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# Tactical planning models for combined biofuel and bioenergy production

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Spécialité : *Automatique, productique et robotique*

Par

**Sobhan RAZM**

**Modèles de planification tactique pour la production combinée de  
biocarburants et de bioénergies**

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# RÉSUMÉ EN FRANÇAIS

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La gestion de la chaîne d'approvisionnement peut jouer un rôle clé en garantissant que la chaîne d'approvisionnement est compétitive en termes de coûts. Cependant, certaines caractéristiques des produits de la chaîne d'approvisionnement compliquent la planification de la chaîne d'approvisionnement. Par conséquent, il y a un besoin, ici, de modèles d'aide à la décision qui peuvent résoudre des problèmes complexes et améliorer le processus de prise de décision. La planification de la chaîne d'approvisionnement peut être effectuée aux niveaux stratégique, tactique et opérationnel. Dans les plans stratégiques, nous recherchons le nombre, l'emplacement et la capacité des installations de production et de stockage. Il comprend un horizon de planification à long terme (généralement plus d'un an). Cependant, dans les plans tactiques et opérationnels, nous recherchons une utilisation efficace des ressources et un flux de matériel à travers la chaîne d'approvisionnement. L'horizon de planification est généralement inférieur à la planification stratégique. Même cela peut être saisonnier, mensuel ou quotidien (Awudu and Zhang [2012], De Meyer et al. [2014], Yue et al. [2014]).

Dans cette étude, l'objectif est de gérer une chaîne d'approvisionnement en bioénergie à l'aide de la recherche opérationnelle (RO). En d'autres termes, la conception et la planification de la chaîne d'approvisionnement de la biomasse à la bioénergie impliquent un grand nombre de décisions. Les décisions sont liées aux différentes opérations tout au long de la chaîne d'approvisionnement. Par exemple, la culture et la récolte de la biomasse, le transport de la biomasse, la conversion de la biomasse en bioénergie/biocarburant, le transport des biocarburants, la transmission de la bioénergie et la distribution aux marchés finaux. La conception, la mise en œuvre et la gestion de cette chaîne d'approvisionnement sont un processus complexe. Toutes les activités de la chaîne d'approvisionnement de la biomasse à la bioénergie doivent être conçues d'une manière spécifique qui garantit l'efficacité des flux matériels, d'informations et financiers dans les réseaux (Eksioglu et al., 2015). Une gestion et une planification efficaces de la bioraffinerie ont un impact important sur la réduction des coûts de production et font de la biomasse une source d'énergie précieuse. La recherche opérationnelle et la modélisation mathématique peuvent nous aider à accomplir cette mission.

Habituellement, il y a trois segments dans les systèmes de production de bioénergie, en aval, au milieu et en amont. Dans chaque segment, il y a plusieurs entités. Les entités en aval font référence aux processus de post-conversion tels que le stockage, le mélange et la distribution des produits finaux. Le secteur intermédiaire fait référence aux installations de conversion où la biomasse est convertie en bioénergie et en d'autres produits grâce à différentes technologies. Les entités en amont désignent l'approvisionnement en biomasse, depuis la production de biomasse jusqu'à la livraison aux installations de conversion. Cela nécessite une bonne coopération entre les entités d'approvisionnement.

Ces entités comprennent la zone de demande, les centres de distribution, les sites de mélange, les sites de prétraitement, les technologies de conversion, les sites de stockage, les centres de collecte, les sites de biomasse. La figure 1.1 montre la structure générale et les activités des chaînes d'approvisionnement bioénergétiques. Il commence par récolter la biomasse cultivée sur les sites de biomasse, puis l'envoie vers des sites intermédiaires ou des centres de collecte, après cela, des sites de prétraitement. Ensuite, la biomasse est acheminée vers des bioraffineries. Dans les bioraffineries, la biomasse est convertie en bioénergie, biocarburant et sous-produits. Il existe trois catégories principales de technologies, thermochimiques, biochimiques et chimiques. Les produits finaux pourraient être l'énergie (électricité), la chaleur, les produits biochimiques, les biocarburants (par exemple, le bioéthanol et le biodiesel). Ensuite, les produits finaux sont livrés aux centres de distribution et aux clients. Notez que certaines études ont envisagé de combiner certaines entités entre elles, par exemple, elles envisagent des installations de mélange à l'intérieur des bioraffineries.

En outre, les principales activités des chaînes d'approvisionnement bioénergétiques sont la culture de la biomasse, la récolte et la collecte de la biomasse, le prétraitement, le stockage, le transport, le mélange et la distribution de la biomasse. Ces activités logistiques peuvent être compliquées et coûteuses lorsqu'elles sont confrontées à certains défis tels que la faible teneur énergétique de la biomasse, la répartition géographique dispersée, la nature saisonnière, la faible densité en vrac, ainsi que les incertitudes variables dans les chaînes d'approvisionnement.

