retrofit to a kraft pulp mill. A simplified process flow diagram of each alternative considering the use of available biomass to the site - including 223 bdt/d hardwood chips and 660 bdt/d forest residues – is presented in Figure 2.

s(a)

(b)

(c)

(d)

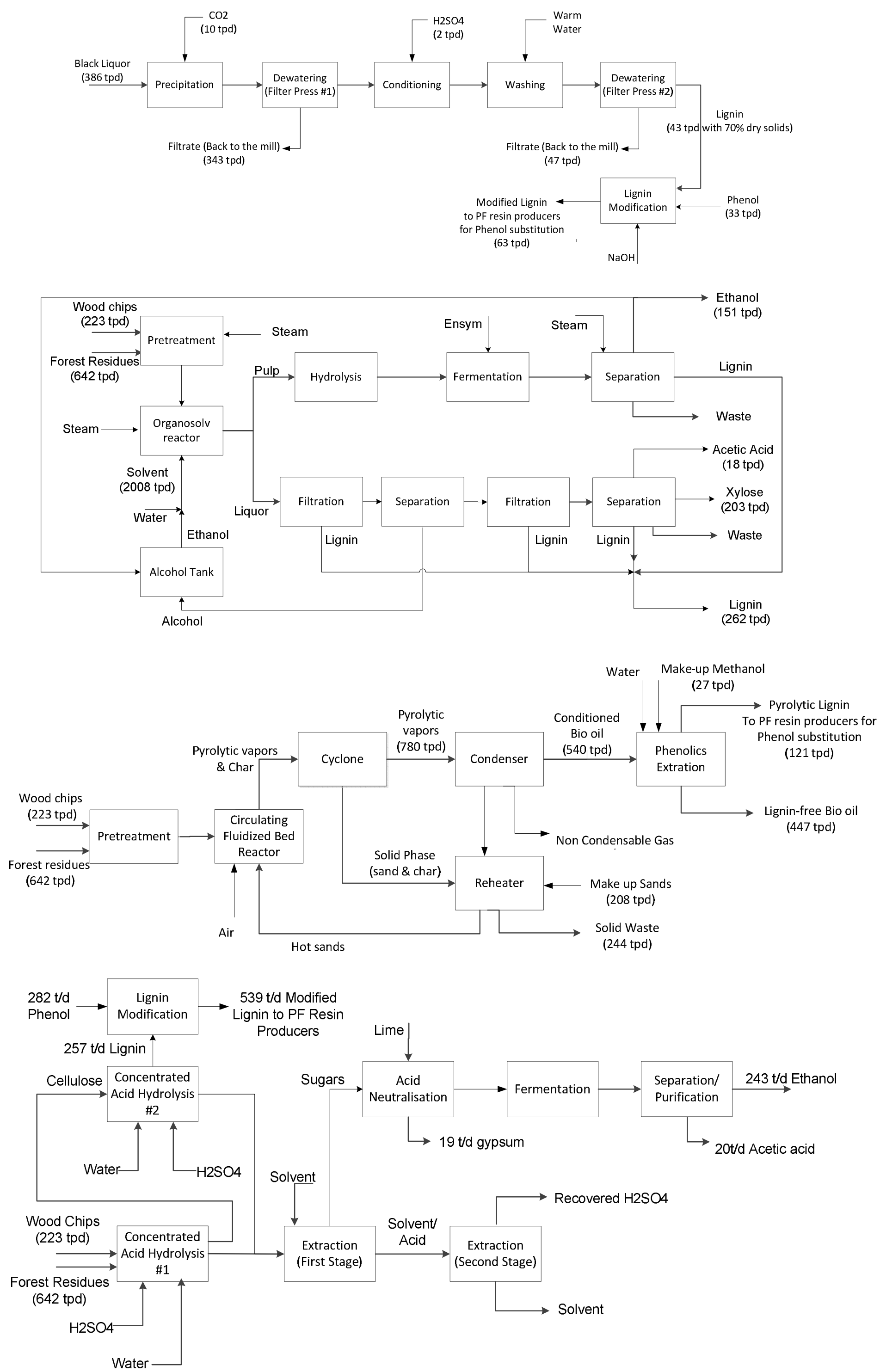


**Figure 2. Simplified process flow diagram for the Phase II of (a) Lignin precipitation, (b) Organosolv Treatment, (c) Fast Pyrolysis, (d) Concentrated acid Hydrolysis**.

Cost synergies and environmental benefits were evaluated using techno-economic analysis and life cycle-assessment (LCA). Using this information as well as other sources (eg for market information) a set of decision criteria including economic, competitiveness and environmental criteria (presented in Table 1) was evaluated. The set of sustainability criteria were then employed in a multi-criteria decision-making (MCDM) panel consisting of six panelists. The results of this MCDM show that lignin precipitation and concentrated acid hydrolysis were not preferred, and should be screened out from the list of possibilities. However two promising alternatives (organosolv process and fast pyrolysis) were not distinguishable in terms of sustainability in the MCDM panel.

**Table 1. Sustainability decision criteria**

| | Criteria Interpretation (result of conducted MCDM I) | | Metric |
|---|---|---|---|
| Economic and Competitiveness Criteria | IRR: Internal Rate of Return | IRR measures overall **project profitability under normal market conditions**. It should be greater than a minimum target value for long-term investments and further increased relative to the riskiness of the option -Higher IRR is preferred as this represents a higher profitability | $NPV = \sum_{t=0}^{22} \frac{CF_t}{(1+IRR)^t} = 0$ |
| | DEP: Downside Economic Performance | DEP measures the financial performance of the biorefinery strategy during poor market conditions. Higher DEP is preferred as a measure of **project robustness**, i.e. that the project can survive even under unfavourable market conditions. | $DEP = \left(\frac{4*\left(\frac{EBIT}{Revenue}\right)_{@Poor\ market} + 8*\left(\frac{EBIT}{Revenue}\right)_{@Normal\ market}}{12}\right) * 100$ |
| | ROCE: Return On Capital Employed | ROCE measures the cash generated relative to the invested capital for a biorefinery strategy and is widely used as a measure by the investment community. It expresses the **efficiency of the investment** measured by how much the biorefinery strategy generates cash flow from investment. Higher ROCE is preferred because it indicates better return on invested capital | $ROCE = \frac{EBIT}{TCI}$ |
| | PIC: Phase I Implementation Capability | PIC is an aggregated measure of **technology risk** that considers technology maturity (pilot demonstration etc), scale-up requirement to commercial scale, and ability to execute the Phase I technology in 24 months. Higher value of PIC is preferred because it represents lower technology risk in Phase I, and represents an **opportunity to be faster to the market** in Phase II. | $PIC = 0.5 * Maturity\ score + 0.25 * scalability\ score + 0.25 * imlementation\ capability\ score$ |
| | CPC: Competitiveness on Production Costs | CPC shows how competitive the biorefinery product portfolio production costs are relative to market prices (and thus pre-existing producers), and is **an indication of the project to penetrate existing markets and achieve market share** in the short term, to guaranty market position in the longer term. A higher value of CPC is preferred as it shows that products can be manufactured below market prices, and thus the investor can better negotiate take-off agreements to penetrate the market and gain market share | $CPC = 100\% - \frac{Production\ Costs}{Revenue_{@Poor\ market\ condition}} * 100$ |
| Environmental Criteria | GHG: Greenhouse Gas Emissions | GHG represents **carbon footprint** of the alternative in terms of CO2 equivalent compared to the established competitive existing product portfolio. It also represents **competitiveness on "greenness"** in terms of potential for meeting GHG Emissions target (eg. 20% reduction compared to competitive fossil-based product portfolio). Lower values represent better environmental performance. | Absolute value: CO2 equivalent<br><br>Relative value compared to a competitive product portfolio: % |
| | NRE: Non-Renewable Energy | This criterion shows **the level of stress on NRE** consumption compared to the competitive product portfolio. It also represents the **level of dependency of the candidate biorefinery alternatives on fossil-based energy** which is a limited energy source. Lower values show more independency on fossil-based resources which can be considered as an advantage especially in long-term vision. | Absolute value: KJ<br><br>Relative value compared to a competitive product portfolio: % |
| | RO: Respiratory Organics | This criterion shows the potential impact of VOCs and other contaminants emissions into air, having an effect on human health, specifically respiratory, compared to the competitive product portfolio. Lower value of this criterion is preferred due to less risk on human health. | Absolute value: kg ethylene<br><br>Relative value compared to a competitive product portfolio: % |

CF: Cash Flow

NPV: Net Present Value

EBIT: Earnings before Interest and Tax

## 3.2. Data uncertainty analysis

Emerging biorefinery technologies are associated with considerable uncertainty and risk. Strategic decisions on these technologies should take into account uncertainty and risk.

### *3.2.1. Economic and competitiveness criteria under uncertainty*

*Uncertain Variables*

Uncertainty in the economic and competitiveness analyses comes mainly from uncertainty in market-based input data used in the techno-economic model including biomass price, product sales price, energy and chemicals prices, as well as uncertainty in estimated investment cost.

Due to data scarcity, three market prediction models for each variable were identified based on pessimistic, optimistic and realistic perspectives considering, for each, minimum possible, most probable (modal) and maximum possible values. This approach was applied to uncertain variables in the techno-economic model including wood chips price, forest residues price (Table 2), fuel price (hog fuel and natural gas), chemicals price, estimated capital investment cost, sales price of lignin-based products (phenol, PAN, carbon black) and sales price of commodity products (ethanol, acetic acid, C5 sugars).

**Table 2. Forest Residues Price Scenarios**

| Forest Residues Price | Value | | Justifications |
|---|---|---|---|
| Base Case | 83.3 $/bdt | | Provided by the mill |
| Pessimistic Perspective | Min | 0% | **Market model**:<br>o In the future, new technologies will be used to convert low quality biomass (residues) to bio-products. The demand and price for forest residues might increase.<br>o Biomass price might increase dramatically due to the development of biorefinery projects leading to increased competition for biomass.<br>o Increase in fossil fuel price might lead to an increase in harvesting costs and consequently to an increase in biomass price<br>o Legislation (food-to-fuel) leads to an increase use of lignocellulosic biomass = increased competition = higher price<br>o Increased social acceptance (increased interest in using waste material and increase in demand of green products) leads to premium in prices.<br>o More governmental support for biorefinery implementation leads to an increase in biomass prices<br>o If nuclear and alternative power demand for bioenergy diminishes, the demand and price of biomass increase. |
| | Modal | +40% | |
| | Max | +80% | |
| Realistic Perspective | Min | -20% | **Market Model**:<br>o Biomass price will have the same volatility as over the last 5 years |
| | Modal | 0% | |
| | Max | +20% | |
| Optimistic Perspective | Min | -45% | **Market Model:**<br>o Alternative biomass (for example, municipal solid waste MSW) will be increasingly consumed in the future leading to a decrease in forest residues price.<br>o Novel harvesting technologies in the future leads to a decrease in the cost of biomass delivered costs.<br>o Governmental support for using waste materials leads to a decrease in biomass price. |
| | Modal | -15% | |
| | Max | +20% | |

***Sensitivity analysis***

Using minimum and maximum values for each variable, a sensitivity analysis was performed for each biorefinery option in order to investigate the impact on IRR. As an example, Figure 3 shows the results of the sensitivity analysis for the organosolv treatment option (Alt.2). Among all uncertain variables, five of them including lignin price, forest residues price, ethanol price and hog fuel price are the most important variables which impact the IRR value by more than 2%.

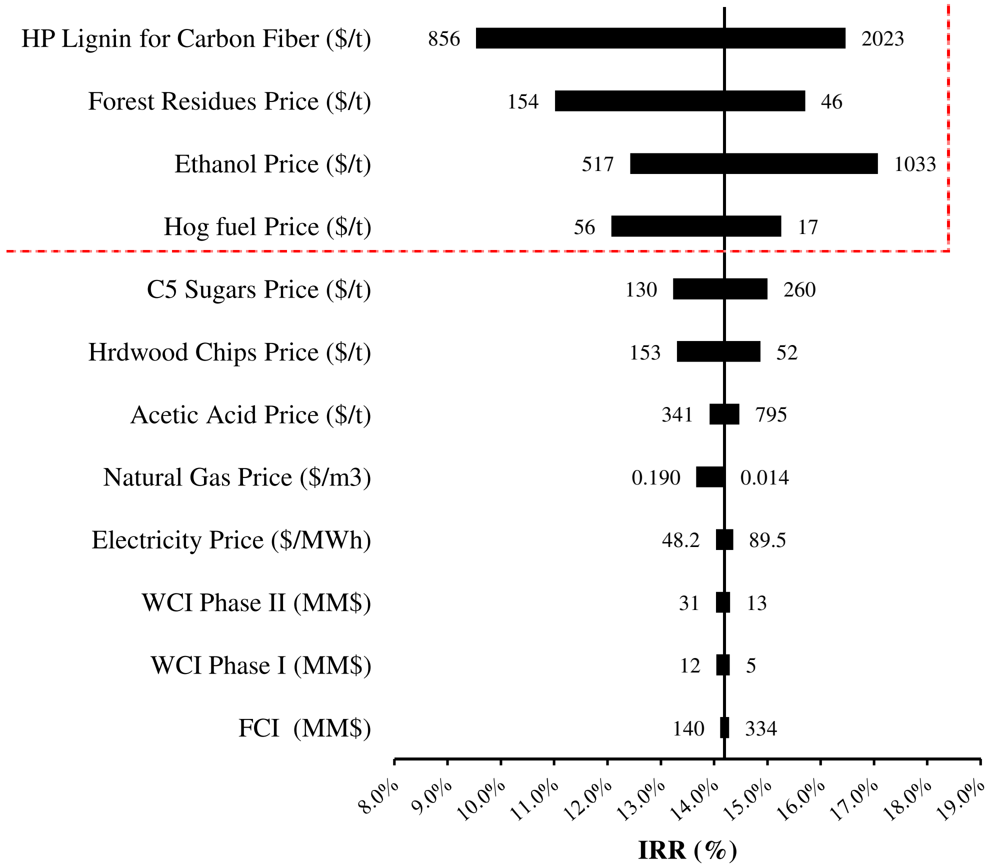


**Figure 3 Sensitivity analysis of organosolv treatment (Alt.2)**

The same type of analysis has been done for the other alternatives also. The results show that for lignin precipitation (Alt.1), four variables including hog fuel price (17 to 56 $/t), phenol price (729 to 1778 $/t), natural gas price (0.014 to 0.19 $/m3) and carbon black price (520 to 1229 $/t) are the most important uncertain variables. The important uncertain variables in fast pyrolysis (Alt.3) option include bio oil price (231to 462 $/t), fixed capital investment cost (109 to 233 MM$), forest residues (46 to 154 $/t), phenol price (729 to 1778 $/t) and natural gas price (0.014 to 0.19 $/m3). The important uncertain variables in the case of concentrated acid hydrolysis (Alt.4) are ethanol price (517 to 1034 $/t), forest residues price (46 to 154 $/t) and phenol price (729 to 1778 $/t).

***Monte Carlo Analysis***

The impact of the uncertainty in the most important variables on the decision criteria was assessed using Monte Carlo analysis. Probability distribution functions for each uncertain variable were developed using triangular distribution functions. For each variable, three triangular distribution functions were developed based on pessimistic, realistic and optimistic perspectives (Figure 4) according to the following equation:

$$P(x) = \begin{cases} \dfrac{2(x-a)}{(b-a)(c-a)} & a \leq x \leq c \\ \dfrac{2(b-x)}{(b-a)(b-c)} & c \leq x \leq b \\ 0 & otherwise \end{cases} \quad (5)$$

Where $a$ is the minimum possible value, $c$ is the most likely (modal) value and $b$ is the maximum possible value.

***Aggregation of probability distribution functions***

After considering the common aggregation methods, linear opinion pool was used in this study, which employs a weighting factor for each distribution. In order to prevent over-emphasizing the extremes (pessimistic and optimistic values), a higher weight was considered for the realistic perspective (60% importance) compared to 20% for each of the optimistic and pessimistic perspective.

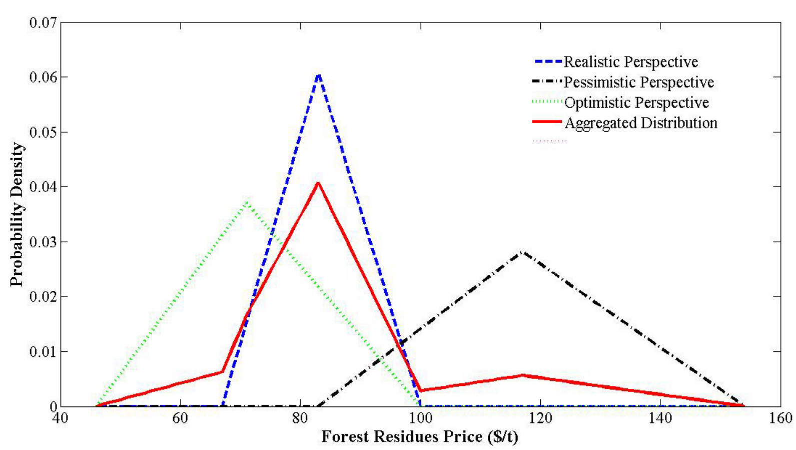


**Figure 4 Probability distribution function of forest residues price as an uncertain variable**

***Sample generation (rejection sampling method)***

For each iteration in the Monte Carlo simulation, a random value is generated from each uncertain variable. It was found that the aggregated probability distribution function of the uncertain variables in this study had an unconventional form. Different techniques for sample generation from unconventional distribution functions were considered, among which the Rejection Sampling (so called Acceptance-Rejection) method was chosen. This method generates samples from the unconventional and complex distribution (p(x)) using a target distribution function (q(x)), where $p(x)<M*q(x)$ and $M>1$. The target distribution is normally a uniform distribution function at maximum density of the distribution. The procedure that is followed in this method is that at first a random value (x) is taken and the ratio of its density based on the studied distribution (p(x)) and the target distribution (q(x)) is obtained. Then a random value (u) between zero and one is taken, if the calculated ratio would be higher than the random u value, the generated random x is accepted otherwise it would be rejected.

This sampling method was applied for the important uncertain variables of each biorefinery alternative. Figure 5 shows an example of the generated samples for organosolv treatment (Alt.2).