Dans la chaîne d'approvisionnement de la bioénergie, il existe des installations qui peuvent convertir la matière première (biomasse) en différents produits : i) la bioénergie comme la chaleur et l'électricité ; ii) les biocarburants tels que le bioéthanol et le biodiesel ; et iii) les produits biosourcés tels que les plastiques, les produits chimiques. Il existe trois catégories principales pour ces installations, thermochimiques, chimiques, biochimiques.

(Demirbaş [2001], Frombo et al. [2009]). Les produits générés sont envoyés aux clients via le réseau, le réseau ou les canaux de distributeurs, grossistes et détaillants (Yue et al. [2014]). La figure 1.2 montre différents types d'installations (technologies) pouvant être utilisées dans les bioraffineries (Adams et al. [2018], Fiorentino et al. [2017], McKendry [2002b,a], Naik et al. [2010], Patel et al. [2016], Patel et al. [2016]).

Le développement durable vise à assurer deux éléments principaux. Premièrement, il est nécessaire que les humains soient en mesure de satisfaire leurs besoins fondamentaux ainsi que de soutenir un développement continu. Les ressources matérielles, humaines, écologiques et sociales sont suffisamment nécessaires pour atteindre cet objectif. L'existence de ce recours doit être garantie par le développement durable. Deuxièmement, la génération future et la génération actuelle doivent avoir un accès égal à ces ressources.

Les ressources matérielles sont constituées de ressources non renouvelables. Les ressources humaines font référence à la santé, à la liberté, au savoir, aux droits de l'homme et à la possibilité d'appliquer le savoir. Les ressources écologiques comprennent les ressources renouvelables (par exemple, le bois ou la nourriture) et les services (par exemple, la protection contre le rayonnement solaire ultraviolet) que des écosystèmes naturels sains peuvent fournir. Les ressources sociales font référence à la confiance, aux normes de réciprocité, à l'équité et à d'autres conditions qui facilitent la coordination et la coopération des avantages mutuels (Rodriguez et al. [2002], Gray [2010]).

Les activités humaines ont causé des problèmes environnementaux, ce qui motive les scientifiques à accorder plus d'attention au développement durable. De nos jours, les problèmes environnementaux ne sont pas seulement des problèmes locaux mais aussi des problèmes nationaux. L'interdépendance des effets environnementaux avec des questions macro telles que la politique, le développement, la société, l'économie et la culture amènent les problèmes environnementaux à être considérés à une plus grande échelle, et considérés comme un enjeu mondial. Par conséquent, les problèmes environnementaux massifs peuvent être classés dans les catégories suivantes : réchauffement climatique (effets de serre), pénurie d'eau douce, pluies acides et pollution de l'air, appauvrissement de la couche d'ozone, destruction de la biodiversité, élimination des déchets toxiques et perte de sols fertiles.

Un être humain en bonne santé est une condition préalable à une société dynamique et saine ainsi qu'un élément vital du développement durable. Néanmoins, de nombreuses personnes ne sont pas en mesure de payer les services de santé de base, ce qui met en péril la santé humaine et les processus de développement. En outre, le chômage, la pauvreté, ainsi que l'inégalité des chances de travailler en fonction du sexe, de l'âge et de la situation

géographique sont d'autres préoccupations sociales essentielles.

Par conséquent, ces préoccupations sociales et environnementales ont reçu plus d'attention et ont conduit à des sommets internationaux. Enfin, ils ont introduit le paradigme du "développement durable". Il existe quelques définitions du développement durable. La Commission mondiale sur l'environnement et le développement (CMED) a formulé une définition du développement durable qui a été largement acceptée. La commission a défini le développement durable (dans le rapport publié) (Imperatives [1987]) comme "un développement qui répond aux besoins du présent sans compromettre la capacité des générations futures à répondre aux leurs". Selon la définition, les objectifs d'un développement durable doivent être fixés sur la base de décisions sociales, environnementales et économiques qui sont également appelées piliers de la durabilité. La figure 1.3 montre ces trois piliers en fournissant :

L'intégration de trois aspects durables doit être assurée dans le réseau de la chaîne d'approvisionnement et ne pas être limitée à une entreprise et à une entreprise. La bioénergie peut être utilisée comme une alternative durable aux combustibles fossiles. Afin d'assurer cette alternative, les aspects sociaux, environnementaux et économiques des chaînes d'approvisionnement en bioénergie doivent être intégrés dans la conception et la planification des secteurs de la bioénergie. Ces dernières années, la durabilité a attiré davantage l'attention dans la littérature relative aux chaînes d'approvisionnement en bioénergie.

L'augmentation des émissions de gaz à effet de serre (GES) a entraîné une augmentation anormale de la température terrestre, des changements climatiques et, par la suite, une augmentation des catastrophes naturelles. Les photographies envoyées par les satellites de mesure des émissions ont montré une augmentation des émissions de gaz à effet de serre et ont suscité de vives inquiétudes. Elle a amené les représentants de plus de 100 pays participant à la Conférence des Nations Unies sur les changements climatiques de 2015 à Paris à signer l'Accord de Paris dans le but de réduire ces émissions. Les préoccupations étaient liées à la demande énergétique et aux problèmes environnementaux, économiques et sociaux générés par l'utilisation des combustibles fossiles. Ces enjeux ont conduit les chercheurs à s'interroger sur les sources d'énergie renouvelables, qui peuvent conduire au développement régional, et protéger l'environnement tout en répondant à la demande énergétique. Les énergies renouvelables - la bioénergie (chaleur et électricité) et les biocarburants (bioéthanol, bio-huile, biodiesel, granulés) - peuvent être obtenues grâce à la biomasse. La bioénergie et les biocarburants peuvent être utilisés comme substituts aux combustibles fossiles. Ils peuvent réduire les émissions de gaz à effet de serre (GES), et créer de nouveaux emplois

et plus de vitalité dans les régions considérées (d'Amore and Bezzo [2016], Shavazipour et al. [2020]).

Une source de biomasse est constituée par les matières premières provenant des résidus agricoles et forestiers. Par exemple, les résidus forestiers pourraient être : a) des copeaux, de la sciure, du bois de chauffage, des copeaux (issus des scieries) ; b) branches, feuilles, cimes d'arbres, tiges non marchandes issues d'exploitations forestières (Razm et al. [2019b]). Les résidus agricoles pourraient être de la paille de blé, de la bagasse de canne à sucre, des tiges de maïs, etc., qui ne sont pas utilisés comme nourriture et proviennent des déchets agricoles (Razm et al. [2019a], Yue et al. [2014]). La bioénergie, le biocarburant et d'autres produits biosourcés (produits chimiques, plastiques, etc.) peuvent être générés par trois processus de conversion de base, processus biochimique, chimique et thermochimique (Demirbas et al. [2009], McKendry [2002b], Campbell [2007]). Deux d'entre eux peuvent être utilisés pour la biomasse forestière et agricole pour générer de la bioénergie et du biocarburant : i) thermochimique (combustion, pyrolyse et gazéification), ii) et biochimique (production d'éthanol par hydrolyse et fermentation) (McKendry [2002b], cite mckendry<sub>energy</sub>2002).

Afin de convertir de manière optimale la biomasse en bioénergie, il est nécessaire de concevoir une chaîne d'approvisionnement optimale pour cela. Ces dernières années, l'importance de la conception, de la mise en œuvre et de la gestion de la bioénergie SC a augmenté. L'obstacle le plus important au développement d'une filière bioénergétique est le coût du réseau d'approvisionnement. Par exemple, des coûts élevés pourraient être encourus en fournissant de la biomasse à la bioraffinerie en raison des implications économiques et environnementales de la collecte et du transport de la matière première de biomasse à partir du site d'approvisionnement en biomasse. La conception de la chaîne d'approvisionnement est fondamentale en termes de réduction des coûts et des émissions de GES (dues par exemple au transport). De plus, l'emplacement de la bioraffinerie est important, car il peut générer de nouveaux emplois et un développement durable dans la zone considérée (You et al. [2012]).

Dans la littérature, il existe différentes politiques et réglementations liées à la bioénergie. En outre, il existe différents noms/catégories pour différents types de biomasse qui ont des liens avec les politiques. Une catégorie pour la biomasse est constituée de matières premières comestibles, telles que le soja, les graines de colza, la canne à sucre, les grains de maïs/maïs, les graisses animales, qui peuvent être converties en biocarburants (première génération) par des processus tels que la transestérification (production de biodiesel) et la fermentation (production de bioéthanol) (Sharma et al. [2013b]). Une autre catégorie est

constituée de matières premières non comestibles (biomasse lignocellulosique) qui peuvent être classées dans les résidus agricoles tels que la paille de blé, les tiges de maïs, la bagasse, la paille de riz ; et les résidus forestiers tels que les cimes d'arbres, les copeaux de bois, les branches, les déchets de bois, la sciure de bois et l'écorce. Les processus thermo-chimiques (pyrolyse, combustion et gazéification) et biochimiques (fermentation et hydrolyse) peuvent convertir la biomasse lignocellulosique en bioénergies et biocarburants (seconde génération) (Mahjoub et al. [2020], Razm et al. [2019b]). Cette seconde catégorie est également nommée bioénergie/biocarburant avancé ([www.etipbioenergy.eu](http://www.etipbioenergy.eu)).