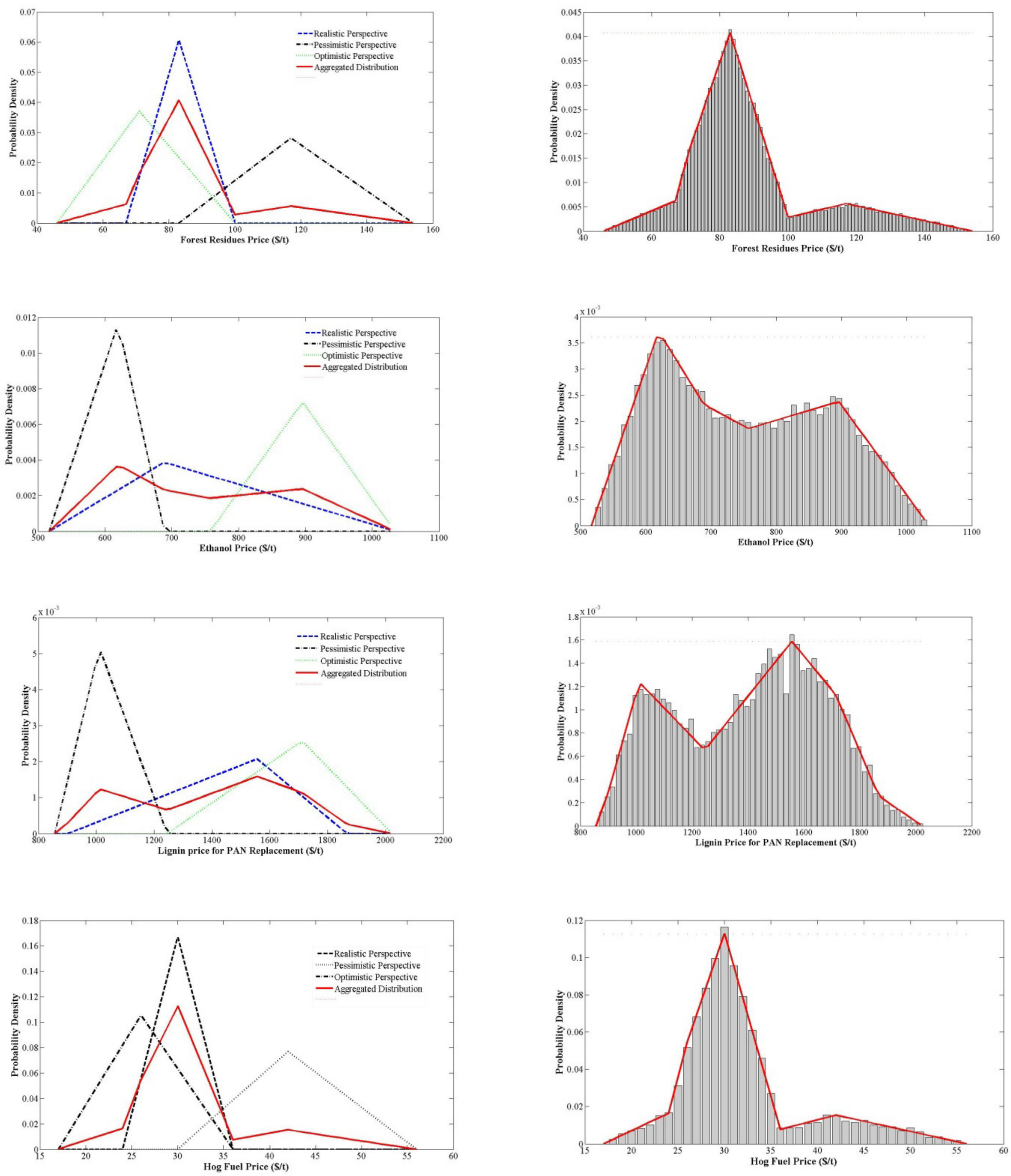


**Figure 5 Distribution functions of important uncertain variables (left side) and the generated samples from aggregated distribution function (right side), both for organosolv treatment option (Alt.2)**

***Probability distribution functions of decision criteria***

Depending on the level of required accuracy, the number of iterations in the Monte Carlo analysis is normally from 1000 to 10000 iterations. In order to decrease computational time, 1000 iterations were applied. In the Monte Carlo method, using the random values generated from uncertain variables, economic and competitiveness criteria are evaluated and presented as probability distribution function. The results show that the economic and competitiveness criteria were not always normally distributed. Thus, the Weibull distribution was defined as the most appropriate distribution type considering the following formula:

$$f(x;\lambda,k)=\begin{cases}\frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1}e^{-\left(\frac{x}{\lambda}\right)^{k}} & x\geq 0\\ 0 & x<0\end{cases} \tag{6}$$

As an example, the probability distribution function of IRR as an economic criteria developed for organosolv treatment is shown in Figure 6.

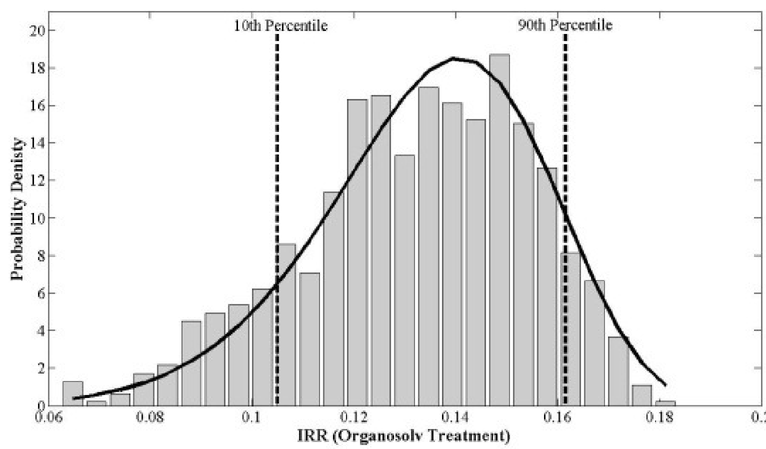


**Figure 6 Distribution function of Internal Rate of Return (IRR) as an economic criteria for organosolv treatment (Alt.2)**

**3.2.2. Environmental criteria under uncertainty**

The data uncertainty in the economic analysis was mainly due to uncertainty in market data, while the source of uncertainty in the environmental assessment was mainly due to mass and energy balance data. Batsy et al. (Batsy etal. 2013) have evaluated a set of environmental criteria under uncertainty for the same biorefinery alternatives. Monte Carlo analysis, integrated into the SimaPro software, was used for developing probability distribution functions of the environmental criteria. Minimum and maximum values were determined for each mass and energy input data according to their level of uncertainty. For instance, low uncertainty was considered for mill data, whereas high or medium uncertainty was considered for data from the literature or technology provider. Using a triangular distribution function, log-normal distribution functions of the environmental criteria were developed separately by employing Monte Carlo analysis (Figure 7).

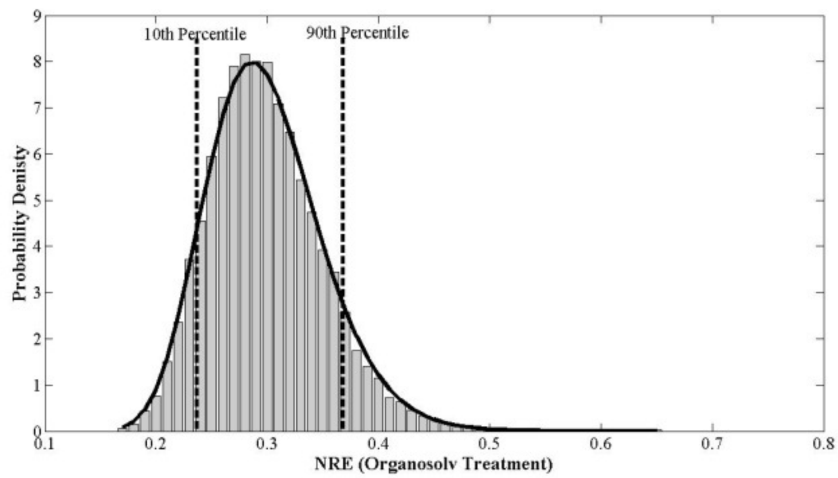


**Figure 7 Distribution function of Non-Renewable Energy as one of environmental criteria for organosolv treatment (Alt.2) (Batsy et al., 2013)**

### 3.3. Decision-making under uncertainty

After developing probability distribution functions for all decision criteria, a MCDM panel was conducted, in order to assess the impact of uncertainty in criteria on the relative importance of the criteria in the decision-making process.

The distribution functions of eight sustainability decision criteria are presented in Figure 8. As can be seen, for each criterion, the values of all four biorefinery alternatives are shown. In this figure the width of the distribution function represent the level of uncertainty (more narrow distribution shows higher certainty) and peak represents the most probable value of the criterion. This figure clearly shows that decision making is not straight forward due to the conflicts between the criteria and because of the overlaps between the alternatives.

In order to simplify knowledge transfer during the MCDM panel, three values from each distribution function was extracted including the most probable (modal) criterion value, maximum value at 90% percentile and the minimum value at 10% percentile (Figure 9). The modal value is shown by a bar and the 90% and 10% percentile are shown as the error bar on the chart. In addition, in Figure 9 dashed lines represent the determined lower and the upper bound by panel members. They are preference boundaries of decision makers, in a way that they don't have any preference among the alternatives for the values below the lower bound and above the upper bound.

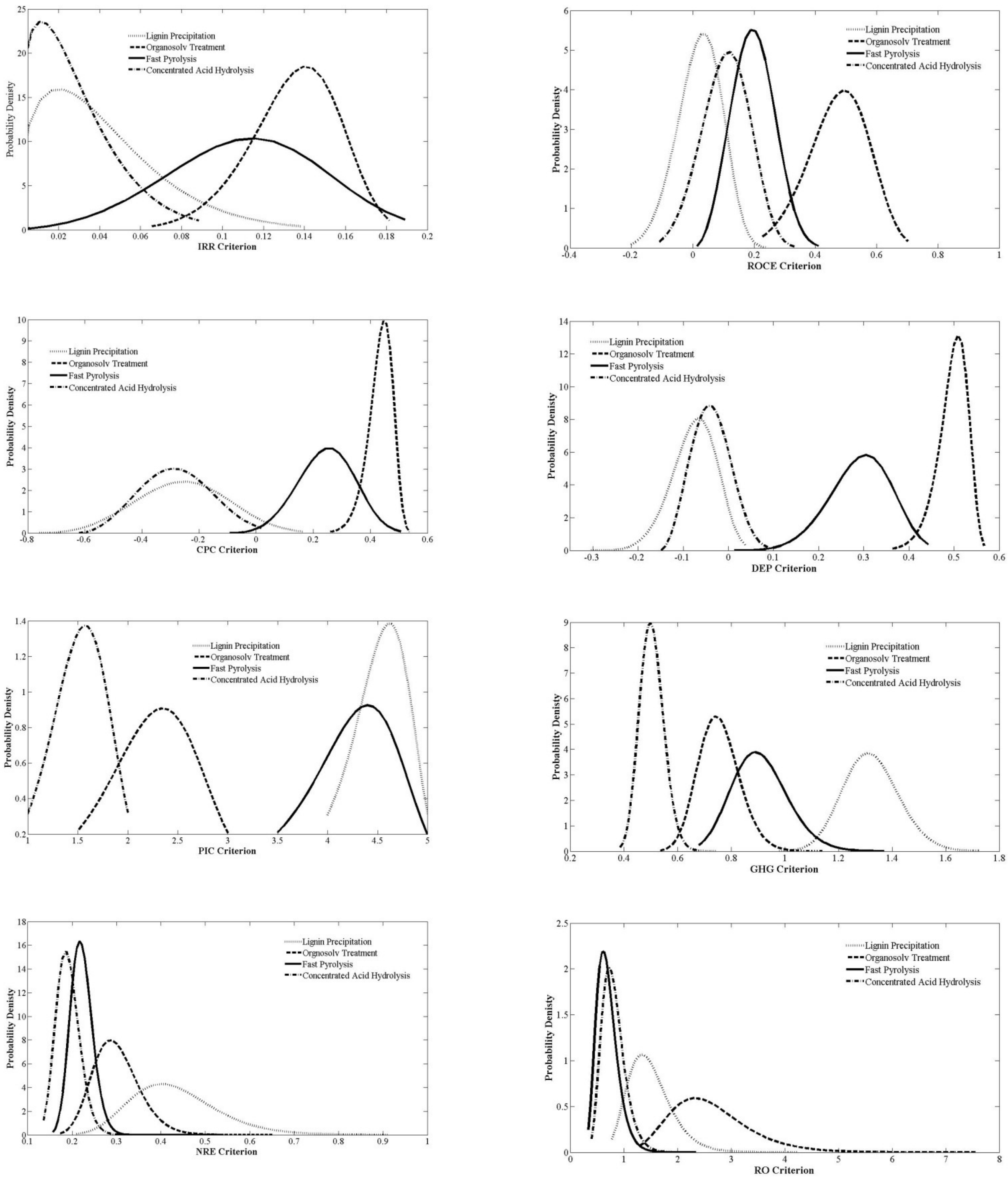


**Figure 8 Distribution functions of the sustainability decision criteria for all four biorefinery alternatives**

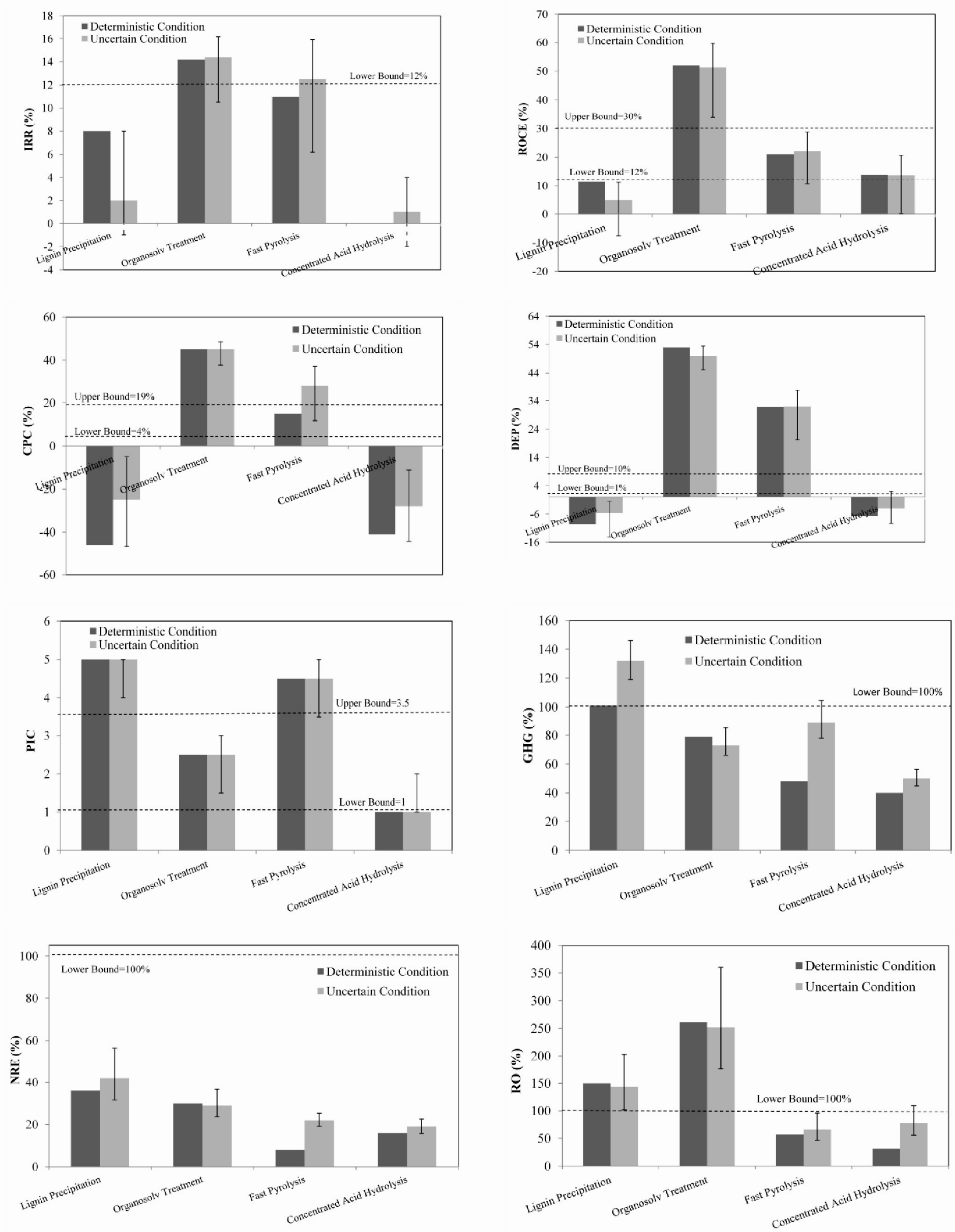


**Figure 9. Criteria values under uncertainty presented to the panel**

*3.3.1. Decision-making*

The results showed that certain weighting factors were significantly affected after considering uncertainty in the decision criteria. Figure 10 shows that for deterministic criteria, panelists had chosen IRR as the most important criterion, however under uncertainty was considered, the same panelists changed their choice to ROCE. The main reason is that the error bars for IRR values had a considerable overlap for some alternatives (Alt.2 with Alt.3 and Alt.1 with Alt.4) and therefore they became relatively indistinguishable. However ROCE helped decision-makers to better differentiate between biorefinery alternatives because of the low overlap of the error bars between the alternatives. To a lesser degree, the relative importance changed also for some other criteria, including PIC, CPC and GHG.

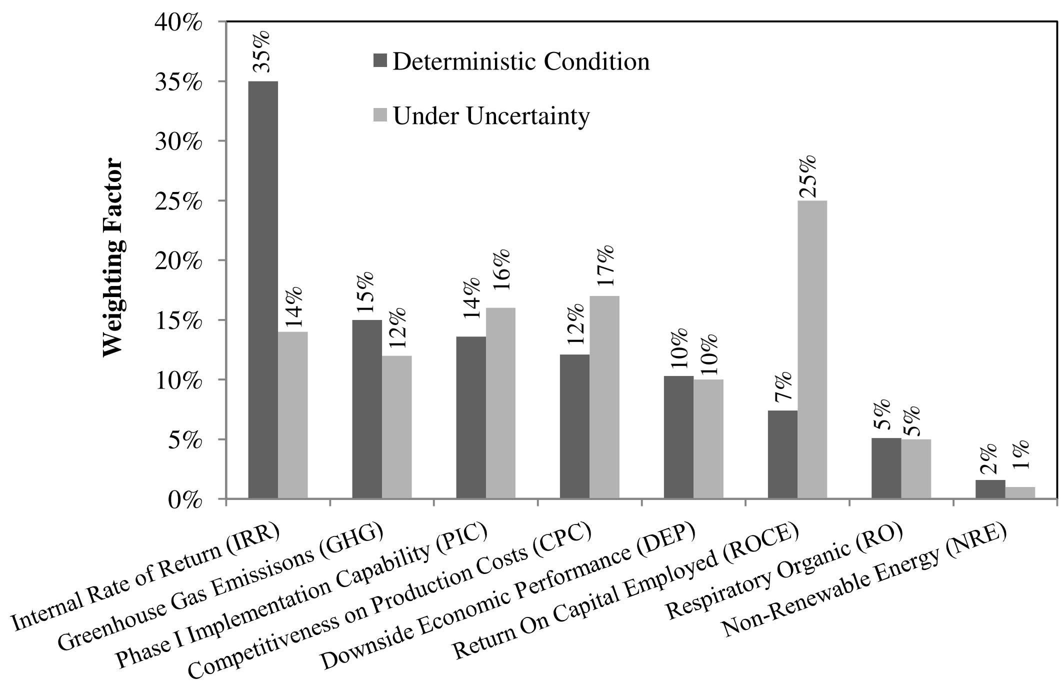


**Figure 10. The effect of considering uncertainty on the weighting factors of the sustainability criteria**

Among the decision criteria, the relative importance of NRE, RO and DEP was not changed. In the case of NRE, even when considering the error bars, the alternative values were much below the lower bound (100%), meaning that they all had very good performance and so panel members could not distinguish between alternatives. For RO, the high level of uncertainty as shown by the error bar supported the decision of the panel members to keep a low weighting factor. For DEP, all alternatives could be well distinguished under deterministic conditions. As this didn't change under uncertainty, the relative importance of DEP was kept unchanged.

The standard deviation of the scores given for each criterion by the panelists is a measure of the level of consensus among the panel members. For instance, the low standard deviation associated with NRE criterion implies a high degree of consensus in the selection of this criterion as the least important criterion.

*3.3.2. Ranking the alternatives*

The probability distribution functions of the sustainability scores for the 4 biorefinery processes have been summarized in Figure 11(a). Lignosolv processing and fast pyrolysis have higher scores (between 0.5 to 0.75 considering 10% and 90% percentiles) and (2) lignin precipitation and concentrated acid hydrolysis have lower scores (between 0.15 to 0.3). In order to investigate how much the ranking of alternatives has been affected by incorporating uncertainty in the decision-making, three values were extracted from each probability distribution function (1) the modal value and (2) minimum (10% percentile) and (3) maximum (90% percentile) possible values (Figure 11(b)). Consistent with the results in deterministic conditions, new rankings confirm that lignin precipitation and concentrated acid hydrolysis are not promising biorefinery transformational strategies in the context of the case study mill. For deterministic conditions, alternatives organosolv treatment and fast pyrolsyis were not distinguishable in terms of their score. When considering uncertainty, the organosolv treatment option clearly was more preferred over fast pyrolysis, ie the maximum possible score of fast pyrolysis option is almost the same as minimum score of the organosolv treatment alternative.

Figure 12 shows the contribution of each decision criterion in the sustainability score of the alternatives, comparing the results for the panels considering and not considering uncertainty. The main reason for the differences in sustainability scores can be attributed to the change in the weighting factor of the most important criterion. On the one hand, a dramatic decrease in the IRR weighting factor resulted in a decrease in the score of almost all alternatives. On the another hand, an increase in ROCE weight resulted in an increase of the contribution of this criterion in the sustainability score, almost in all alternatives except lignin precipitation.