L'importance du changement climatique et de la sécurité de l'approvisionnement énergétique a conduit à une série de politiques réglementaires dans les pays industrialisés. Dans l'Union européenne (UE), l'orientation de la réglementation énergétique montre l'importance de la question. Par exemple, la directive européenne 2009/28/CE (directive sur les énergies renouvelables-RED) est au cœur de la réglementation européenne sur les biocarburants. Il a introduit une part obligatoire de 10

En s'orientant vers le développement de l'énergie de l'UE pour l'avenir, l'UE a défini ses objectifs à moyen et à long terme (Mandley et al. [2020]). Les objectifs à moyen terme : i) l'amélioration de l'efficacité de la consommation d'énergie d'au moins 32,5 %, ii) des réductions d'au moins 40 % des émissions de GES par rapport aux niveaux de 1990 (l'année de base pour les émissions également utilisée dans la CCNUCC et le Protocole de Kyoto), sont envisagées pour la période 2021-2030 ([www.ec.europa.eu](http://www.ec.europa.eu)). L'objectif à long terme, maintenir l'augmentation de la température mondiale entre 1,5 et 2 °C est envisagé d'ici 2050 ([www.ec.europa.eu/2050](http://www.ec.europa.eu/2050)). Cet objectif à long terme est également conforme à l'objectif de l'accord de Paris ([www.ec.europa.eu/clean-energy-all-europeans](http://www.ec.europa.eu/clean-energy-all-europeans)). La réglementation sur les biocarburants a été introduite pour la première fois dans l'UE en 1997 pour aider le développement de l'industrie des biocarburants (Prussi et al. [2019]). En 2009, le Parlement européen et le Conseil visaient une limite de 10 % pour les biocarburants de première génération (les biocarburants à base de cultures) d'ici 2020 dans la directive sur les énergies renouvelables (RED) (directive 2009/28/CE du 23 avril). En septembre 2013, la limite de 10% a été ramenée à 6%, et le Parlement européen et le Conseil ont également imposé un objectif de 2,5% pour les biocarburants avancés (constitués de matières non comestibles) d'ici 2020 (directive 98/70/CE).

Néanmoins, en juin 2014, un nouvel accord proposé par les ministres de l'énergie de l'Union européenne était tout autre. Il a suggéré qu'il n'y a pas besoin d'un objectif obligatoire pour les biocarburants avancés, et a suggéré que la limite de 6 % doit passer à 7

% pour les biocarburants à base de cultures (Doumax-Tagliavini and Sarasa [2018]). En 2016 (automne), la directive sur les énergies renouvelables de 2009 a été révisée par la commission de l'Union européenne afin de fixer les nouveaux objectifs pour les carburants de transport renouvelables, les énergies renouvelables et l'efficacité énergétique pour la période de 2021 à 2030. Ces révisions avaient deux objectifs : i) en utilisant un mandat contraignant pour stimuler les biocarburants avancés, ii) en envisageant un plafond pour l'utilisation des biocarburants d'origine végétale, un taux d'incorporation de 3,8% dans le transport routier. Ce groupe de suggestions est connu sous le nom de RED II ou directive de l'Union européenne sur les énergies renouvelables post-2020. Cependant, la nouvelle orientation (RED II) prise par la Commission de l'Union européenne a impliqué un ralentissement considérable de l'utilisation des biocarburants dans certains États. Ensuite, en janvier 2018, certaines de ces propositions ont été amendées par des députés européens (Union [2009]). Par conséquent, d'ici 2021, un mandat contraignant de 1,5 % est envisagé pour les biocarburants avancés, puis il pourrait passer à 10 % d'ici 2030. Les biocarburants à base de cultures sont fixés dans un plafond de 7 % d'ici 2030.

Il convient de mentionner que dans la directive sur les énergies renouvelables (2009), il n'y avait aucun objectif obligatoire pour les biocarburants avancés. Les gouvernements auraient seulement encouragé la production des biocarburants avancés, et envisagé l'incorporation de 0,5% de rete (les biocarburants avancés) dans le transport routier. Les craintes liées à l'industrie des biocarburants de l'Union européenne et à sa rentabilité à long terme avaient conduit à de telles ambitions moindres. Cependant, une croissance des biocarburants avancés et non des cultures comestibles est un message clair des récentes négociations à l'industrie des biocarburants de l'Europe Union. La figure 1.4 résume les politiques et réglementations les plus courantes liées aux chaînes d'approvisionnement en bioénergie.

Toute matière biologique vivante ou récemment vivante générée sur notre planète par le processus de la photosynthèse peut être considérée comme de la biomasse (Allen et al. [1998]). Notez qu'il peut entrer dans certains cycles (par exemple, d'abord comme nourriture, puis il se convertit en biomasse). Comme le montre la figure 1.4, la biomasse peut inclure une grande variété de sources telles que les sources agricoles et forestières, les déchets biodégradables industriels et municipaux et les excréments d'animaux (An et al. [2011]).

Bien que la culture/collecte, le transport et la conversion de la biomasse conduisent à la pollution de l'air (Hall and Scrase [1998]), il existe un potentiel important d'économie d'émissions de gaz à effet de serre (GES) lorsque la bioénergie générée est remplacée par des combustibles fossiles (même négative émissions) (Ahtikoski et al. [2008]). Selon l'Agence

internationale de l'énergie, la transformation de la biomasse en biocarburant de manière appropriée et durable peut conduire à neutraliser la production de carbone. Le cycle de vie du biocarburant est illustré à la figure ??, la quantité de CO<sub>2</sub> générée par la consommation de biomasse est égale à la quantité de CO<sub>2</sub> extraite de l'atmosphère par la plante pendant la phase de croissance (Saidur et al. [2011]) .

Comparée à d'autres sources renouvelables telles que le solaire ou l'éolien, la biomasse est une source d'énergie flexible pour produire de la chaleur, de l'électricité, des biocarburants et de la bioénergie, car elle peut être stockée et utilisée à la demande (Demirbaş [2001]).

Comme mentionné, une grande variété de matériaux peuvent être considérés comme de la biomasse pour générer de la bioénergie et du biocarburant. Par exemple, premièrement, les résidus forestiers : a) branches, feuilles, cimes d'arbres, tiges non commercialisables provenant des opérations forestières ; b) déchets de scierie : copeaux, sciure de bois, copeaux de bois (Cambero et al. [2015]). Deuxièmement, les résidus agricoles : paille de blé, bagasse de canne à sucre, tiges de maïs, etc., qui ne sont pas utilisés comme nourriture et proviennent des déchets issus de l'agriculture (Yue et al. [2014]). Troisièmement, les cultures énergétiques comme le panic raide, le jatropha (Osmani and Zhang [2013]). Quatrièmement, différents types d'algues (Mohseni et al. [2016]).

Les biomasses mentionnées ci-dessus sont plus connues et courantes dans la littérature, bien qu'il existe plus de types de biomasse. La figure 1.5 montre les différents types de biomasse.

La littérature a également nommé différentes générations pour la bioénergie en fonction de la biomasse consommée. Dans cette section, les avantages et les inconvénients de chaque génération sont examinés sous trois rubriques : a) besoins en eau, en terres et en éléments nutritifs, b) concurrence avec la production alimentaire et c) coût de production et commercialisation. Ce sont des questions importantes dans les systèmes de production de bioénergie, en particulier dans la production à grande échelle.

La première génération de bioénergies provient de cultures vivrières qui nécessitent une grande quantité d'eau et de terres agricoles et d'autres intrants. Les cultures énergétiques ont besoin de moins d'eau, de terres et d'engrais que les cultures vivrières. La raison en est que les cultures énergétiques ont le potentiel de pousser sur des terres marginales, une meilleure efficacité d'utilisation de l'eau et une plus grande tolérance à la privation de nutriments (Mehmood et al. [2017]). Notez que les cultures énergétiques ont besoin de moins d'engrais, de la qualité du sol et de la disponibilité de l'eau. S'ils sont cultivés sur

des terres arables, leur productivité peut s'améliorer considérablement avec suffisamment d'eau et d'engrais (Heaton et al. [2004], Smith and Slater [2010]).

Par rapport aux cultures énergétiques et aux cultures vivrières qui sont cultivées sur des terres marginales ou arables, les résidus de cultures n'ont pas besoin de terres supplémentaires, ils ne sont pas en concurrence pour les terres, de sorte que les changements d'utilisation des terres ne se produisent pas (Carriquiry et al. [2011]). Néanmoins, l'élimination excessive des résidus a des effets négatifs tels que la fluctuation de l'érosion des sols et le changement climatique mondial, la dégradation du réservoir de carbone organique du sol, la réduction de la qualité du sol (Lal [2005]). Les microalgues sont un autre type de biomasse qui nécessite moins de terres pour la culture. Cependant, l'utilisation du cycle de vie de l'eau, du phosphate et de l'azote est élevée (Yang et al. [2011]).