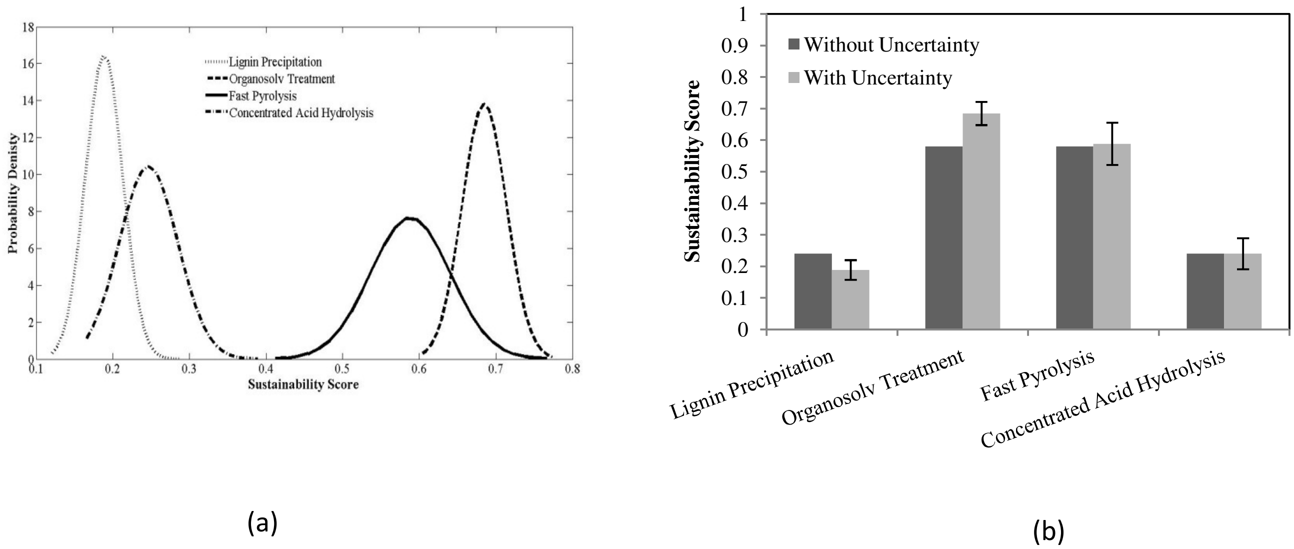


**Figure 11 Sustainability score of the biorefinery alternatives under uncertainty**

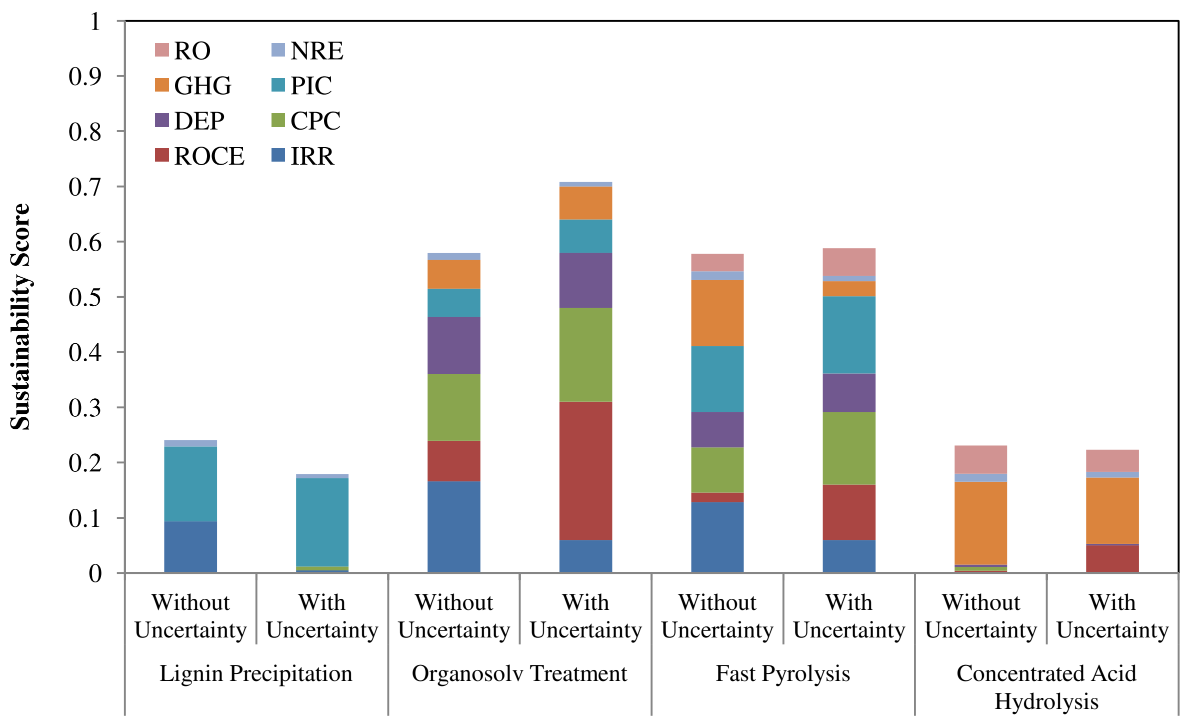


**Figure 12 The effect of considering uncertainty on the sustainability scores**

## 4 CONCLUSION

This study presents a methodology for sustainability assessment of biorefinery strategies at the strategic design level, employing MCDM under uncertainty. This method was demonstrated for the context of a kraft pulp mill by assessing four biorefinery technologies to identify the sustainable strategy for being integrated into the studied pulp mill. This developed method combined Monte Carlo for uncertainty analysis with multi criteria decision making (MCDM) for aggregating conflicting sustainability criteria. Addressing uncertainty in criteria evaluation did considerably affect relative importance that panel members attributed to the criteria, in a way that the most important criterion was switched from IRR to ROCE while the importance of the former was decreased about 21% and the latter increased about 18%. Involving uncertainty changed the basis of decision making.

In this particular study, addressing uncertainty in decision-making helped decision-makers to screen out more options at the early-stage design level, because of better differentiation between the promising alternatives as a result of involving uncertainty in analysis, using an objective and transparent decision-making method.

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# APPENDIX F – Article 6:

## Strategic Decision-Making under Uncertainty to Identify Sustainable Biorefinery Strategies, Part II: Risk Attitude

# Strategic Decision-Making under Uncertainty to Identify Sustainable Biorefinery Strategies, Part II: Risk Attitude

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## ABSTRACT

A practical methodology for decision-making between sustainable biorefinery processes during early-stage design is critical for forest product companies examining transformation strategies. Uncertainty and attitude towards risk should both be considered in a systematic decision-making process to increase the quality of the decision.

In Part I of this paper, a methodology was presented where uncertainty was considered in strategic decision making. In this part of the paper, we address a methodology to incorporate attitude towards risk for the same decision. The methodology uses a lottery-based risk analysis in order to quantify the risk attitude of decision-makers, and formulating utility functions for a set of "smart" sustainability criteria. The results show that quantifying the risk attitude of decision-makers helped clarify the choice of preferred process alternatives for strategic biorefinery transformation.

**Keywords:** risk attitude, decision under uncertainty, Monte Carlo analysis, sustainability assessment, biorefinery strategies, Multi-criteria Decision Making (MCDM)

## 1 INTRODUCTION

Increasingly, North American forest product companies are seeking to transform their business through the integration of biorefinery technologies into their existing pulp and paper mills, for the manufacture of an expanded product portfolio. The set of preferred biorefinery strategies is expected to be unique for different forest product companies, depending on their pre-existing characteristics across the value chain including for example biomass availability and logistics, existing process configurations and capacities, product portfolio and logistics. How companies determine preferred biorefinery strategies is an important challenge, and a systematic approach for transformation decision-making is needed. Only certain biorefinery strategies will be sustainable for the long-term, and different strategies imply different levels of technology and market risk.

At the early stage of design, there is significant uncertainty in the information available to decision-makers regarding technology as well as market risk. Multi-criteria decision-making (MCDM) is a powerful tool that can be employed for strategic decision-making, with the following advantages:

- It permits effective know-how transfer to a panel of decision-makers
- It is an interactive approach that reflects the preferences of decision-makers
- It builds consensus between decision-makers
- It requires that decision-makers interpret decision criteria explicitly
- It structures the decision problem for decision-makers to permit the resolution of conflicting criteria

In Part I of this paper (Sanaei and Stuart 201X), a methodology was presented where uncertainty was considered in MCDM for identifying preferred biorefinery processes. It was shown that addressing uncertainty can change the relative importance of decision criteria, considering additional information that uncertainty analysis can provide to panel members. Thus the basis of decision-making changed when uncertainty was recognized and quantified.

As well, company decision-makers should recognize explicitly the impact that their attitude towards risk plays, ie whether they are risk-averse or risk-prone as a decision-making group. The second part of this paper presents a methodology to address risk attitude, and the impact that this has on biorefinery decision-making for the case study.

Decision-makers face risk due to the potential outcome of uncertain events (Van Bossuyt, Hoyle et al. 2012), which is an inseparable component of any business. For example, how fast demand for carbon fiber will grow in the coming years is a key issue that forestry companies must consider when considering lignin-based derivatives as part of their biorefinery strategy. Based on uncertain information, decision-makers must address these questions and depending on their risk attitude, their preference for a carbon fiber strategy can be quite different. In the context of the forest products industry transformation, decision-makers must accept risk and take it into account in decision-making. If they do not accept risk, they will not invest in the biorefinery.

Each individual decision-maker has their own attitude toward risk (Schuwirth, Reichert et al. 2012). However generally speaking, the decision regarding biorefinery strategy is not made by a single individual, but by a group of stakeholders having different perspectives and expertise. Together, depending on group dynamics and other factors, the group of stakeholders will have a profile that can be risk averse or risk prone. In order to make the best decisions possible, the risk attitude of decision-makers should be taken into account for strategic design decision-making.

Normally, managing risk within an organization would be done qualitatively through an informal procedure. A quantitative approach by which stakeholders can make informed decisions accounting for risk attitude is rare (Van Bossuyt, Hoyle et al. 2012). There are several methods (Van Bossuyt, Hoyle et al. 2012) by which risk can be measured. These methods include Fault Tree Analysis (FTA) (Ericson 1999), Failure Modes and Effects Analysis (FMEA) (Franklin et al., 2012), Risk in Early Design (RED) (Lough, Stone et al. 2009), Functional Failure Identification Propagation (FFIP) (Kurtoglu and Tumer 2008), and Function Failure Design Method (FFDM) (Stone, Tumer et al. 2005). However many of these methods are not practical (Van Bossuyt, Hoyle et al. 2012). For example in FTA and FMEA (that have been used in the industrial context), risk is addressed as an expected value. If decision-makers must choose between (a) a risky option with a 1% chance of accruing a 100 $ loss, and (b) another risky option with a 0.1% chance of accruing 1000 $ loss, these would be considered identical according to the expected value. However this approach ignores the risk attitude of decision-makers in an organization, and does not take into account the willingness to take risk that changes from one context into another (Van Bossuyt, Hoyle et al. 2012). There are three types of attitude toward risk including (a) risk averse, (b) risk neutral, and (c) risk prone (Van Bossuyt, Hoyle et al. 2012). Individuals can have different attitude toward risks in different domains. For example, a person can be risk-averse for financial decisions, but risk-prone in social situations.
Generally, one could imagine that innovative technology providers and entrepreneurs tend to be risk-takers, whereas the leadership of public companies who tend to be risk-averse (Van Bossuyt,

Hoyle et al. 2012). Quintero-Bermudez et al. (Quintero-Bermudez, Janssen et al. 2012) compared 3 different MCDM panels for the same decision-making objective, using the same data on biorefinery investment choices. Surprisingly, their results showed that there was high level of consensus in the results between academic and industrial panels. Assuming that academics and industry would be different in terms of their risk attitude, it might be concluded that this difference had not been captured in their study because of not quantifying the risk attitude of decision-makers in the decision-making procedure.

There are four major steps in conventional risk assessment including risk identification, risk analysis, risk evaluation and risk treatment (Australia and Newsland 2009), that there are some studies focusing on each of these steps. The importance of considering uncertainty and risk attitude in decision-making has been discussed by (Hazelrigg 1998). When these two concepts are involved in decision-making, among the MCDM methods, multi-attribute utility theory (MAUT) is preferred to pair-wise comparison decision-making. In this method utility is a measure of satisfaction of a result and represents decision makers preference (Keeney and Raiffa 1976), that is often expressed as a quadratic, logarithmic or exponential function in which the shape of the function denotes the risk attitude of decision-makers (Van Bossuyt, Hoyle et al. 2012). In the literature, the inclusion of multi-attribute problems under uncertainty and risk for a complex decision-making problems is rare, among which Thevenot et al. (Thevenot, Steva et al. 2006) have shown how these two concepts (uncertainty and risk attitude) can be integrated into design decision-making. Currently most methods for developing risk-based utility function require making lotteries with decision-makers. In a lottery-making activity, decision-makers are offered a choice between receiving a certain outcome (an offer), and a lottery in which there is 50% chance of receiving more than the certain offer and a 50% chance of receiving less than the initial offer. If the decision-maker is risk averse, they prefer to choose the certain offer. In this way, lottery-making can be used to determine decision-maker risk attitudes (Becker and Sarin 1987).

The objective of this study is to develop a systematic and practical approach that addresses uncertainty and risk attitude of decision-makers in strategic design decision-making, for the case of biorefinery strategy selection. This has been done employing a set of sustainability criteria in

MCDM approach with quantified uncertainty by Monte Carlo analysis and measuring risk attitude of decision makers through a panel-based lottery activity using risk aversion theory. This publication has been presented in two parts, Part I mainly focuses on uncertainty analysis and Part II (the current article) focuses on the quantification and impact of decision-makers risk attitude.

## 2 METHODOLOGY

The overall methodology shown in Figure 1 was employed for sustainability assessment of the biorefinery alternatives, taking into account both concepts of uncertainty and risk attitude.

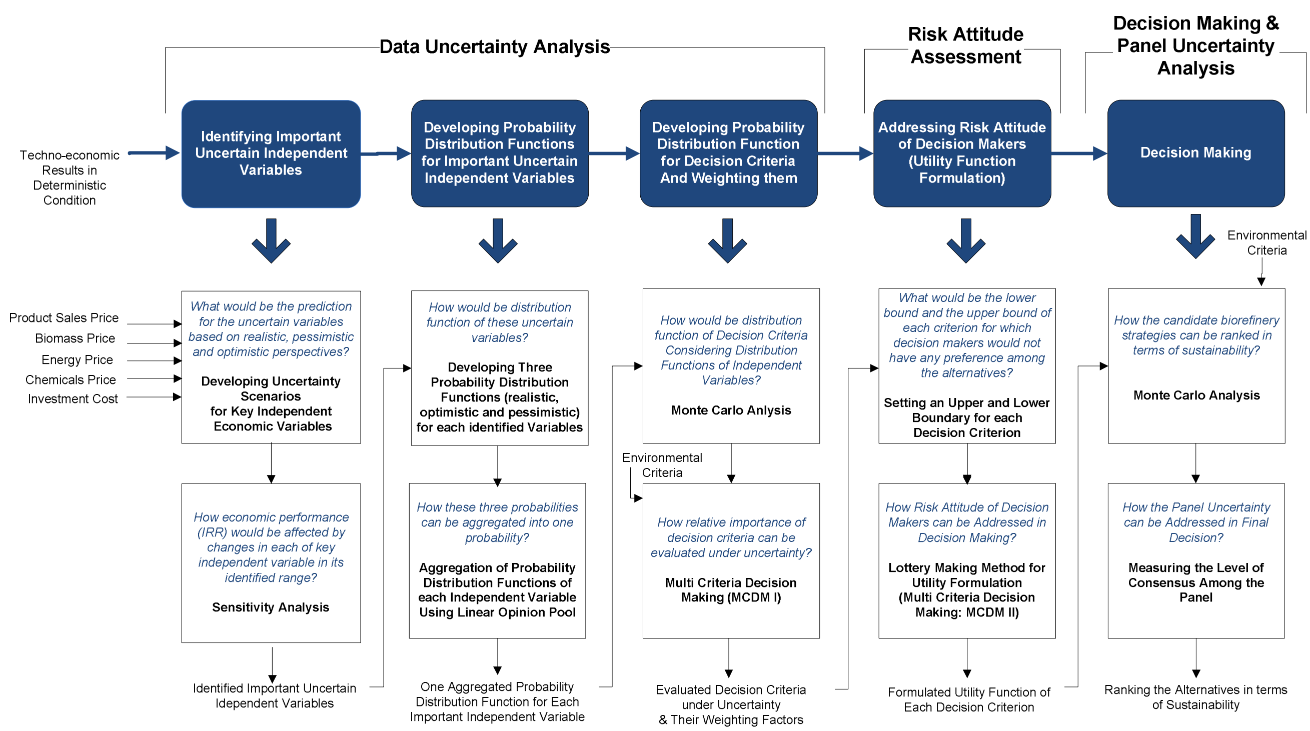



**Figure 1. Overall methodology for addressing uncertainty and risk in decision making for Sustainability assessment of biorefinery strategies**

In any multi-criteria decision-making (MCDM), there are two determining parameters used to rank the design alternatives in terms of their sustainability performance. The first parameter is the “weighting factor” representing the relative importance of decision criteria, and the second parameter is the "utility value" representing the preference of decision-makers for each criterion. It was shown in Part I of this publication (Sanaei and Stuart 201X) how involving uncertainty in decision-making can affect the weighting factor of decision criteria. In order to address data uncertainty, a Monte Carlo analysis was employed to evaluate decision criteria under uncertainty, and these results were used in an MCDM panel ("MCDM I" in Figure 1) to calculate weighting factors of the criteria.

In this study it will be shown how involving risk attitude of decision makers can change the "utility function" in decision-making. Utility is a function that converts the criterion value into a dimensionless number between zero to one representing decision-maker preference. For instance, since a higher value for internal rate of return (IRR) is preferred by decision-makers, the utility value of the best (highest) IRR value is set to one and the utility value of the worst IRR value is set to zero. In addition utility value of any IRR value between these two limits is determined by the "utility function" between the two boundaries that the shape of this function denotes the risk attitude of decision-makers.  The methodology used in this study shows how risk attitude of decision-makers can be taken into account in decision-making.

By considering both the new weighting factors (result of "MCDM I") and the new utility functions (result of "MCDM II"), the impact on decision-making is examined in this study.

### 2.1.Risk attitude assessment (utility function formulation)

The main objective of this part of the methodology is formulating the utility function for each criterion considering the risk attitude of decision-makers. This has been done in two steps including (1) preference boundary setting, and (2) lottery-making to measure the attitude of decision-makers towards risk. Boundary setting and lottery-making was completed in MCDM II with the same panel members as in MCDM I. In this panel activity, each decision-maker determines a lower and an upper bound for each criterion. The lower bound shows a value below which decision-maker does not have any preference among the alternatives. Similarly the upper bound represents a value above which decision-maker does not have any preference among the alternatives. For instance, taking internal rate of return (IRR) as an example, if a decision-maker determines 12% as the lower bound it means that any value below 12% for IRR is not preferred less. Moreover if a decision-maker sets 30% as the upper bound, then any IRR value above 30% is adequate.

In order to quantify risk attitude, the panel compares a lottery option with a certain condition to measure their willingness to take risk. For example, imagine that a decision-maker is asked to compare Option A: accepting a gamble in which he will have 50% chance to win 100$ and 50% to get 0$, and Option B: accepting a specific amount with 100% certainty. The average payoff of the gamble is known as the "expected value" of 50$. If the decision-maker accepts less than expected value in option A, then he/she is risk averse. If the decision-maker accepts only more than expected value in option A, then he/she is risk prone.

The number that decision-makers give to these lotteries is called certainty equivalent (CE), which is the value for which there is no difference for decision-maker to achieve the CE and a lottery between the best and worst criterion value. The risk tolerance (RT) value represents the attitude of decision-makers towards risk (level of risk aversion) in the form of curvature of the utility function, which is calculated using the CE value. Among different types of utility functions the exponential function is the most common one, presented in equation 1:

$$U_i(x_i) = A - Bexp\,(-\frac{x_i}{RT_i}) \tag{1}$$

Where A, B and RT are obtained through equations 2 to 4:

$$A = \frac{\exp\left(-\frac{Min(x_i)}{RT_i}\right)}{\left[\exp\left(-\frac{Min\,(x_i)}{RT_i}\right) - exp\left(-\frac{Max(x_i)}{RT_i}\right)\right]} \tag{2}$$

$$B = \frac{1}{\left[exp\left(-\frac{Min(x_i)}{RT_i}\right) - exp\left(-\frac{Max(x_i)}{RT_i}\right)\right]} \tag{3}$$

$$RT_i = \frac{-CE_i}{Ln\left(\frac{A - 0.5U_i\left(Max(x_i)\right) - 0.5U_i\left(Min\,(x_i)\right)}{B}\right)} \tag{4}$$

Where $x_i$ is the criterion value, $Max(x_i)$ is the upper bound value at which utility value is equal to one, $Min\ (x_i)$ is the lower bound value at which utility value is equal to zero, and $CE_i$ is the average of certainty equivalent values given by the panel members.

### 2.2. Decision-making

Among the available Multi-Criteria Decision-making (MCDM) methods, Multi-Attribute Utility Theory (MAUT) (Keeney and Raiffa 1976) was chosen for this study, and explained in Part I of this publication. In the MAUT method, there are two key parameters using which the design alternatives can be ranked in terms of their performance. They include (1) a utility function ($u_i\ (x_i)$) and (2) relative importance of each decision criteria ($w_i$).

Using these two parameters, the overall utility value ($U(x)$) of each design alternative, that in this study represents the overall sustainability performance of that alternative, is calculated according to the following equation:

$$U(x) = \sum_{i=1}^{N} w_i u_i\ (x_i) \tag{5}$$

Where U(x) is the overall utility value or sustainability score, N is the number of criteria, $w_i$is weighting factor of criterion i such that $0 \leq w_i \leq 1$ and $\sum_{i=1}^{N} w_i = 1$, $u_i(x_i)$ is utility value of criterion i.

## 3 RESULTS

### 3.1. Sustainability assessment in deterministic condition

The same biorefinery technologies that were assessed previously by Sanaei and Stuart (Sanaei and Stuart 201X) in terms of sustainability performance are analyzed this time considering uncertainty and risk attitude in order to identify the promising technologies for being integrated into an existing pulp mill. The biorefinery technologies include lignin precipitation, organosolv treatment, fast pyrolysis and concentrated acid hydrolysis. A phased approach has been assumed for implementation of the biorefinery alternatives to minimize technology and market risks. A simplified process flow diagram of each alternative was presented in Part I of this publication (Sanaei and Stuart 201X).

Cost synergies and environmental benefits associated with biorefinery integration into an existing pulp mill were evaluated, and then addressed using techno-economic analysis and life cycle assessment (LCA). Using the results of these analyses, a set of economic, competitiveness and environmental criteria were evaluated. These criteria were conflicting between biorefinery process options, and so evaluated in a multi-criteria decision-making (MCDM) panel consisting of six panelists having different backgrounds and expertise. The results of the MCDM for "deterministic conditions" (uncertainty not considered) showed that lignin precipitation and concentrated acid hydrolysis were not preferred, and should be screened out from the list of possibilities. Two promising alternatives remained (organosolv treatment and fast pyrolysis), however were not distinguishable for the deterministic assumption.

Emerging technologies such as the biorefinery are associated with a considerable level of uncertainty and risk. Thus making strategic decisions about these technologies should not be made without taking into account uncertainty and risk attitude.

## 3.2.Risk attitude assessment

### *3.2.1. Setting an upper and a lower bound for decision criteria*

In order to develop utility functions for the economic and competitiveness criteria (introduced in Table 1) considering risk attitude of decision makers, panelists were asked first to set a lower and an upper bound for each criterion. The average value of the numbers that panelists gave to each boundary for each criterion has been summarized in Table 2. A lot of consideration took into account by panelists as a result of discussions among them, in order to set these boundaries for each criterion. The thinking behind setting these boundaries for some of the decision criteria have been concertized in the following paragraphs.

# Table 1. Economic and competitiveness criteria

| Criteria Interpretation (result of conducted MCDM I) | | Metric |
|---|---|---|
| IRR:<br>Internal Rate of Return | IRR measures overall **project profitability under normal market conditions**. It should preferably be greater than a minimum target value for long-term investments and further increased relative to the riskiness of the option -Higher IRR is preferred as this represents a higher profitability. | $\mathrm{NPV} = \sum_{t=0}^{22} \frac{\mathrm{CF_t}}{(1+\mathrm{IRR})^t} = 0$ |
| DEP:<br>Downside Economic Performance | DEP measures the financial performance of the biorefinery strategy during poor market conditions. Higher DEP is preferred as a measure of **project robustness**, ie that the project can survive even under unfavourable market conditions. | $DEP = \left(\frac{4*\left(\frac{EBIT}{Revenue}\right)_{@Poor\ market} + 8*\left(\frac{EBIT}{Revenue}\right)_{@Normal\ market}}{12}\right)*100$ |
| ROCE:<br>Return On Capital Employed | ROCE measures the cash generated relative to the invested capital for a biorefinery strategy and is widely used as a measure by the investment community. It expresses the **efficiency of the investment** measured by how much the biorefinery strategy generates cash flow from investments. Higher ROCE is preferred because it indicates better return on invested capital. | $ROCE = \frac{EBIT}{TCI}$ |
| RTMU:<br>Resistance to Supply Market Uncertainty | This criterion measures **sensitivity of the biorefinery margin to the cost of energy and chemicals**. More robust biorefinery strategies are less sensitive to changes in energy and chemicals price and are less affected by these external sources of uncertainty. | $\frac{\mathrm{EBIT}}{\mathrm{Cost\ of\ Chemiclas} + \mathrm{Cost\ of\ ENergy}}$ |
| TCI:<br>Total Capital Investment Costs | TCI is the amount of **capital** that must be raised in order to execute the project. There is a larger challenge to assemble larger capital amounts. | $TCI = FCI + WCI$ |
| SBV:<br>Short term Business Viability | SBV measures **project profitability as IRR in the short-term under normal market conditions** which supports longer term corporate transformation. Larger SBV values is preferred representing greater margin in short term which accordingly supports Phase II implementation. | $NPV = \sum_{t=0}^{22} \frac{\mathrm{CF_t}}{(1+\mathrm{SBV})^t} = 0$ |
| PIC:<br>Phase I Implementation Capability | PIC is an aggregated measure of **technology risk** that considers technology maturity (pilot demonstration etc), scale-up requirement to commercial scale, and ability to execute the Phase I technology in 24 months. Higher value of PIC is preferred because it represents lower technology risk in Phase I, and represents an **opportunity to be faster to the market** in Phase II. | $PIC = 0.5 * Maturity\ score + 0.25 * scalability\ score + 0.25 * imlementation\ capability\ score$ |
| CAB:<br>Competitive Access to Biomass | CAB represents the **ability to guarantee supply of biomass** in competitive environment. The margin on biomass is a fundamental competitive factor related to securing feedstock over the longer-term, since it is a measure of capacity to pay more to retain cutting rights and to be competitive against other proponents seeking to use the same type of biomass. | EBITDA per ton of biomass |
| CPC:<br>Competitiveness on Production Costs | CPC shows how competitive the biorefinery product portfolio production costs are relative to market prices (and thus pre-existing producers), and is **an indication of the project to penetrate existing markets and achieve market share** in the short term, to guaranty market position in the longer term. A higher value of CPC is preferred as it shows that products can be manufactured below market prices, and thus the investor can better negotiate take-off agreements to penetrate the market and gain market share. | $CPC = 100\% - \frac{Production\ Costs}{Revenue_{@Poor\ market\ condition}} * 100$ |
| QR:<br>Quality Revenue | QR measures the **ability of biorefinery strategy to maintain strong margins** due to added value products in the product portfolio. The greater the value of QR as a percentage of total revenue, the stronger the biorefinery strategy. | $\frac{\mathrm{Revenue\ from\ value\ added\ products}}{\mathrm{Total\ revenue}}$ |

NPV: Net Present Value
CF: Cash Flow
EBIT: Earnings before Interest and Tax
FCI: Fixed Capital Investment Cost
WCI: Working Capital Investment Cost
EBITDA: Earnings before Interest, Tax, Depreciation and Amortization

**Table 2. The lower and upper bound, certainty equivalent and risk tolerance of economic and competitiveness criteria**

| Criteria | Average Lower bound | Average Upper Bound | Average Certainty Equivalent (CE) Value | A | B | Risk Tolerance (RT) |
|---|---|---|---|---|---|---|
| **IRR** | 12% | 25% | 20.5% | -0.39 | -0.12 | -10.9 |
| **ROCE** | 12% | 30% | 24.2% | -0.27 | -0.1 | -11.7 |
| **CPC** | 4% | 19% | -11.3% | 11.4 | 11.7 | -1.6 |
| **DEP** | 1% | 10% | 7.9% | -0.09 | -0.06 | -0.04 |
| **PIC** | 1 | 3.5 | 2.3 | -3.3 | -2.9 | -9.4 |
| **TCI** | 170 | 20 | 47.8 | -1.3 | -0.06 | 43.8 |
| **RTMU** | 1 | 6 | 4.8 | -0.03 | -0.01 | -1.25 |
| **CAB** | 31 | 113 | 92.5 | -0.1 | -0.04 | -34.4 |
| **SBV** | 10% | 17% | 16.7% | 0 | 0 | 0 |
| **QR** | 40% | 79% | 66.7% | -0.26 | -0.05 | -24.6 |

For the IRR criterion, panelists believe that the minimum acceptable IRR for the biorefinery technologies should be 12% meaning that any IRR value below 12% is unacceptable to the same extent. In addition, they believe that at this level of design any IRR value above 25% will be good to the same extent convincing decision-makers to invest on biorefinery technologies.

Panelists believe that it is critical to be able to give a discount on product sales price to secure market share, and that at least 5% discount over the minimum sales price in the last 5 years is required to be able to compete with pre-existing competitors. Thus the average lower bound for the CPC criterion has been set at 5%. Similarly, accordingly to panelist opinions, projects that can survive after applying more than a 20% discount on products sales prices (upper bound) are preferred to the same extent.

As another example, for the DEP criterion, panelists thought that biorefinery alternatives must be able to make positive margins for worst market condition; and for margins below 1%, they are not distinguishable. Moreover, they believe that creating 10% overall margin considering worst market condition for a finite period of time in a year is acceptable and any DEP value above that would be good enough to the same extent.

For the PIC criterion, panelists required a minimum level of implementation capability (meaning attribution of score 1 to all sub-components of this criterion, PIC=1). However for the upper bound, panelists agreed that any investment option that is at commercial scale with the production capacity of maximum 20% less than designed capacity in this study will be good at the same extent even if they can not be implemented within two years. This means attributing score 5 to the first sub-component, score 3 and 1 respectively to the second and third sub-component of this criterion. These scores would result in 3.5 as the overall PIC value to be set as the upper bound.

For setting the upper bound of TCI criterion, panelists assumed that investors should be able to provide at least 50% of the required investment for the low cost projects. In order to evaluate the lower bound, panelists considered 50 MM$ as the maximum amount that the studied company can afford to invest in transformational strategies, and they assumed that this amount will be about 25% of the total required capital. The reason is that for capital intensive projects, government may support up to 50% of the investment cost as a subsidy and assuming that 25% of the investment cost can be provided by the potential partners in future, just 25% of the total amount need to be supplied by the forest products company itself.

Based on the way environmental criteria have been assessed in this study, the only boundary that can be logically set for them is the lower bound as 100%. It means that any biorefinery technology that would have the same or worst environmental performance compared to the competitive product portfolio would not be acceptable and its utility value will be set to zero.

### *3.2.2. Lottery-making*

The risk attitude of decision-makers towards risk has been assessed using lottery making in order to formulate the utility function of each criterion. For example, for the ROCE criterion, panelists considered that there would be 50% chance that the biorefinery project would have ROCE=12% (lower bound of ROCE) and 50% chance that the project would have ROCE=30% (upper bound of ROCE). Then panelists were asked “How much ROCE as a minimum guaranteed value for a proposed project would convince you not to go with the gamble, and you would agree to invest in the proposed biorefinery option with a certain ROCE?”

A panelist who agrees to give up on the gamble, by accepting to invest in a biorefinery project with ROCE value the same as expected value in the gamble (0.5*12%+0.5*30%=21%) is risk neutral. A risk averse panelist might select ROCE=18%, agreeing to a lower ROCE value but being sure about the result. Risk prone panelists prefer to try their chance to have a ROCE better than 21%, and would agree to give up going with the gamble only if the proposed certain amount would be a higher value.

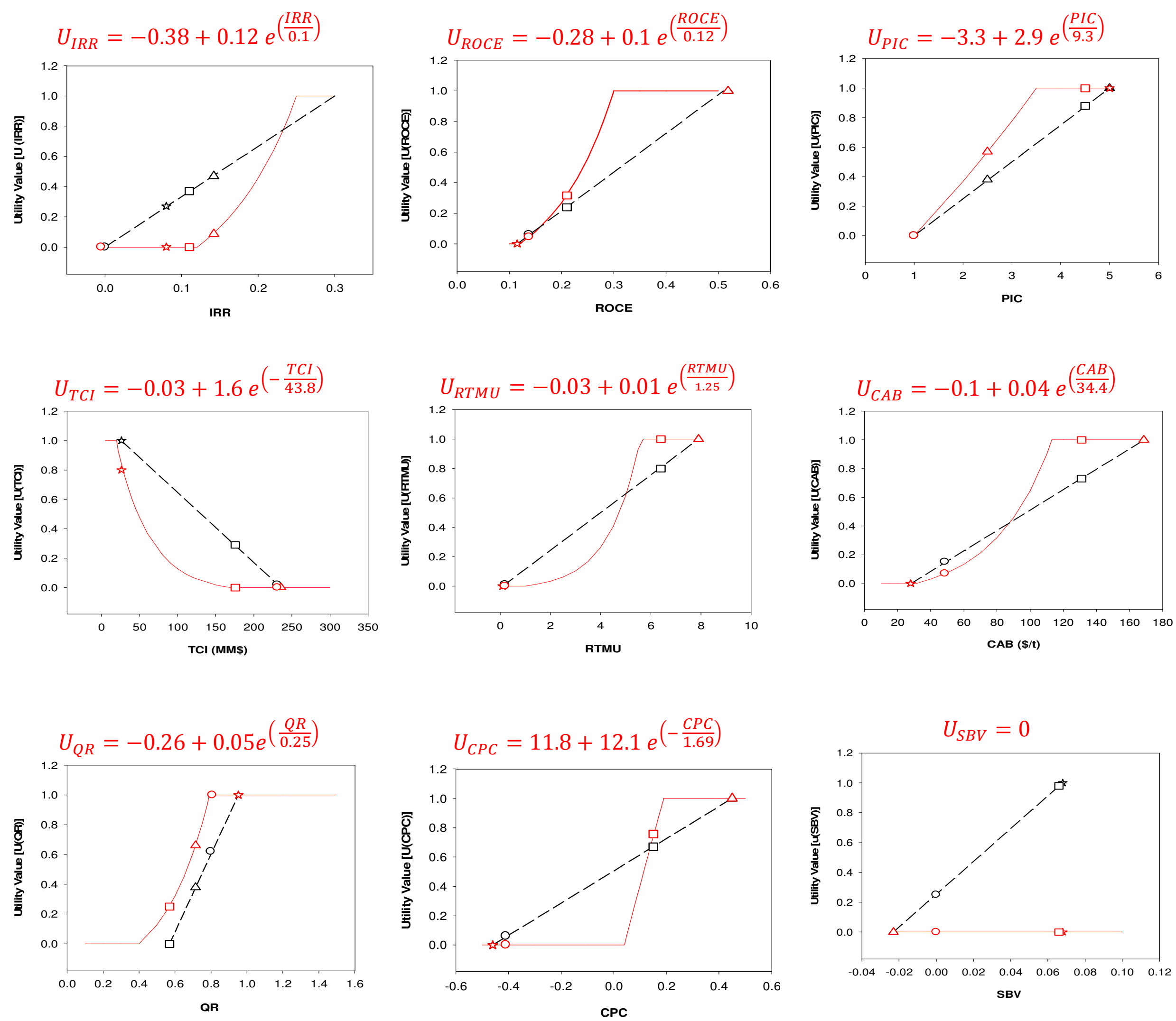
Following the same procedure, lotteries were made for each criterion using the lower and the upper bound. Using the values that the panelists gave to the lottery making (Certainty Equivalent (CE) value), their attitude toward risk for each criterion was evaluated. One panelist can be risk averse for one criterion and risk prone or risk neutral for another.

After obtaining the average CE values, parameters A and B and RT value are calculated based on equations (2) to (4), and the utility functions are developed based on equation (1). The CE, A, B and RT values for the panel are summarized in Table 2.

The utility functions of the economic and competitiveness criteria are shown in Figure 2. If we assume a "risk neutral" linear preference between the lower bound and the upper bound of each criterion, then when the utility function (red curve) is located above the arbitrary line, it means that decision-makers are risk averse in that region. However when the utility function is located below the line, it means that decision-makers are risk prone in that region. For instance for the RTMU criterion, the red curve is below the line that links ($x_{RTMU}$ =1, $U_{RTMU}$=0) and ($x_{RTMU}$ =6, $U_{RTMU}$ =1) respectively as the lower bound and the upper bound, meaning that decision-makers are risk prone for this criterion. In another example, for the PIC criterion, the red curve is located on the line between ($x_{PIC}$ =1, $U_{PIC}$=0) and ($x_{PIC}$ = 3.5, $U_{PIC}$ =1) meaning that decision-makers are risk neutral.

Individuals can be risk prone or risk averse, however the panel dynamic determines the overall risk attitude of decision-makers.

As a dramatic example, after addressing risk attitude the considerable change is seen for the SBV criterion in which the utility value of all alternatives became zero. Moreover, among the alternatives, the biggest change in utility values belongs to the fast pyrolysis biorefinery option, in which utility value of almost all criteria except IRR, TCI and SBV, were increased based on the new utility function after addressing risk attitude of decision-makers.



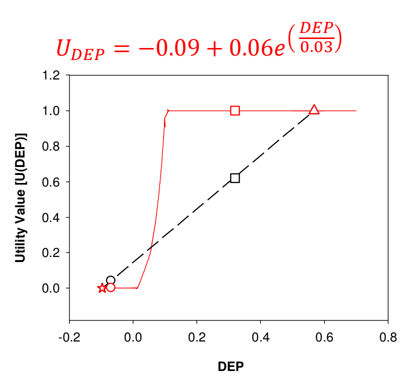




**Figure 2. Utility functions of economic and competitiveness criteria, Red color: new utility values after addressing risk attitude, black color: utility values before addressing risk attitude (*): lignin precipitation (Alt.1), (△: organosolv treatment (Alt.2), (□): fast pyrolysis (Alt.3), (○): concentrated acid hydrolydid (Alt.4).**

**3.3.Economic and competitiveness assessment considering the risk attitude of decision-makers**

In multi-attribute utility theory (MAUT), which has been used in this study as a decision-making tool, weighting factors ($w_i$) are obtained by solving the following matrix as a result of indifferent judgment between the alternatives:

$$\begin{bmatrix} 1-u_k(x^B_{k,m=1}) & -1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 1-u_k(x^B_{k,m=N}) & 0 & \cdots & -1 \\ 1 & 1 & \cdots & 1 \end{bmatrix} \begin{bmatrix} w_1 \\ \vdots \\ \vdots \\ w_N \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} \quad \forall m \neq k \qquad (6)$$

Where $u_k$ represents utility value of the most important criterion in each comparison. According to this matrix, the weighting factors change when the utility function of the most importance criterion changes. The new weighting factors of the economic and competitiveness criteria after addressing the risk attitude of decision-makers compared with their values for the deterministic assumption has been shown in Figure 3.