La première génération de bionergie est directement produite à partir de cultures vivrières. Une grande production de cultures vivrières à utiliser comme biomasse entraîne le détournement de grandes quantités de cultures des marchés alimentaires vers le marché de la bioénergie, ce qui entraîne une réduction de la sécurité alimentaire et une augmentation des prix des denrées alimentaires (Rulli et al. [2016]).

La deuxième génération de bioénergie provient de matières premières non alimentaires (par exemple, les résidus organiques et les cultures énergétiques). Cependant, ils n'ont pas pu résoudre entièrement le conflit entre la nourriture et le carburant. Dans la production à grande échelle de cultures énergétiques, la demande supplémentaire d'intrants (par exemple, engrais, terre et eau) augmente dans leur prix. En outre, l'adoption généralisée des cultures énergétiques entraîne une réaffectation des engrais, des équipements, du capital, de la main-d'œuvre et d'autres intrants de l'agriculture à la production de bioénergie. Cela influence négativement le prix et la production des denrées alimentaires, et peut être responsable d'une concurrence négative entre la nourriture et l'énergie (Thompson and Tyner [2014]).

Les macroalgues n'ont pas besoin de grandes terres pour pousser et peuvent être cultivées sur des terres marginales sans concurrencer les terres agricoles. D'autre part, il nécessite une grande quantité d'eau et de nutriments. Échelle de bière blonde la production de microalgae pourrait concurrencer la production de nourriture pour l'eau et les engrais. Par conséquent, cela peut accroître la pression sur les prix des denrées alimentaires et les ressources en eau.

Depuis de nombreuses années, la première génération de bioénergie est utilisée à grande échelle dans le monde entier. Les technologies adoptées pour convertir les cultures vivrières

en bioénergie ont atteint un bon niveau de maturité, ce qui a rendu la première génération de bioénergie compétitive avec les combustibles fossiles.

Même si le coût de production dépend du type de culture et de la région géographique, le coût de production de la première génération de bioénergie est proche de celui des combustibles fossiles. Des progrès considérables ont été réalisés dans l'amélioration des performances techniques de la première génération de bioénergie. Cependant, la deuxième et la troisième génération de production de bioénergie présentent des défis tels que : 1) des coûts de production élevés (Carriquiry et al. [2011]), 2) dans certaines bioraffineries, la technologie n'est pas assez mature (Bairamzadeh et al. [2015]), et 3) les microalgues ont besoin de plus de processus et d'efforts technologiques pour accélérer la transition vers la production à grande échelle (Mohseni et al. [2016]). La figure 1.6 résume les inconvénients et les avantages des trois générations.

La demande croissante d'énergie et les problèmes environnementaux posés par l'utilisation des combustibles fossiles ont conduit les chercheurs à considérer les différentes sources d'énergie renouvelable pour satisfaire la demande énergétique. La biomasse, une source d'énergie renouvelable, est une alternative propre pour produire de l'énergie (au lieu d'utiliser des combustibles fossiles) qui peut également protéger l'environnement (avec des émissions nettes nulles). Une bio-raffinerie est une usine qui transforme la biomasse en bioénergie. La bioraffinerie a besoin d'une planification de production optimale pour produire commercialement de la bioénergie à partir de la biomasse (une alternative peu coûteuse aux combustibles fossiles). Ce n'est pas facile, car les bioraffineries sont confrontées à différents défis dans le monde réel qui ont un impact direct sur la planification de la production et les coûts totaux. L'objectif principal de cette étude est, dans un premier temps, de définir les défis et les problèmes. Ensuite, il leur propose des solutions. Cinq chapitres pour cet objectif dans cette thèse sont définis comme suit.

Dans le premier chapitre, une introduction générale, et les principales questions ainsi que les termes qui sont utilisés dans le reste de la thèse sont proposés. La biomasse et les différents types de biomasse sont définis. Le cadre du système de production, les bioraffineries et les technologies sont décrits plus en détail. La définition du développement durable est fournie. Ensuite, les politiques associées et les différentes générations de bioénergie sont décrites. À la fin, le stockage de la biomasse est expliqué, le stockage de l'énergie et certains défis connexes.

Dans le chapitre deux, une revue de la littérature générale est proposée qui est liée à la modélisation et à l'optimisation des chaînes d'approvisionnement en bioénergie. Dans ce

chapitre, les études sont considérées qui sont incluses dans la modélisation mathématique et l'optimisation des chaînes d'approvisionnement en bioénergie. Ces études sont étudiées sous différents aspects tels que la planification de la production, le développement durable, la conception de la chaîne d'approvisionnement et l'incertitude.