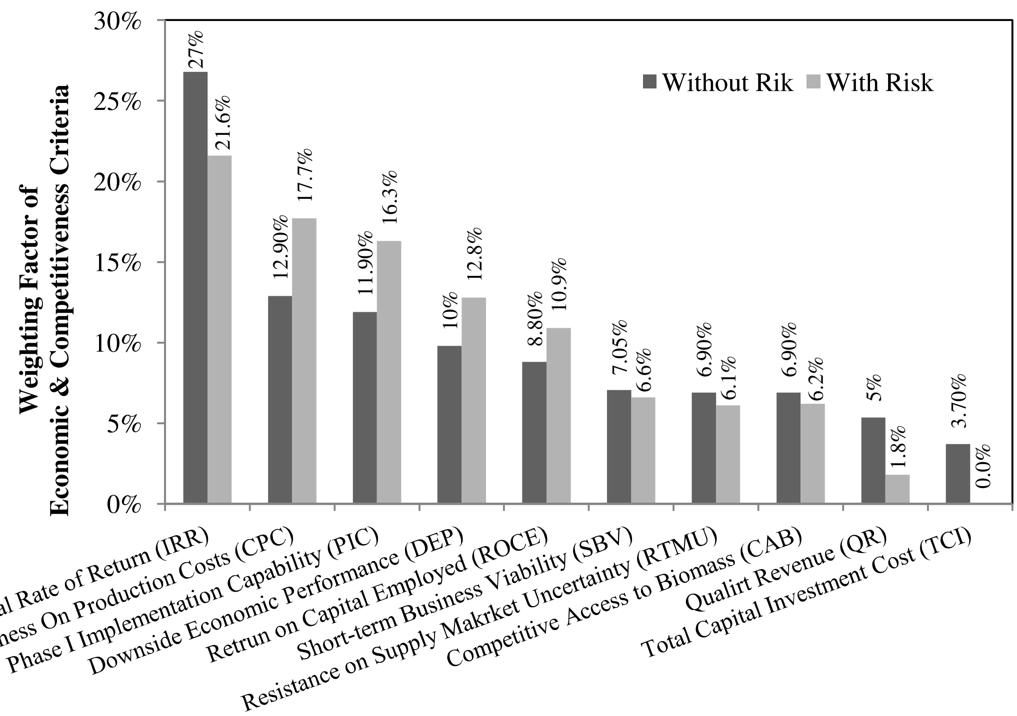



**Figure 3. The effect of considering non-linear utility function on the weighting factors of the economic and competitiveness criteria**

Using new weighting factors and utility functions, the economic and competitiveness scores of the alternatives were calculated (Figure 4). The score for lignin precipitation has decreased considerably, whereas for organosolv treatment and fast pyrolysis it was slightly increased, and for concentrated acid hydrolysis it remains the same.

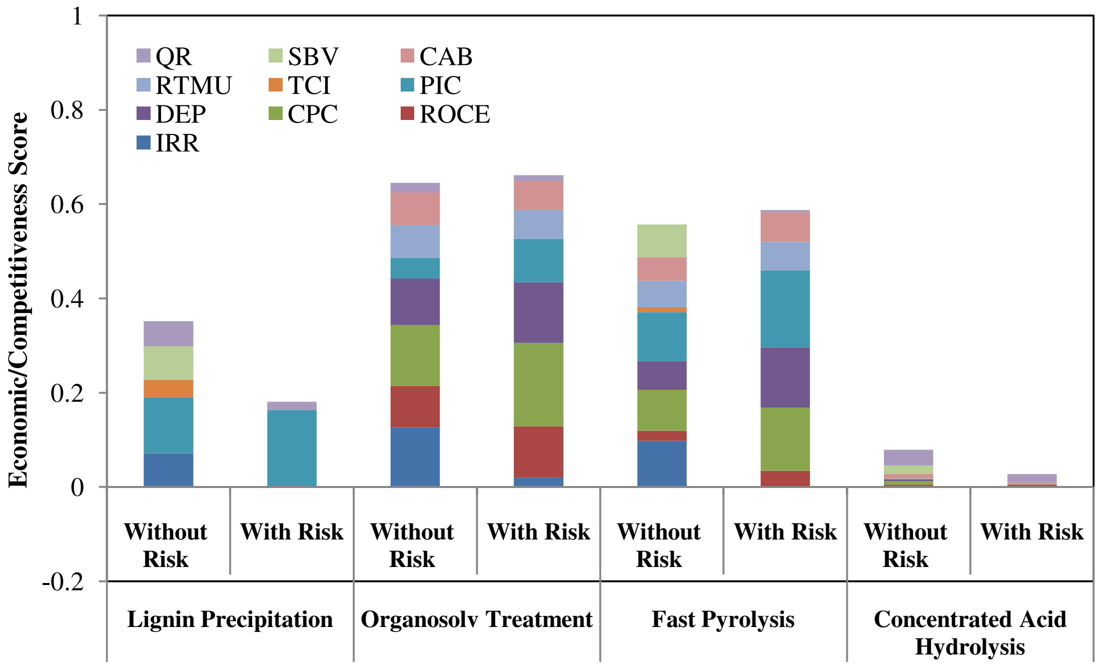



**Figure 4. The effect of considering non-linear utility function on Economic/Competitiveness**

The decision of the panel regarding the preferred biorefinery options in terms of economic and competitiveness performance, considering their risk attitude was selecting the organosolv treatment and fast pyrolysis options as the most promising strategies, but this time with more confidence due to the clearer difference between these alternatives with the other two options.

**3.4. Sustainability assessment considering uncertainty and risk attitude of decision-makers**

It has been shown earlier that involving *uncertainty* in sustainability assessment can change the basis of decision-making. In addition the results of the current study showed that addressing *risk attitude* of decision-makers also changed the basis of decision-making. Both factors had an important impact on the panel results, and so addressing both is important in guiding decision-making of which biorefinery process to select.

The set of sustainability criteria (introduced in part I of this publication (Sanaei and Stuart 201X)) was evaluated considering sources of data uncertainty, presented as probability distribution functions. Employing these criteria in an MCDM panel, and applying a non-linear utility function developed by addressing the risk attitude of decision-makers, resulted in the criteria weighting factors shown in Figure 5. In this case, the weighting factors of ROCE, CPC and PIC increased compared to the weights which were evaluated using the criteria under uncertainty only.

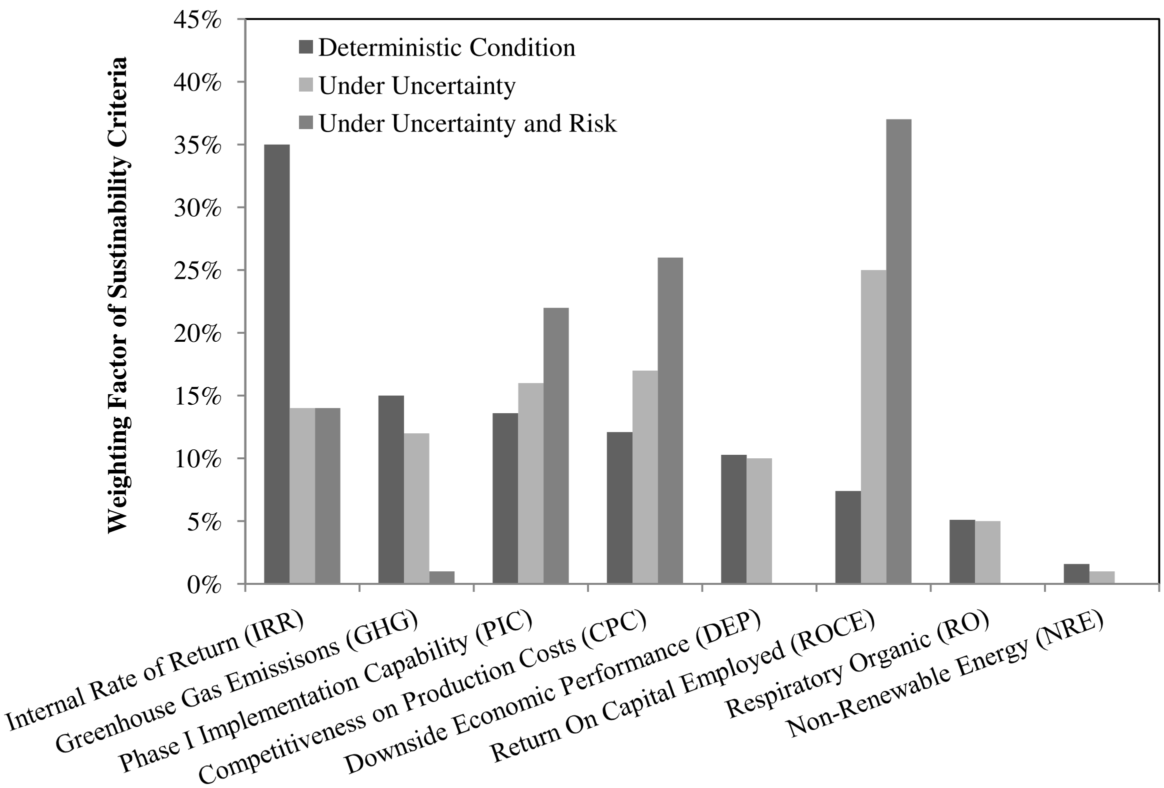
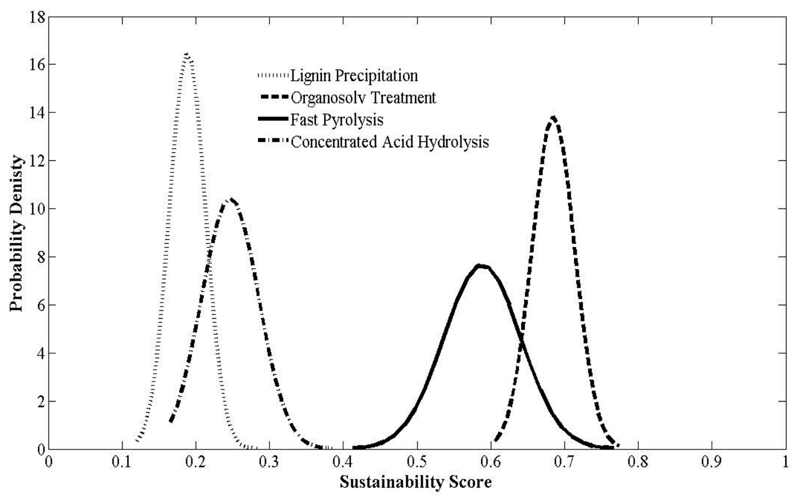
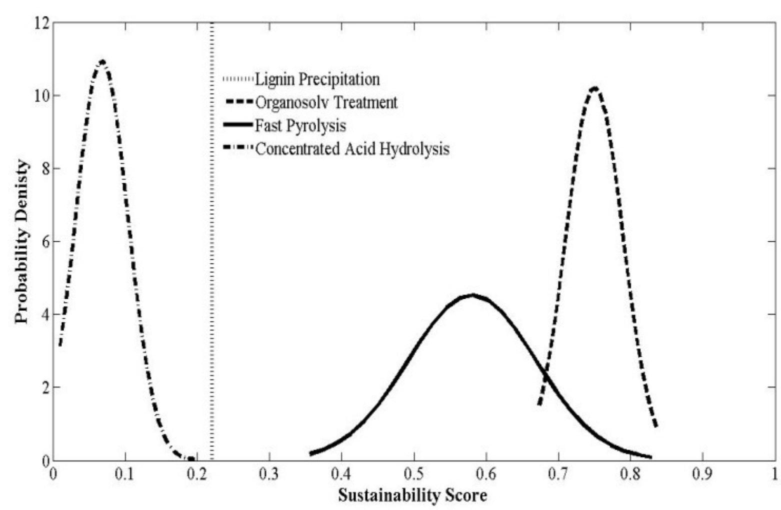



**Figure 5. Weighting factors of sustainability criteria after addressing uncertainty and risk**

Using the Monte Carlo analysis method, in each iteration a random value is generated from the probability distribution function (PDF) of each criterion and according to the utility function which has been developed for each criterion, it is converted into a utility value. By applying the weighting factors of the criteria, the sustainability scores of all alternatives were calculated for each iteration. This procedure was repeated for at least 1000 iterations, and the results are presented in the form of a PDF for the sustainability score of each alternative. These PDFs are shown in Figure 6, in comparison with the PDFs obtained by involving only uncertainty in decision-making. Involving risk attitude of decision-makers in addition to uncertainty analysis clarified better the differences between the alternatives such that organosolv treatment had a higher sustainability score, while concentrated acid hydrolysis and lignin precipitation had lower sustainability scores.




**(a)**




**(b)**

**Figure 6. Probability distribution function (PDF) of sustainability scores of the alternatives (a) under uncertainty (b) under uncertainty and risk**

Extracting three values from these PDFs including the modal value, minimum value (10th percentile) and maximum value (90th percentile) resulted in the values shown in Figure 7. This figure shows that although involving uncertainty in decision-making helped decision-makers to better distinguish between the alternatives (particularly between organosolv treatment and fast pyrolysis), involving both uncertainty and risk attitude of decision-makers helped even more in this regard by exaggerating the differences. In addition, although the differences between the less-preferred options was not clear even after involving uncertainty, as soon as risk and uncertainty were both taken into consideration, the low-end performance of concentrated acid hydrolysis compared to lignin precipitation became more clear.

Using the most probable value of each criterion and applying the criteria weighting factors, the contribution of each criterion to the sustainability score of each biorefinery option has been shown in Figure 8. There was a considerable increase in the weighting factor of ROCE, CPC and PIC, and also an increase in their utility value after addressing the risk attitude of decision-makers. This increase compensated for the decrease in the contribution of other decision criteria, so that the sustainability score of these two alternatives increased. In contrast, a considerable decrease in the weighting factor of the GHG criterion resulted in a decrease in the sustainability score of concentrated acid hydrolysis.

## 4 CONCLUSION

This study presents a systematic methodology for the sustainability assessment of biorefinery strategies at the strategic level of design, employing multi-criteria decision-making (MCDM) and involving concepts of uncertainty and risk attitude of decision-makers.

This approach uses a lottery-based risk analysis in order to quantify risk attitude of decision-makers to formulate a non-linear (exponential) utility function for each decision criterion. These utility functions along with the results of uncertainty analysis are then employed in a multi-criteria decision-making (MCDM) panel, and combined with Monte Carlo analysis in order to compare the sustainability performance of the candidate biorefinery process alternatives.

The results show that addressing the risk attitude of decision-makers on top of involving uncertainty in decision-making permitted a better differentiation between the process alternatives, and consequently enabled decision-makers to screen out process options with more confidence.

The methodology was applied in a case study in which four biorefinery strategies were compared using a set of sustainability criteria, at a kraft pulp mill. The results for the deterministic assumption showed that organosolv treatment and fast pyrolysis were the most preferred strategies but were not distinguishable. This study showed that involving both uncertainty and risk attitude of decision-makers exaggerated the difference between the two most promising alternatives, such that organosolv treatment had sustainability performance score that was 25% higher than fast pyrolysis.

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# APPENDIX G – Book Chapter:

# LCA-Based Environmental Evaluation of Biorefinery Projects

# LCA-Based Environmental Evaluation of Biorefinery Projects

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**Executive Summary**

The North American industry is facing critical challenges related to climate change and energy supply. The implementation of a biorefinery strategy (either stand-alone or retrofit) is a potential solution that is becoming more attractive thanks to environmental policies that stimulate the production of biofuels. However, many new biorefinery technologies are currently emerging about which little information can be found in the public domain. This leads to difficulties in accurately analyzing these technologies and consequently impedes decision-making about which strategy to implement in the future.

Strategies that are able to create more profit, have lower environmental impacts, and have more social benefits in the long term can be considered promising for the future. These three aspects are the pillars of sustainable development, and therefore there is a need to assess the sustainability of possible biorefinery strategies in this light. One of the most applicable methodologies by which the potential environmental impacts of a system can be assessed is life-cycle assessment (LCA). The main purpose of this method is to provide a quantitative assessment of the potential environmental impacts of products over their entire life cycle. Different LCA applications lead to different methodological requirements. In the biorefinery context, LCA can be used to highlight the motivation for replacing fossil-based products by bioproducts, or it can be used for decision-making regarding possible biorefinery strategies. The results of LCA-based environmental evaluation can be interpreted in conjunction with technical, economic, and social criteria by employing a multi-criteria decision making (MCDM) method to screen out unsustainable biorefinery strategies. This chapter illustrates the role of LCA-based environmental evaluation in identifying promising future biorefinery strategies.

The first part of this chapter gives an overview of the LCA methodology, its applications in sustainable design and its limitations and challenges, specifically uncertainty. In the second part, the environmental concerns regarding biorefinery plants (specifically climate change and land use) are addressed, and studies that have evaluated the environmental performance of biorefinery projects are discussed. To illustrate the application of LCA in the biorefinery context, an example is presented in which the environmental performance of bioethanol production using two different technology pathways (from forest residues using a thermochemical process, and from corn stover using a biochemical process) is compared. Finally, the results of an MCDM

panel are addressed, which confirm the necessity of paying more attention to the evaluation of environmental criteria for biorefinery systems.

## 1. Introduction

Continuing fossil-based energy consumption is leading to increased depletion of fossil resources and consequently increased greenhouse-gas (GHG) emissions [1]. It has been observed that GHG emissions (carbon dioxide, methane, and nitrous oxide) are upsetting the Earth's climate due to fossil-fuel combustion and land-use change as a result of human activities [2]. Using new technologies that will guarantee economic growth and environmental sustainability in the long term can overcome these issues. As a potential solution, over the past decades, attention has been paid to using renewable sources for providing energy and chemicals. Although heat and power can be produced by several renewable resource alternatives (wind, solar, hydro, biomass, etc.), biomass is the only alternative that by use of biorefinery technologies can be converted into fuels and chemicals [2]. To prove that replacing fossil-based products by bioproducts leads to decreases in environmental impacts, several studies have performed an environmental evaluation of biorefinery systems.

Although most of these studies confirm that bioproducts have fewer environmental impacts than fossil-based fuels, a new concern is that there are several alternatives for biomass feedstock and emerging conversion technologies, from which the most promising need to be chosen for future implementation of a biorefinery strategy. Comparison of the environmental performance of possible strategies plays an important role in distinguishing them from a sustainability point of view. One of the most applicable methodologies by which the potential environmental impacts of a system can be assessed is life-cycle assessment (LCA). The main purpose of this method is to provide a quantitative assessment of the potential environmental impacts of products over their entire life cycle. A life cycle, as illustrated in Figure 1, consists of extracting raw materials from natural resources, production, distribution, use and eventually the recycling, reuse, recovery, or final disposal of the product. Life-cycle thinking goes beyond the traditional focus on production by including the impacts of a product, process, or service over its entire life cycle.

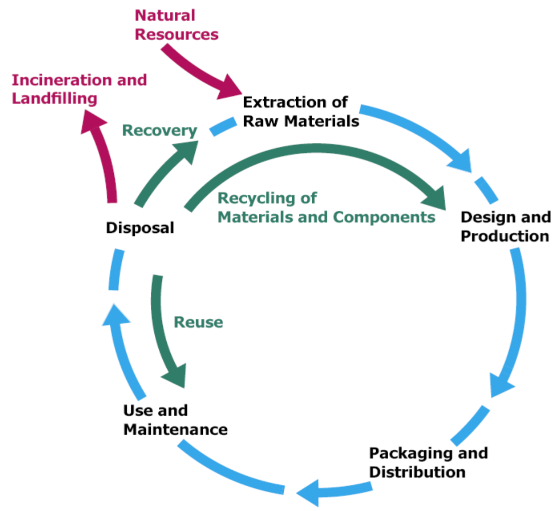


**Figure 1. Product life cycle [3].**

The following sections describe the use of LCA methodology to evaluate the environmental performance of biorefinery systems.

## 2. Overview of Life-Cycle Assessment (LCA) methodology

The LCA methodology is defined in the ISO 14040 and 14044 standards. As illustrated in Figure 2, the standard framework of LCA methodology has four steps: goal and scope definition (ISO 14040), inventory analysis (ISO 14041), impact assessment (ISO 14042), and interpretation (ISO 14043). Goal and scope definition defines the problem and system to be studied. During inventory analysis, polluting emissions, the use of renewable and nonrenewable resources, and the use of land are quantified. In the third step, these inventory data are transformed into potential impact indicators. Finally, during the interpretation step, key points are identified, and sensitivity analyses are performed to test the robustness of the results.