Dans le chapitre trois, le modèle mathématique de base est présenté. Disponibilité des changements de biomasse au cours des différentes saisons. C'est un défi pour les bioraffineries pour une production continue. Une solution à ce problème est le stockage de la biomasse. Cependant, le stockage de la biomasse pendant une longue période conduit à une réduction de la qualité, car la biomasse est une matière périssable. Cela affecte la production des bioraffineries. Pour ce problème, cette thèse propose la solution pour contrôler le stockage de la biomasse en surveillant l'âge de la biomasse. En d'autres termes, l'âge de la biomasse est intégré au modèle mathématique pour contrôler la périssabilité de la biomasse. Enfin, quelques résultats (non exhaustifs) sont proposés dans ce chapitre.

Dans le chapitre quatre, plus d'expériences et de résultats liés à une meilleure étude de la périssabilité de la biomasse sont proposés. De plus, le stockage de l'énergie est un défi dans la planification de la production des bioraffineries. La bioénergie doit être vendue immédiatement après sa génération. Le stockage de l'énergie n'est pas économique. Pour ce défi, cette thèse propose une méthode. Le stockage des biocarburants est utilisé pour stocker l'énergie. à ma connaissance, aucune étude antérieure n'a considéré le biocarburant comme un moyen de stockage d'énergie dans le modèle de planification de la production pour convertir la biomasse en bioénergie et/ou biocarburant. Bien que le stockage de biocarburant existe dans d'autres études, le biocarburant stocké est ensuite converti en bioénergie à l'intérieur de la bioraffinerie dans cette thèse. Cette stratégie est intégrée au modèle mathématique et à la planification de la production. Enfin, différentes perspectives managériales sont proposées.

Dans le chapitre cinq, cette thèse est prolongée en considérant deux autres défis. Premièrement, la fluctuation des prix du marché et la corrélation entre le prix du biocarburant et le prix d'autres sources (par exemple, le gaz naturel, le pétrole brut, etc.) ont un impact sur le prix de vente du biocarburant. Cette thèse considère donc le prix du biocarburant comme un paramètre incertain. . Dans ce cas, l'incertitude existe dans chaque ligne. Deuxième. des conditions climatiques imprévisibles impactent la disponibilité de la biomasse, la matière première des bioraffineries. Pour ce problème, cette thèse définit trois critères : i) les précipitations, ii) la température, et iii) la lumière du jour pour modéliser les conditions climatiques. Sur la base de ces critères, le nouveau paramètre incertain est défini

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dans le modèle qui représente l'incertitude météorologique. Dans ce cas, l'incertitude existe dans chaque colonne. Cette thèse propose un modèle hybride, un modèle d'optimisation robuste en ligne et en colonne, pour attaquer l'incertitude. De plus, différentes perspectives managériales sont proposées.



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# ABSTRACT

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The increasing demand for energy and environmental problems made by using fossil fuels have led researchers to consider the different sources of renewable energy to satisfy the energy demand. Biomass, a source of renewable energy, is a clean alternative to generate energy (instead of using fossil fuels) that can also keep the environment safe (with net zero emissions). A bio-refinery is a plant that transforms biomass into bioenergy. The biorefinery needs optimal production planning to commercially generate bioenergy from biomass (a low-cost alternative to fossil fuels). This is not easy, because biorefineries are facing different challenges in the real world that directly impact production planning and total costs. The main goal of this study is, first, to define the challenges and problems. Then, it proposes solutions for them. Five chapters for this goal in this thesis are defined as follows.

In chapter one, a general introduction, and the main issues as well as the terms that are used in the remainder of the thesis are proposed. Biomass and the different types of biomass are defined. The framework of the production system, biorefineries, and technologies are described in more detail. The definition of sustainable development is provided. Then, the related policies and the different generations of bioenergy are described. At the end, biomass storage is explained, energy storage, and some related challenges.

In chapter two, a general literature review is proposed which is related to the modeling and optimization of the bioenergy supply chains. In this chapter, the studies are considered that are included mathematical modeling and optimization for bioenergy supply chains. These studies are investigated in different aspects such as production planning, sustainable development, supply chain design, and uncertainty.

In chapter three, the basic mathematical model is introduced. Availability of biomass changes in different seasons. This is a challenge for biorefineries for continuous production. One solution to this problem is biomass storage. However, storing biomass for a long time leads to quality reduction, because biomass is a perishable material. This affects the production of biorefineries. For this problem, this thesis propose the solution to control biomass storage by monitoring the age of biomass. In other words, the age of biomass is incorporated into the mathematical model to control biomass perishability. Finally, some

results (not comprehensive) are proposed in this chapter.