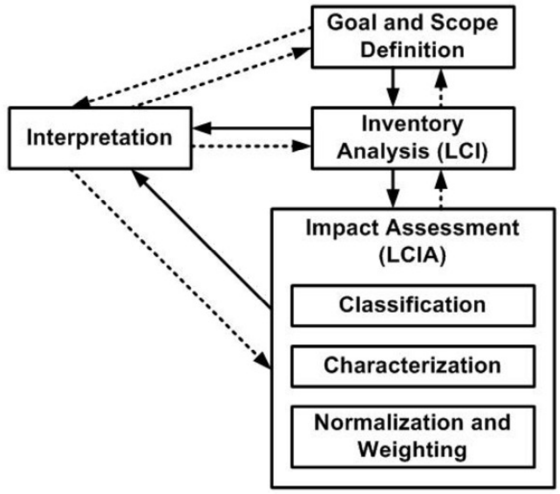


**Figure 2. Main steps in the standard life-cycle assessment framework [4]**

### 2.1. Goal and scope definition

Goal and scope definition consists of describing the objectives of the study, its applications, and its target audiences. Then, the function to be studied is introduced, and a representative unit for this function is selected (functional unit). The system boundary is set, and reference flows (a measure of the outputs from processes) are determined. The functional unit is the quantified performance of the product system used as a reference unit, while the reference flow is a measure of the outputs from processes in a given product system required to fulfill the functions carried out by the functional unit. The system boundary definition determines which unit processes are to be included in the study and must be consistent with the goal of the study. In general, the life-cycle stages that are included are extraction and preparation of raw materials, transportation, manufacturing, use of the product, and waste management. In the comparison of alternatives, any life-cycle stages that do not vary among the alternatives can be excluded. The LCA methodology can be applied, with proper justification, in studies that do not cover the entire life cycle of the product studied (cradle-to-gate and gate-to-gate studies). There are two approaches for determining the start and end point of the life cycle in LCA, which are cradle-to-gate and cradle-to-grave [5].

**2.2. Life-cycle inventory analysis**

Life-cycle inventory analysis (LCI) gathers information about all resource inputs and environmental outputs for each process technology. This information can be obtained by mass and energy balances. A schematic form of this step is presented in Figure 3.

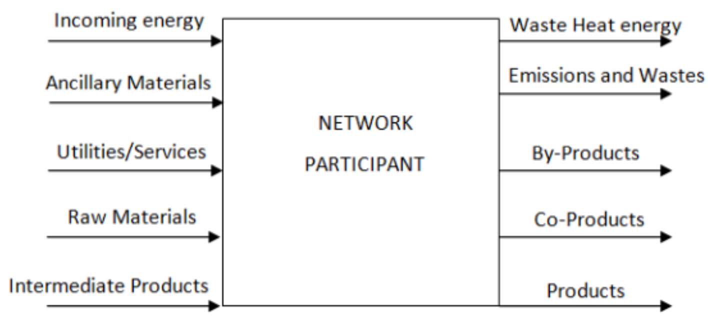


**Figure 3. Mass and energy balance for LCI step [6].**

**2.3. Life-cycle impact assessment**

The aim of life-cycle impact assessment (LCIA) is to evaluate the magnitude of the potential environmental impacts of a product. It converts the results from LCI into environmental information by aggregating the LCI information into environmental indicators. When a substance is emitted into the environment, its concentration, state, or medium may change and often it is transformed into other substances. The steps that are followed by a substance before it causes an effect are called the *impact pathway* or the *cause-effect chain*. Impact characterization methods try to model the impact pathways to relate each piece of inventory data to its potential environmental impact as much as possible. Some methods, the so-called midpoint methods, stop at an intermediate level of the impact pathway, while others try to reach the endpoint and to describe environmental impacts using damage categories [5]. An example of indicators at both levels and how they relate to each other is given in Figure 4.

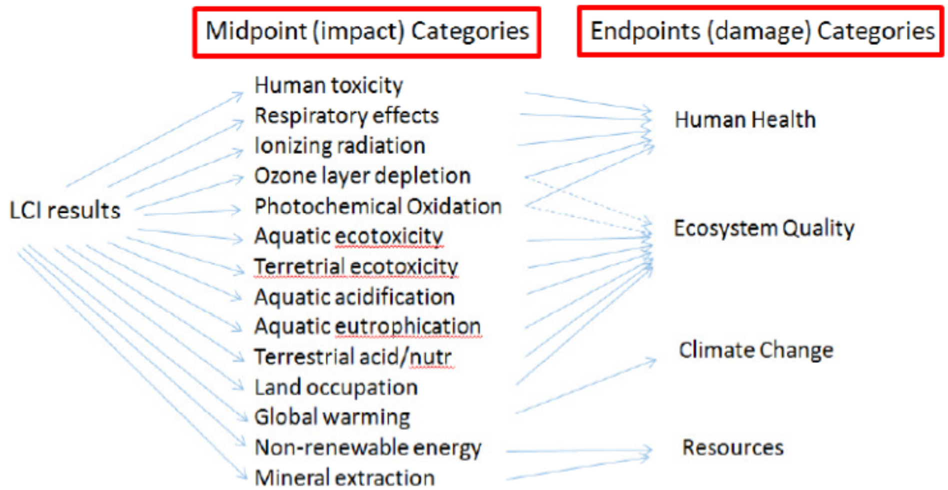


**Figure 4. Example of IMPACT 2002+ indicators at midpoint and endpoint categories [7].**

LCIA can also include optional elements such as normalization and weighting. Normalization expresses the results of LCIA relative to a reference and aims to provide a better understanding of the relative significance of the different impact category results. It also prepares the LCIA results for weighting by transforming them into dimensionless indicators. Weighting expresses the relative importance of the different impact categories by using value-based numerical factors. It enables the environmental information to be aggregated into a single indicator if desired [5].

**2.4. Life-cycle interpretation**

During life-cycle interpretation, the findings are evaluated to obtain conclusions and recommendations. This activity consists of two main steps: identification of significant issues, and evaluation of the results. In this step, completeness, sensitivity, and consistency checks as well as uncertainty and data quality analyses can be done to ensure that the final results are reliable. The completeness check ensures that all relevant information and data needed for the interpretation are available and complete. The sensitivity check assesses the reliability of the final results and conclusions by determining how they are affected by uncertainties in the data and the methodological choices. The consistency check determines whether the assumptions, methods, and data are consistent with the goal and scope of the analysis [5].

## 3. LCA applications

In general, there are two main categories of LCA. The first includes all applications which aim to describe the environmental performance of systems (accounting LCA, attributional LCA), while the second includes applications which aim to describe the environmental consequences of a specific decision (change-oriented LCA, consequential LCA). On the one hand, attributional LCA is more related to the classical definition of LCA by ISO. On the other hand, in consequential LCA, any process that is affected by a given decision, whether it is in the life cycle being investigated or even in another life cycle, should be included in the analysis. This distinction is still young, and there are still debates on how and when one or the other of these approaches should be applied.

In the biorefinery context, LCA can be used to highlight the motivation for replacing fossil-based products by bioproducts, or it can be used for decision-making on possible biorefinery strategies. In both cases, the results of LCA-based environmental evaluation can be interpreted in conjunction with technical, economic, and social criteria to evaluate the sustainability of a biorefinery strategy.

## 4. LCA challenges and limitations

In spite of the strengths of the LCA methodology, it also has its weaknesses. The large amount of data and time needed to apply LCA can be considered as one of the main weaknesses of this methodology [8]. In addition, some of the important challenges are as follows [9]:

- Establishment of the system boundary;
- Product functionality;
- Choosing an allocation approach to assign environmental impacts to multiple products;
- Selection of the impact assessment method;
- Weighing of different impact categories against each other;
- Temporal and special resolution.

To increase the reliability of an LCA, the choice made in responding to each of the challenges mentioned above should be well documented [34]. In addition, the robustness and sensitivity of the results should be assessed by considering a number of possible choices.

Besides the challenges already mentioned, an unavoidable concern in LCA methodology is uncertainty. The sources of LCA uncertainty and methods to analyze them have been presented by Bjorklund [10]. Some of the sources of LCA uncertainty include data inaccuracy, data gaps, spatial and temporal variability, model uncertainty, and uncertainty of choices [11]. It is claimed that the most important source of uncertainty is site-specific information gathered in the inventory phase [11]. In general, LCA uncertainty can be categorized into three types: (1) parameter uncertainty (e.g., inventory data), (2) scenario uncertainty (e.g., choices concerning allocation), and (3) model uncertainty (e.g., lack of suitable characterization factors) [12].

Only a few studies have considered LCA uncertainty in the biorefinery context. Tan et al. [13] have used probabilistic modeling approaches for uncertainty evaluation of the life-cycle inventory of biofuels. Malca and Freire [14] have considered both parameter and scenario uncertainties for biofuel systems. Although some studies have covered one or two types of LCA uncertainty [15], there is no available LCA study in the biorefinery context that covers all three types of uncertainty simultaneously.

## 5. Environmental concerns for biorefinery plants

The environmental issues which have been studied most extensively in the biorefinery context are greenhouse-gas (GHG) emissions, nonrenewable energy (NRE), and land-use change (LUC). GHG emissions may cause dangerous anthropogenic interference with the climate system and result in global warming. The most important greenhouse gases are carbon dioxide, methane, and nitrous oxide. Usually, a 500-year time horizon is chosen as a time period to represent the full impacts. With carbon dioxide as the baseline and a 500-year horizon, methane has been shown to have approximately 21 times more impact than $CO_2$ and nitrous oxide 310 times more [16].

Assessing GHG emissions of biorefinery systems depends strongly on the inclusion of emissions caused by land use, including direct land-use change (LUC) and indirect land-use change (ILUC) [17]. Direct land-use change (LUC) occurs when a piece of land with its previous land cover is changed to cultivated cropland to produce energy crops for biorefinery plants [18]. Fargione et al. [19] and Searchinger et al. [20] have shown the necessity of including land-use change impacts in the GHG balance for biofuels. Depending on the methodology used, the effect of land-use change on the GHG balance of a biorefinery system can be positive or negative. The conversion of forests, wetlands, and grasslands to cropland has a negative effect on GHG because of the emission of carbon from biomass and soils into the atmosphere. However, converting sparsely vegetated or disturbed lands to cropland results in a net gain in biomass production and sequestration of carbon into soil [17].

Besides the direct land-use change effects of producing bioproducts, there are also indirect effects. Because production of bioproducts competes with agricultural resources, this competition results in a price increase for agricultural products, and this price increase causes additional conversion of the world's grasslands and forests to cultivated cropland. This additional land conversion results in the release of previously sequestered carbon from grassland and forest ecosystems [21]. These emissions are an indirect result of producing bioproducts, and they should be considered in estimating the amount of GHG emissions for each biorefinery system. In addition to the agricultural-based biorefinery, indirect land-use change can also be associated with the forest-based biorefinery. For instance, using forest residues in biorefinery systems may cause feedstock shortages for energy production, which is another industrial application of forest residues. Activities to overcome this issue (increasing extraction of woody biomass to provide energy) will probably change GHG balance indirectly.

Because of the depletion of fossil resources in the world, nonrenewable energy use is considered as another important environmental concern in the biorefinery context. Among several proposed metrics for quantifying nonrenewable energy (NRE) use, the ratio of energy output of the resultant bioproduct to the fossil energy input required for its production is more representative and applicable.

The amount of water required to manufacture a bioproduct is another limiting factor for its future success. In addition, pollutants entering water sources, such as fertilizers and pesticides that are applied to the land to enhance plant growth, can affect water quality. These adverse effects can appear as eutrophication of fresh and ocean waters [22].

Among all the mentioned important environmental concerns in the biorefinery context, most available studies have focused on evaluating GHG and NRE, especially for biofuels production. However, more recent studies are also paying more attention to the impacts of direct and indirect land-use change caused by biorefinery systems. It has been confirmed that bioproducts use less NRE and release fewer GHGs during the cradle-to-gate segment of their life cycle (including feedstock preparation and manufacturing stages). However, when the product use and disposal stages are brought within the boundary of analysis (in a cradle-to-grave assessment), the outcomes become less predictable [23]. In addition, biorefinery systems sometimes have greater eutrophication and acidification impacts compared to their equivalent fossil-based pathways [23].

Because of the lack of information in the literature about possible environmental impacts of biorefinery systems (such as indirect land-use change, acidification, eutrophication, ozone depletion, and toxicity), it is difficult to conclude that bioproducts have a better environmental performance compared to their equivalent fossil-based products [23]. This difficulty underlines the importance of environmental evaluation of biorefinery systems.

## 6. LCA studies for biorefinery projects

Most studies on the environmental evaluation of bioproducts have been carried out for biofuels, especially for bioethanol. Reviews of available publications during 1999–2004 and 2001–2008 which have used LCA for the environmental evaluation of biofuels production were presented by Blottnitz and Curran [24] and Ranjbar et al. [25]. In addition to biofuels, some studies have focused on other bioproduct categories. For instance, Wellisch et al. [23] reviewed 67 LCA-based environmental evaluations of several categories of bioproducts. They concluded that except for the biopolymer category, all bioproducts consume less nonrenewable energy and have lower GHG emissions compared to their fossil-based counterparts. However, they mentioned that it cannot be concluded that any particular bioproduct has the best environmental performance compared to other bioproducts.

There are several studies in the literature on LCA-based environmental evaluation of biorefinery systems. However, because they have considered various frameworks (a boundary and allocation method) and have different levels of accuracy, transparency, and consistency, it is very difficult to compare their results on a rational basis [26]. In addition, environmental evaluation of the biorefinery context is not yet mature for two main reasons: (1) not all the probable environmental issues (such as ILUC) are covered, and (2) the various types of uncertainty are not considered [27]. Therefore, LCA-based environmental evaluation plays a very critical role in strategic decision-making about future implementations of biorefinery strategies.

## 7. Illustrative example

The aim of presenting this example is to illustrate the procedure for environmental assessment of two biorefinery strategies for biofuel production using the LCA methodology and the SimaPro 7.1 software. Because of a desire for more sustainable fuel sources, recently greater attention has been paid to second-generation liquid biofuels, which can be produced through a variety of feedstocks and conversion technologies. Therefore, it is desirable to compare the environmental impacts of the various conversion processes for second-generation biofuels production. The two main types of conversion technologies by which biofuels are produced are biochemical and thermochemical technologies. The two biorefinery strategies which have been chosen for comparison using LCA are:

1. Bioethanol production from a forest-residues feedstock using a thermochemical process (mixed alcohols are produced as coproducts)
2. Bioethanol production from corn-stover feedstock through a biochemical process (electricity is produced as a coproduct).

**7.1. Goal and scope definition**

This study intends to evaluate and compare the potential environmental impacts of two different pathways for producing bioethanol within the specified scope to determine which process has smaller potential environmental impacts. The “cradle-to-gate” impacts of the two competing processes for producing ethanol from biomass sources are assessed. This means that the potential environmental impacts are evaluated from growing the feedstock until the production stage, because the other steps are the same in both cases. Therefore, the system boundary includes the unit processes of growing, harvesting, and transporting the biomass and the production of ethanol from biomass for both processes. Incorporated into these primary unit processes are other units such as infrastructure, transportation, fuel, chemicals, and waste treatment. The primary mass balance for the processes is based on two NREL reports [28,29] which present fully developed mass balances and flowsheets for the production stage. The system boundaries as determined are shown in Figures 5 and 6. The common function of both processes is the production of ethanol, and the functional unit is defined as producing 1 kg of ethanol. However, different coproducts are produced through the two chosen pathways. ISO’s recommendation is to avoid allocation by expanding the system limits to include the additional functions. However, when physical properties are not appropriate, ISO suggests using a different basis for allocation, such as the mass, energy, or economic value of the products. Although allocation is not the preferred method for handling multifunction systems, it is used in this example because of several existing multifunction issues. In the biochemical process in which electricity is produced as a coproduct, allocation is performed on an economic basis because it best represents the functionality of the process. In the thermochemical process in which mixed alcohols are produced as coproducts, because of the lack of reliable data about the market for mixed alcohols, allocation is performed on a mass basis. Another allocation problem exists with the feedstocks for both processes because they are both byproducts of a primary function: corn stover of maize production, and forest residues of forestry. For both these cases, an economic basis is chosen because it can represent the current nature of their production. Based on the defined functional unit, the reference flows and key parameters of the systems under study are summarized in Tables 1 and 2.

# System Boundaries

**Figure 5. Thermochemical Process Using Forest Residues Feedstock**

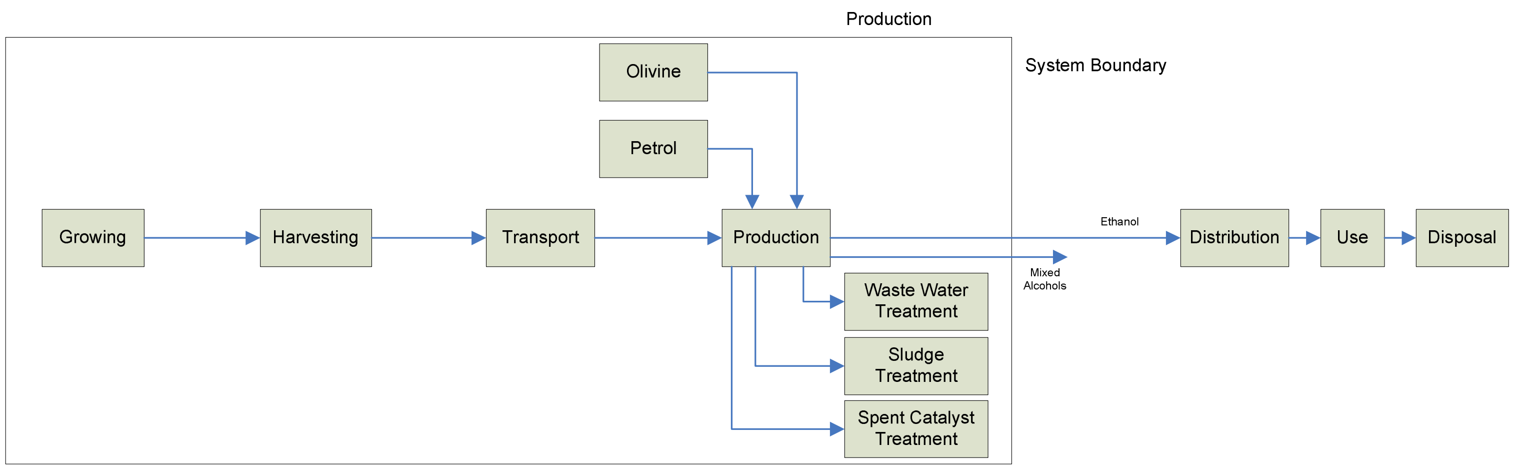


**Figure 6. Biochemical Process Using Corn Stover Feedstock**

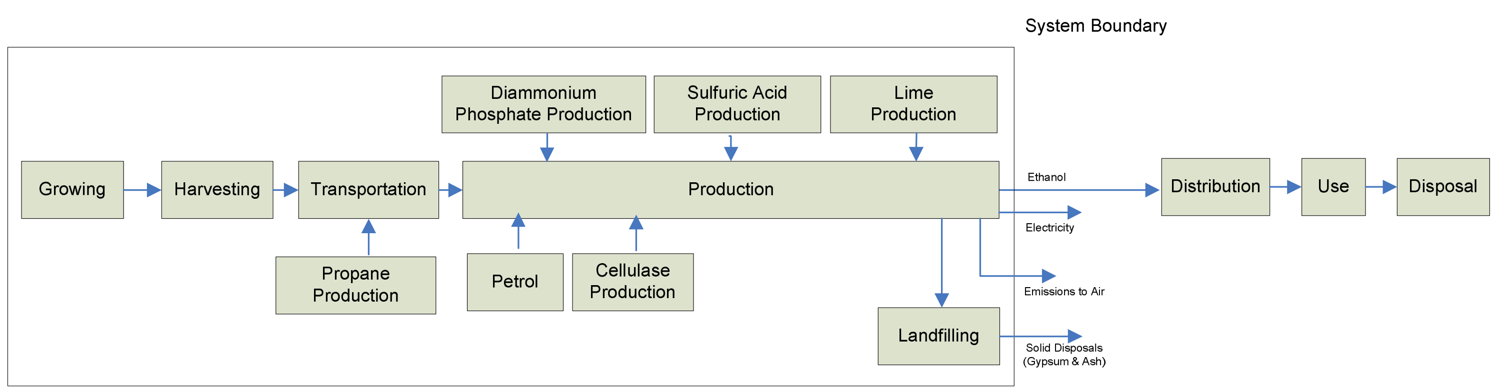

**Table1. Reference Flows**

| Reference Flows in ethanol production from forest residues through thermochemical process | Amount |
|---|---|
| Forest Residue Feedstock | 9.25 kg |
| Ethanol to Storage | 1 kg |
| Mixed Alcohols | 0.181 kg |
| **Reference Flows in ethanol production from corn stover through biochemical process** | **Amount** |
| Corn Stover Feedstock | 3.81 kg |
| Ethanol to Storage | 1 kg |
| Electricity | 2625.5 kJ |

**Table 2. Key parameters**

| Parameter | Value | References |
|---|---|---|
| **In ethanol production from corn stover through biochemical process** | | |
| Corn/Stover Ratio | 1 | - |
| Harvestable Stover | 50% | - |
| Corn Stover EtOH yield | 98039 kg stover /25705 kg EtOH | [28] |
| Electricity ratio | 18747kW / 25705 kg/hr EtOH | [28] |
| **In ethanol production from forest residues through thermochemical process** | | |
| Forest Residue (FR) Yield | 367437 lb FR / 39731 lb EtOH | [29] |
| Mixed-Alcohols Ratio | 7204 lb mixed alcohols / 39731 lb EtOH | [29] |

## 7.2. Life-Cycle Inventory (LCI)

All the assumptions made for estimating inventory data are presented in Tables 3 and 4 for the thermochemical and biochemical processes respectively.

**Table 3. Assumptions and their justifications in the thermochemical process**

| Stages | Assumption | Amount | Justification |
|---|---|---|---|
| Growing | Removed 70% of fuel consumption | 70% | Growing includes harvesting to side of road, so because harvesting is considered separately in this study, 70% of fuel consumption in the growing step is removed arbitrary |
| | Residue density | 648.5 $kg/m^3$ | Same as the density of bundles |
| Harvesting | Tractor can carry 9998 kg (22 bundles) | 9998 kg | - |
| | Bundle weight and volume | 454 kg / 0.7$m^3$ | - |
| Transportation | Distance from cropland to long-term storage | 25 km | - |
| | Truck 28 t for transporting logs | - | Bundles were assumed similar enough to logs to be handled as such |
| Production | Infrastructure | - | A methanol plant is used as a proxy for infrastructure impacts, assuming a 20-year life and scaled to capacity |
| | Olivine | - | Assumed that making olivine involved the same process as sand, because it is a mineral and used as a heating medium and gasifying fluid |
| | Economic-based allocation | 67% to EtOH | Heavy alcohol price (assumed same as butanol price) = \$5587<br><br>Ethanol price = \$11370 |
| | Energy-based allocation (used in sensitivity analysis) | 65% to EtOH | Based on energy content:<br><br>477801 MJ to EtOH, 262631 MJ to mixed alcohols |

**Table 4. Assumptions and their justifications in the biochemical process**

| Stages | Assumption | Amount | Justification |
|---|---|---|---|
| Growing | Mass ratio of corn to corn stover | 1 | - |
| | Harvestable stover | 50% | 30% to 50% of stover should be left on land as nutrition for the land |
| | Economic-based allocation | Allocating 54% of impacts to corn and 46% to corn stover | (sensitivity analysis will be done)<br>Corn price: 2.35 \$/bushel, Corn density: 721 kg/$m^3$,<br>Corn stover price: 60 \$/dt |
| Harvesting | Two step harvesting | - | In two-step harvesting, corn is harvested first (its environmental impacts have been included in The corn plant that has been extracted from Ecoinvent in this project), and then stovers are harvested by mowing, baling, and loading the bales |
| | Weight of each stover bale | 700 kg | - |
| | Number of bales/hr for the plant with capacity of 2000 t/day feedstock | 140 | |
| Transportation | Distance from cropland to long-term storage | 20 km | Plants which use agricultural feedstocks generally are located approximately 20 km from cropland |
| | Distance from long-term storage to short-term storage | 1 km | Short-term storage should be close enough to long-term storage and also to the production process |
| | Truck 28 t for transporting round bales from cropland to long-term storage and also from long-term storage to short-term storage | - | Each truck can carry 17 round bales, so selecting a 28t truck for transportation is consistent |
| | Number of Forklifts | 8 | 4 for unloading the trucks and 4 for putting the bales on the conveyor. Each forklift is capable of operating with a 33-lb propane tank for an 8-hour shift |
| Production | Infrastructure | - | A methanol plant (same as in the thermochemical process (see Table 3)) |
| | Chemical organics | - | Chemical organics has been chosen as a representative for Enzyme in SimaPro |
| | Economic-based allocation | Allocation of 99% of impacts to ethanol and 1% to electricity | Economic-based allocation<br><br>Sensitivity analysis will be done |

**7.3. Life-Cycle Impact Assessment (LCIA)**

The impact assessment was conducted using the Impact 2002+ method [7]. This means that the normalization data were based on European emissions. The two processes were characterized using 15 midpoint impact categories and four endpoint categories, and a comparison of the processes was undertaken. Figure 7 shows the comparison of midpoint impacts for the processes. It can be seen that the thermochemical process (green bars) shows smaller potential impacts in most of the midpoint impact categories. The noncarcinogenicity and terrestrial ecotoxicity categories show net impact credits for the biochemical process, which therefore outperforms the thermochemical process in these areas. This is due to the absorption of toxic metals in the growing of corn.

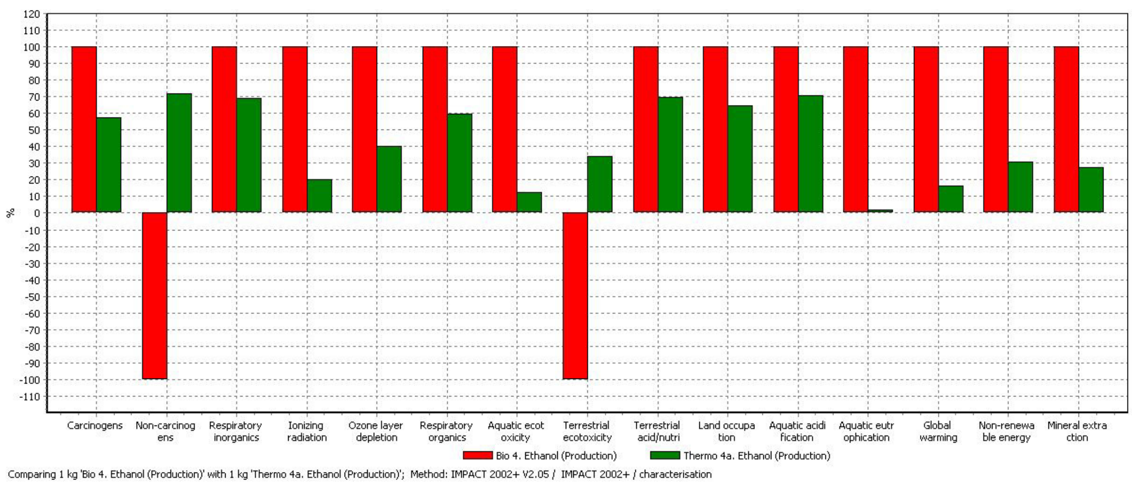


**Figure 7. Midpoint characterization comparison of the thermochemical (green bars) and biochemical (red bars) processes /1kg ethanol**

Figure 8 shows the comparison of endpoint impacts for the two processes. As can be seen, all of the endpoint damage categories have lower scores for the thermochemical process.

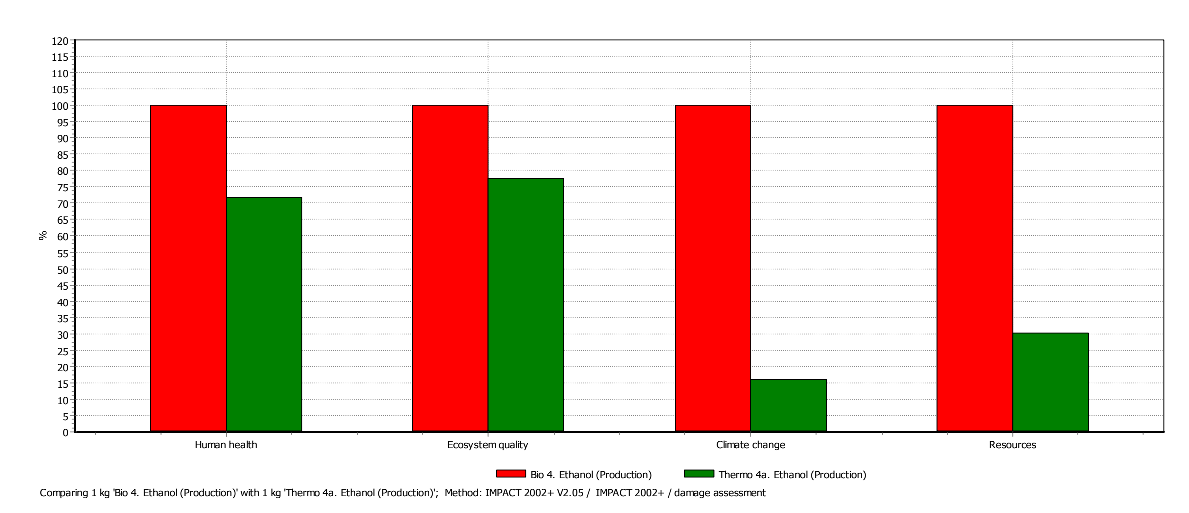


**Figure 8. Endpoint characterization comparison of the thermochemical (green bars) and biochemical (red bars) processes / 1 kg ethanol**

The impact categories can be normalized to present the plant emissions as a fraction of the emissions in a geographical area. This is useful in understanding whether the amount of emissions from a given process is significant compared to the overall emissions of the same damage type in the area. As can be seen in Figure 9, only five of the impact categories present large potential impacts when normalized to European emissions. In four of the impact categories, the thermochemical process clearly has lower impacts. However, for the terrestrial ecotoxicity impact category, the biochemical process outperforms the thermochemical process because of the credits obtained from metal absorption during the growing phase.

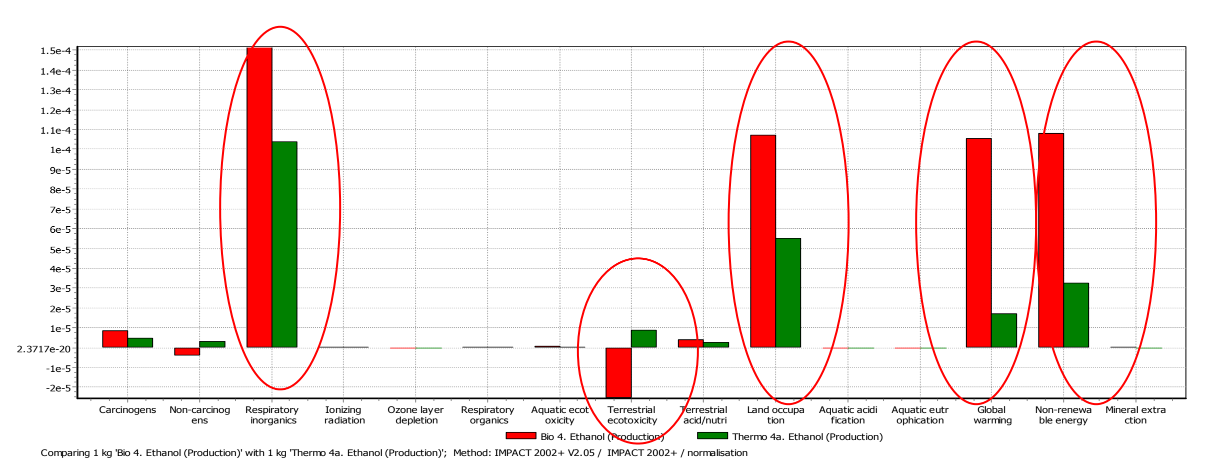


**Figure 9. Midpoint normalization comparison of both processes / 1 kg ethanol (Impact 2002+)**

Weighting is not necessary for this study because based on the results for the endpoint categories, it can be concluded that the thermochemical process is the environmentally more favorable process of the two examined in this study. No matter how the categories are weighted, the thermochemical process will remain the more environmentally favorable process.

**7.4. Interpretation**

This section aims to provide an overview of the contribution of potential damages and will enable the readers to be able to interpret the results and gain a better understanding of the cause of the impacts. Using normalization and weighting (by considering an equal weighting factor for each impact category), the contributions of each stage to the endpoint categories for both processes have been obtained and are shown in Figures 10 and 11. It is apparent that the growing and production stages are responsible for a large portion of the environmental impacts compared to harvesting and transportation. In both processes, the production stage is dominated by human health issues, which in turn is due to the midpoint impacts of respiratory inorganics and nonrenewable energy use. This is because of large emissions of $NO_2$ and $SO_2$ in the case of respiratory inorganics and the use of petrol as a denaturant in the case of nonrenewable energy. The impacts of biomass growing are dominated by ecosystem quality issues due to the occupation of land for growing trees and crops.

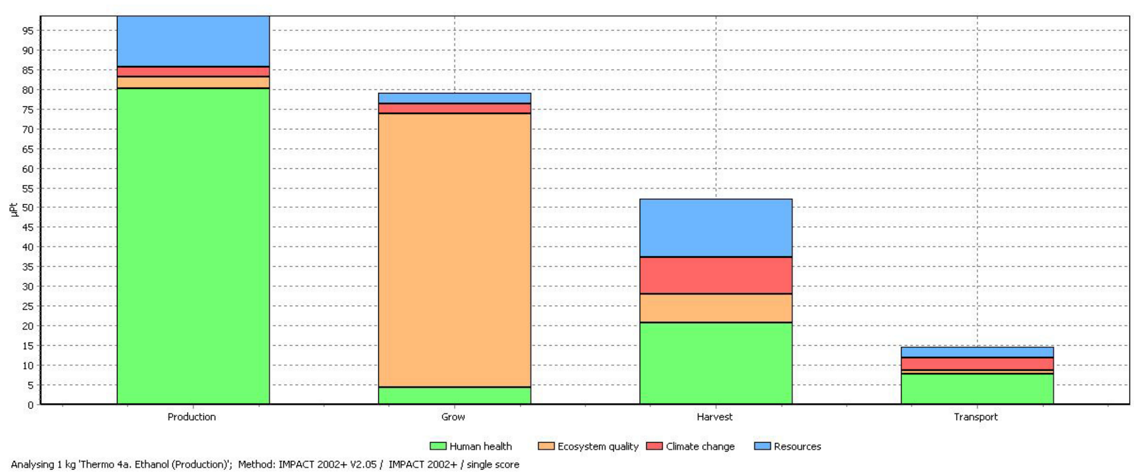


**Figure 10. Thermochemical process single-score contributions / 1 kg ethanol (Impact 2002+)**

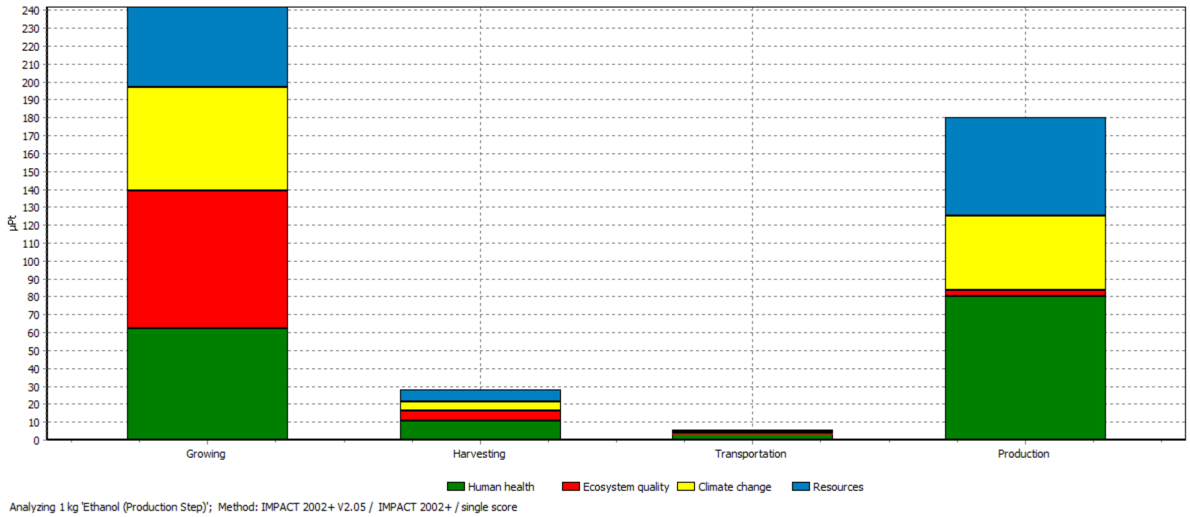


**Figure 11. Biochemical process single-score contributions / 1 kg ethanol (Impact 2002+)-endpoint**

A substance contribution analysis was conducted by looking at the endpoints. In both cases, it was concluded that human health impacts arise mostly from nitrogen dioxide. $NO_2$ is generated primarily in the production process and also from the burning of fuel during the transportation stage. It can be seen that for both processes, fossil $CO_2$ emissions make up the largest part of the climate change category. This is due to the quantities of fossil fuels used for harvesting, transportation, and cultivation.

For each life-cycle stage, it is useful to know its contribution to the impact categories. In this section, the impact damages at both the midpoint and the endpoints are shown, and the significance of the contributions of each life-cycle stage is explored to determine the reasons for hotspots. Normalized midpoint values for both processes show that among all the midpoint impact categories, respiratory inorganics, land occupation, nonrenewable energy, and global warming make the largest overall contributions to potential environmental impact (Figures 12–13).

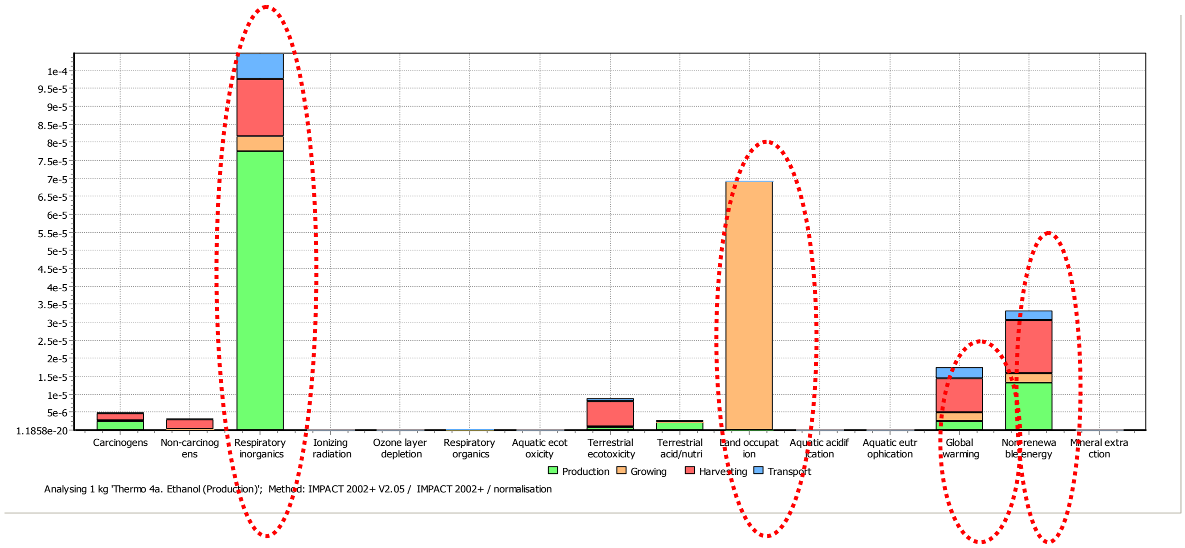


**Figure 12. Thermochemical process category midpoint stage contributions (normalized) / 1 kg ethanol (Impact 2002+)**

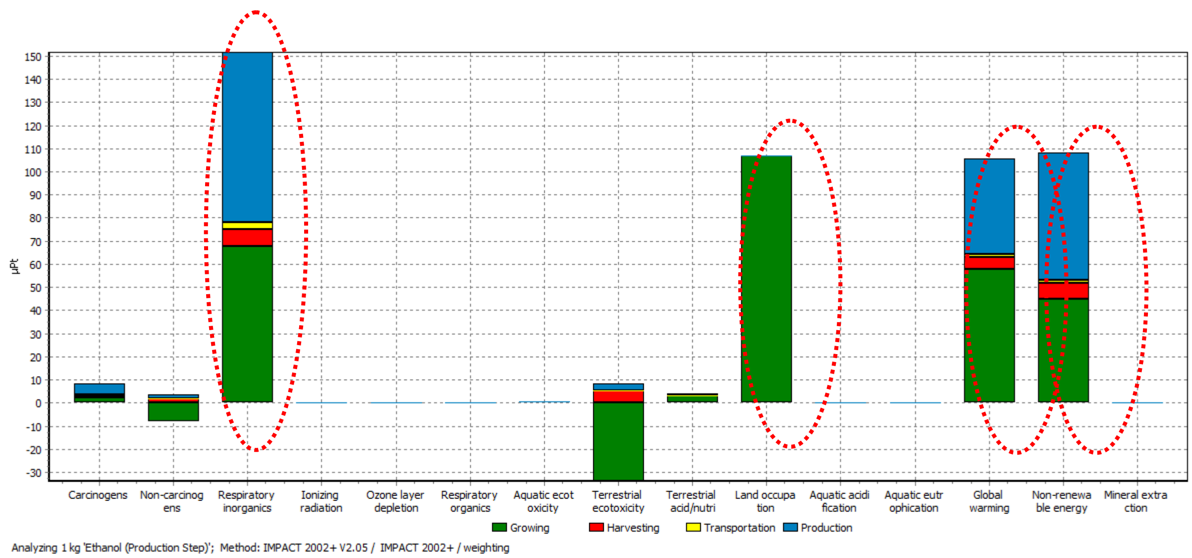


**Figure 13. Biochemical process category midpoint stage contributions (normalized) / 1 kg ethanol (Impact 2002+)**

As can be seen in Figure 12 for respiratory inorganics (which cause human health impacts), this impact is dominated by the production stage, which in turn is a result of the amount of $NO_2$ and $SO_2$ emitted to the atmosphere. Land occupation (which causes ecosystem quality impacts) results almost entirely from the growing stage and is due to the amount of land required for growing biomass. For nonrenewable energy (which causes resources impacts), the impacts are caused primarily by production and harvesting and are due to fossil-fuel consumption: use of gasoline as a denaturant during production and diesel consumption during harvesting. The majority of the global warming impact comes from the harvesting stage.

### 7.4.1. Sensitivity analysis of allocation

There are several uncertainties based on the assumptions that were made that may affect the results. To assess how much the results might possibly change based on the assumptions that were made, a sensitivity analysis was undertaken. One of the most important assumptions, to which most projects are sensitive, is related to the method of allocation. This section therefore tests the sensitivity of the final results to the allocation methods used in both feedstock and product stages. For all the parameters tested, the output was taken to be the normalized endpoint impacts, and the impacts were compared between the scenarios and also against the base case of the competing process (thermochemical or biochemical) to see how the overall results were affected.

To test the sensitivity of forest-residues allocation (vs. roundwood), the allocation was not changed directly; instead, the amount of forest-residues impact was increased and reduced to see what overall impact this would have on the comparison. Allocation had already been performed on the collected data for forest residues, and no data were available on the split used, only that it was economic. This was acceptable for the base case because it was decided that economic allocation was the most meaningful allocation method to use. To perform a sensitivity test, the impacts were therefore tested at levels of plus or minus 20% of the total impacts of the growing stage, and then the sensitivity of the overall process was measured.

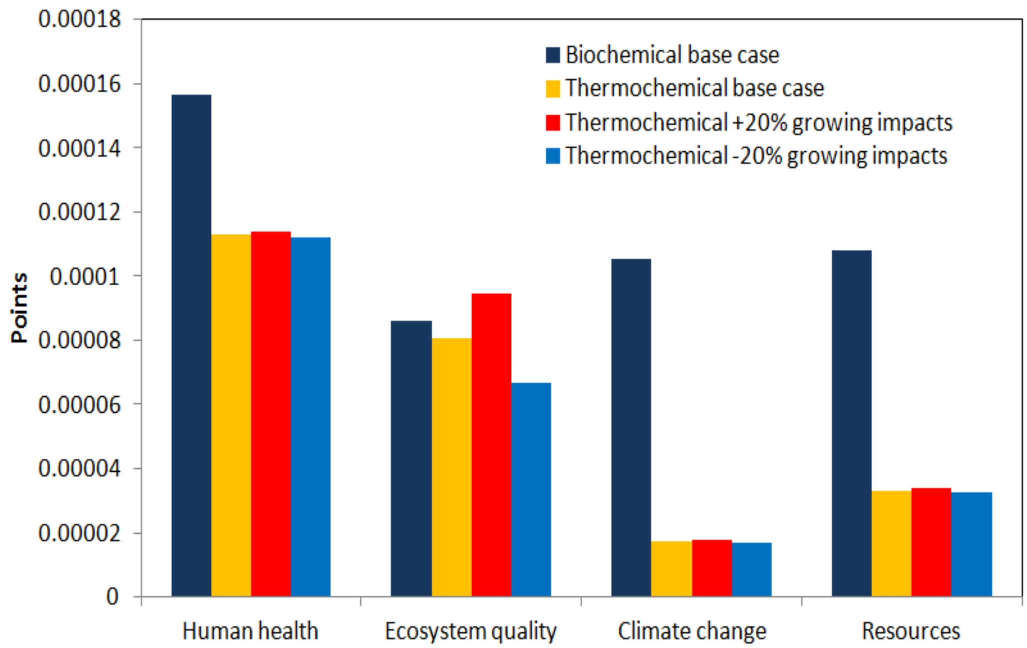


**Figure 14. Thermochemical growing-stage allocation sensitivity.**

Figure 14 shows that changing the allocation of the growing-stage products (roundwood and forest residues) would significantly affect only the ecosystem quality endpoint. This could potentially give a result where the biochemical process would be superior to the thermochemical process in this category, which means that in this case, it would be less clear which process has lower environmental impacts on ecosystem quality.

In the thermochemical process, mass allocation was selected for products in the base case. An economic allocation might have been more appropriate, but was not used in the base case due to gross uncertainties in the economic assumptions. The economic allocation was used as a comparison to reveal any differences. Furthermore, an allocation was performed using the energy content of the two products.

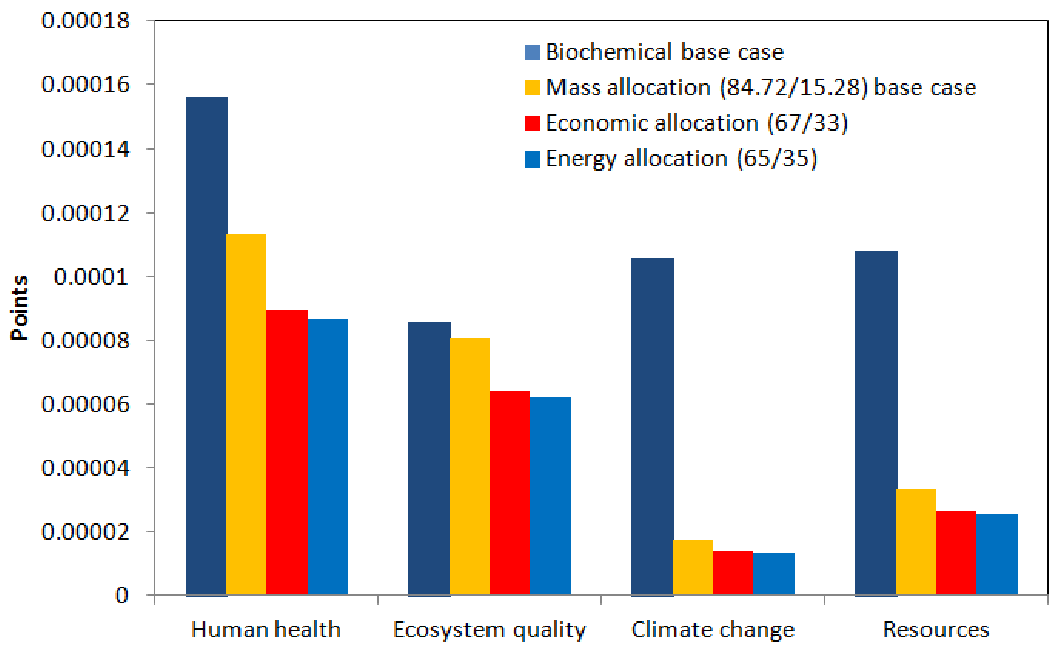


**Figure 15. Thermochemical production-stage allocation sensitivity**

Figure 15 shows that climate change was not affected strongly by the change in allocation. Because both allocation scenarios allocate relatively few impacts to the product, as expected, these reduce the impact in the other three categories. Resource use is not significantly affected; however, human health is affected very significantly, as is ecosystem quality. Although this does not change the results, it shows that the nonselective nature of mixed-alcohol synthesis may not necessarily prove to be a significant environmental problem.

In the biochemical case, two allocations were undertaken, one in the production stage for allocating impacts to the main product and byproduct, and another in the feedstock stage for allocating growth impacts to corn and corn stover. The economic allocation was used in the base case, which led to allocating 46% of impacts to corn stover and 54% to corn. To check the sensitivity of the biochemical case to the allocation strategy, two runs were done in which a mass allocation (corn:corn stover = 50:50) and an energy allocation (corn:corn stover = 46:54) were used. Because corn stover is a byproduct of the corn plant, it can be assumed that all the impacts of the growing stage can be allocated to corn, which is the main product of the cropland. Therefore, one of the cases that were studied is allocating 100% of impacts to the corn produced. The results obtained for all the sensitivity-analysis case studies mentioned are shown in Figure 16.

Because the allocation percentages in all the allocation strategies (economic, mass, and energy allocations) are similar, there is no significant difference among the results obtained. Figure 16 shows that the thermochemical process shows better environmental performance than the biochemical process when using the economic, mass, and energy allocations. However, in the case in which all the impacts were allocated to corn, a significant change was seen. In this case, for human health and ecosystem quality, the biochemical pathway will have a lower impact than the thermochemical process. Therefore, it can be concluded that the results are sensitive to allocation procedure.

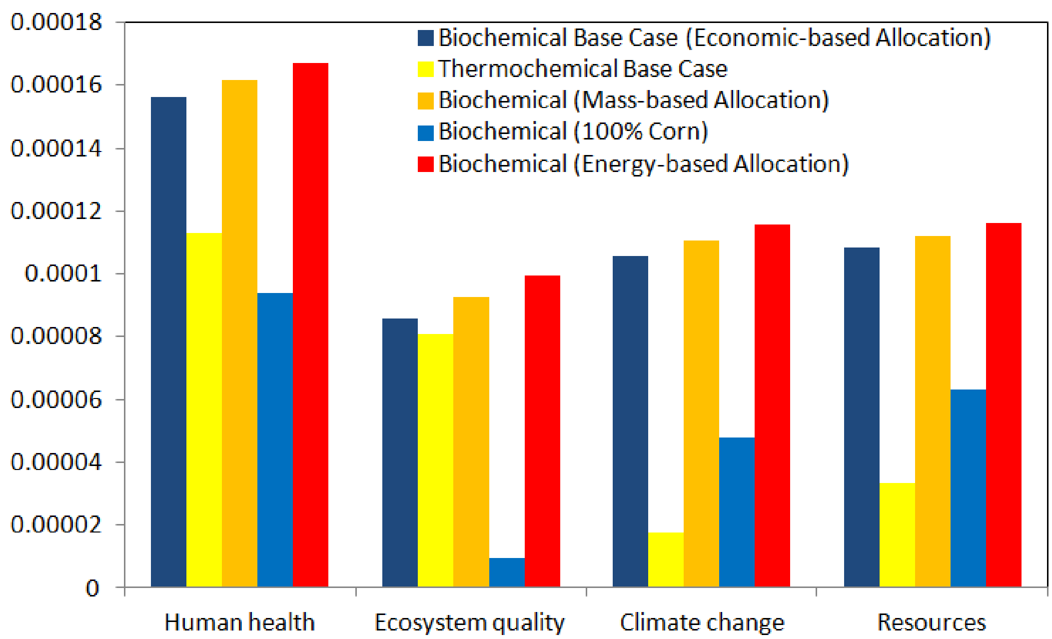


**Figure 16. Sensitivity analysis of growing-stage product allocation in the biochemical project**

Another parameter which can affect the results is the allocation of impacts to the final products. In the biochemical process, there are two products, ethanol as the main product, and electricity as the byproduct. In the base case, economic allocation was used to allocate the environmental impacts to these two products. The other allocation option that can be used is energy-based allocation. In addition, because the amount of produced electricity is not significant compared to the main product, another option could be to consider electricity as an avoided burden (a method which subtracts surplus function results in a monofunctional system). The results obtained for these scenarios are presented in Figure 17. This figure shows that in all these cases, the thermochemical process shows better environmental performance than the biochemical process.

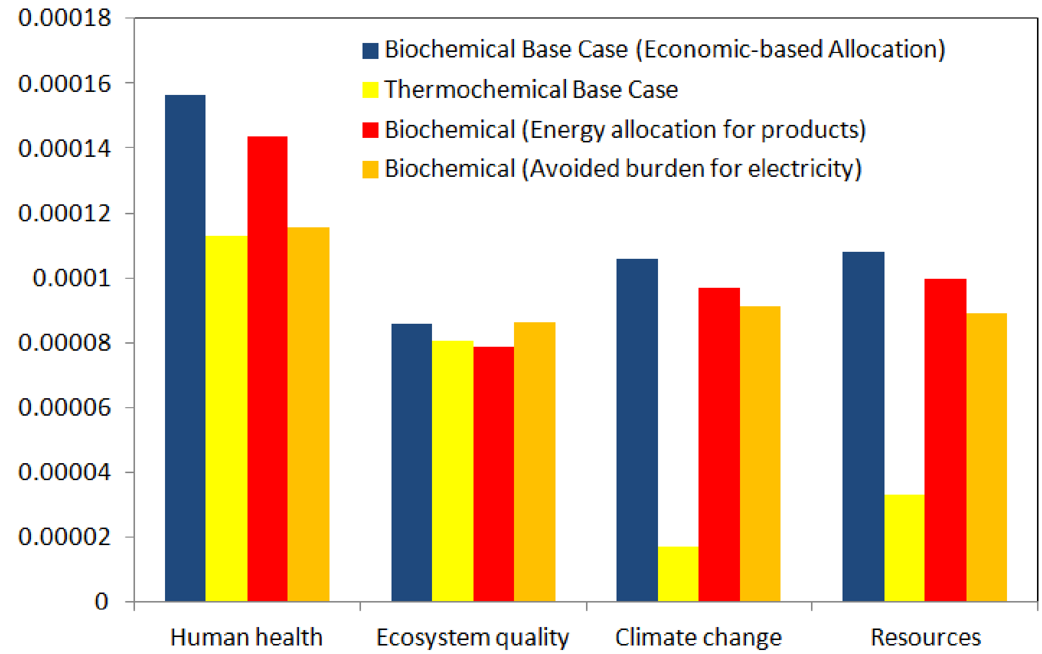


**Figure 17. Sensitivity analysis of impact allocation in the production stage of the biochemical project**

Based on the results presented in Figures 14–17, it can be concluded that both thermochemical and biochemical case studies are sensitive to allocation method in the feedstock stage; however, they are not sensitive to the chosen allocation method in the product stage.

### 7.5. Limitations of this study

The results of this study are considered to be very preliminary and are therefore quite general and contain a significant margin of error. In general, the data quality is rather poor because the data are not based on a specific site or even an existing process. Therefore, assumptions were made and proxies used, which limit the accuracy of the study. Some of the assumptions used had the potential to affect the outcome of the study and the extent of their effects has been investigated by carrying out sensitivity analyses. In general, allocation of impacts to feedstocks was found to be the most sensitive, although not in all impact categories. Different methods of dealing with multifunctional systems should be tried in the future, including a wider variety of allocation models and expanding the system and its functions. The most widely used methodology for allocation is system expansion, after which economic allocation is the second most widely used procedure [26]. Many of the data used were based on a European database, which could limit the applicability of this work. The most highly limiting part of the methodology, however, would be the European impact assessment method, Impact 2002+, as well as the normalization step because it is based solely on European emissions.

**8. Role of LCA in Multi-criteria Decision Making (MCDM)**

As mentioned earlier, although several possible biorefinery strategies exist, only those that at the same time can create more profit, have lower environmental impacts, and provide more social benefits in the context of a long-term vision can be considered as promising to implement in the future. This developing industry is at an early stage in which, instead of selecting the most sustainable strategies, less promising options should be screened out before any detailed engineering analysis which requires significant amounts of time and money. This goal will be achieved not only by considering environmental criteria, but also by interpreting the results of LCA-based environmental evaluation in conjunction with technical, economic, and social criteria using multi-criteria decision making (MCDM) methods. MCDM methods inform decision maker(s) about problem complexity and at the same time address decision uncertainty.

Cohen et al. [30] have recently defined a set of multidisciplinary criteria (including an environmental criterion) and have established an MCDM panel in which biorefinery experts were asked to elicit the importance of the defined criteria to be used to assess possible biorefinery technologies for the production of bioethanol that could be implemented at pulp and paper mills. The results of this study show that compared to the defined criteria, the environmental criterion achieved the lowest level of consensus among the panel members and finally obtained a low weight, i.e., a low importance. A similar study was carried out by Quintero-Bermúdez et al. [31] with different panel members. The result for the environmental criterion was almost identical. The lower weight obtained for the environmental criterion compared to the other defined criteria can be attributed to the similarity of the environmental performance of all selected bioethanol production technologies compared to the corn-to-ethanol routes. It has been suggested by Quintero-Bermúdez et al. [31] that comparing biorefinery technologies with similar fossil-route counterparts would provide a better representation of the environmental advantages of biorefinery strategies. In addition, the low level of consensus on this criterion among panel members in both MCDM panels can be attributed to the perceived necessity of defining the environmental criterion as a “show-stopper” for screening biorefinery strategies in future studies, which would change its relative importance.

## 9. Conclusions

Biorefinery strategies are a set of potential solutions for the environmental concerns that the world faces today, including climate change and energy supply. However, among all possible biorefinery options, only those strategies that are sustainable and that can create more profit and achieve lower environmental impact and more social benefits in the long term can be considered promising for the future. Life-cycle assessment (LCA) has been introduced as a methodology by which the environmental performance of biorefinery strategies can be assessed. To illustrate the application of the LCA methodology in the biorefinery context, an example was presented comparing two processes for bioethanol production (bioethanol production from forest residues through a thermochemical process, and bioethanol production from corn stover through a biochemical process). The results show that in both processes, four impacts are dominant: global warming, land occupation, nonrenewable energy, and respiratory inorganics. This result is consistent with available studies in the literature which claim that GHG emissions, NRE, and land use are the most important environmental concerns for biorefinery systems. In addition, the results showed that the thermochemical process using forest residues as a feedstock is more environmentally favorable than the biochemical process using corn-stover feedstock. However, it should be remembered that these results are fairly uncertain, with many errors introduced because of low data quality, regional differences in the data used and their assessment, and assumptions made because of missing data. Therefore, the results of this example can be considered suitable only for early-stage assessment or for confirming the outcomes of similar studies [32,33].

To judge the sustainability of biorefinery strategies, the results of an LCA-based environmental evaluation should be interpreted in conjunction with technical, economic, and social criteria using multi-criteria decision making (MCDM). The available results from MCDM panels convened to select promising biorefinery strategies show the lowest level of consensus for the environmental criterion among the panel members, which indirectly shows the necessity of defining the environmental criterion as a “show-stopper” for screening biorefinery strategies in future studies.

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