In chapter four, more experiments and results related to better study biomass perishability is proposed. In addition, energy storage is a challenge in the production planning of biorefineries. The bioenergy must be sold immediately after its generation. Storing energy is not economic. For this challenge, this thesis propose a method. Biofuel storage is used for storing energy. to the best of my knowledge, no previous study considered biofuel as a way of storing energy in the production planning model for converting biomass to bioenergy and/or biofuel. Although biofuel storage exists in other studies, the stored biofuel later is converted into bioenergy inside the biorefinery in this thesis. This strategy is incorporated into the mathematical model and production planning. Finally, different managerial insights are proposed.

In chapter five, this thesis is extended by considering two more challenges. First, fluctuating market prices, and the correlation between the price of biofuel and the price of other sources (e.g., Natural gas, crude oil, etc.) impact the biofuel selling price, so this thesis considers the price of biofuel as an uncertain parameter. In this case, uncertainty exists in each row. Second, unpredictable climatic conditions impact the availability of biomass, the feedstock of the biorefineries. For this problem, this thesis defines three criteria: i) rainfall, ii) temperature, and iii) daylight to model the climatic conditions. Based on these criteria, the new uncertain parameter is defined in the model that represents weather uncertainty. In this case, uncertainty exists in each column. This thesis proposes a hybrid model, a row and column-wise robust optimization model, to attack uncertainty. In addition, different managerial insights are proposed.

# AN OVERVIEW ON THE BIOENERGY SUPPLY CHAIN MANAGEMENT

---

## 1.1 Introduction

Supply chain management can play a key role in ensuring that the supply chain is cost-competitive. However, some characteristics of products in the supply chain complicate the supply chain planning. Therefore, there is a need, here, for decision support models that can solve complex problems, and improve the decision-making process. Supply chain planning can be carried out at strategic, tactical, and operational levels. In strategic plans, we are looking for the number, location, and capacity of the production and storage facilities. It includes a long time planning horizon ( more than one year usually). However, in tactical and operational level plans, we are looking for efficient utilization of resources and flow of material through the supply chain. The planning horizon is usually less than the strategic planning. Even it can be seasonal, monthly, or daily (Awudu and Zhang [2012], De Meyer et al. [2014], Yue et al. [2014]).

In this study, the goal is to manage a bioenergy supply chain using Operations Research (RO). In other words, biomass-to-bioenergy supply chain design and planning include a large number of decisions. The decisions are related to the different operations along the supply chain. For example, the cultivation and harvesting of biomass, transportation of biomass, conversion of biomass to bioenergy/biofuel, biofuel transportation, bioenergy transmission, and distribution to the final markets. The design, implementation, and management of this supply chain are a complex process. All activities in the biomass-to-bioenergy supply chain should be designed in a specific way that guarantees the efficiency of the material, information, and financial flows in the networks (Eksioglu et al., 2015). Effective management and planning of the biorefinery have a prominent impact on decreasing production costs and making biomass a valuable source of energy. Operations research and mathematical modeling can help us accomplish this mission.

## 1.2 General framework of the bioenergy supply chains

Usually there are three segments in the bioenergy production systems, downstream, midstream, and upstream. In each segment, there are several entities. The downstream entities refer to post conversion processes such as storing, blending, and distribution of final products. Midstream refers to conversion facilities where biomass is converted into bioenergy and other products through different technologies. Upstream entities refer to supplying of biomass, from producing biomass to delivery to conversion facilities. This needs a good co-operation among the supply entities.

### 1.2.1 The entities and activities

These entities include demand zone, distribution centers, blending sites, pre-processing sites, conversion technologies, storage sites, collection centers, biomass sites. Figure 1.1 shows the general structure and activities of the bioenergy supply chains. It starts by harvesting the cultivated biomass from biomass sites, then sending to intermediate sites or collecting centers, after that, preprocessing sites. Next, the biomass is carried to biorefineries. In biorefineries, biomass is converted into bioenergy, biofuel and byproducts. There are three main categories for technologies, Thermochemical, biochemical, and chemical. Final products could be power (electricity), heat, biochemicals, biofuel (e.g., bioethanol and biodiesel). Then, final products are delivered to distribution centers and customers. Note that some studies considered combination some entities with each other, for example, they consider blending facilities inside the biorefineries.

In addition, the main activities in the bioenergy supply chains are cultivation of biomass, harvesting and collection of biomass, biomass pre-processing, storage, transportation, blending and distribution. These logistics activities can be complicated and costly when they are facing some challenges such as low energy content of biomass, scattered geographical distribution, seasonal nature, low bulk density, as well as various uncertainties in the supply chains.

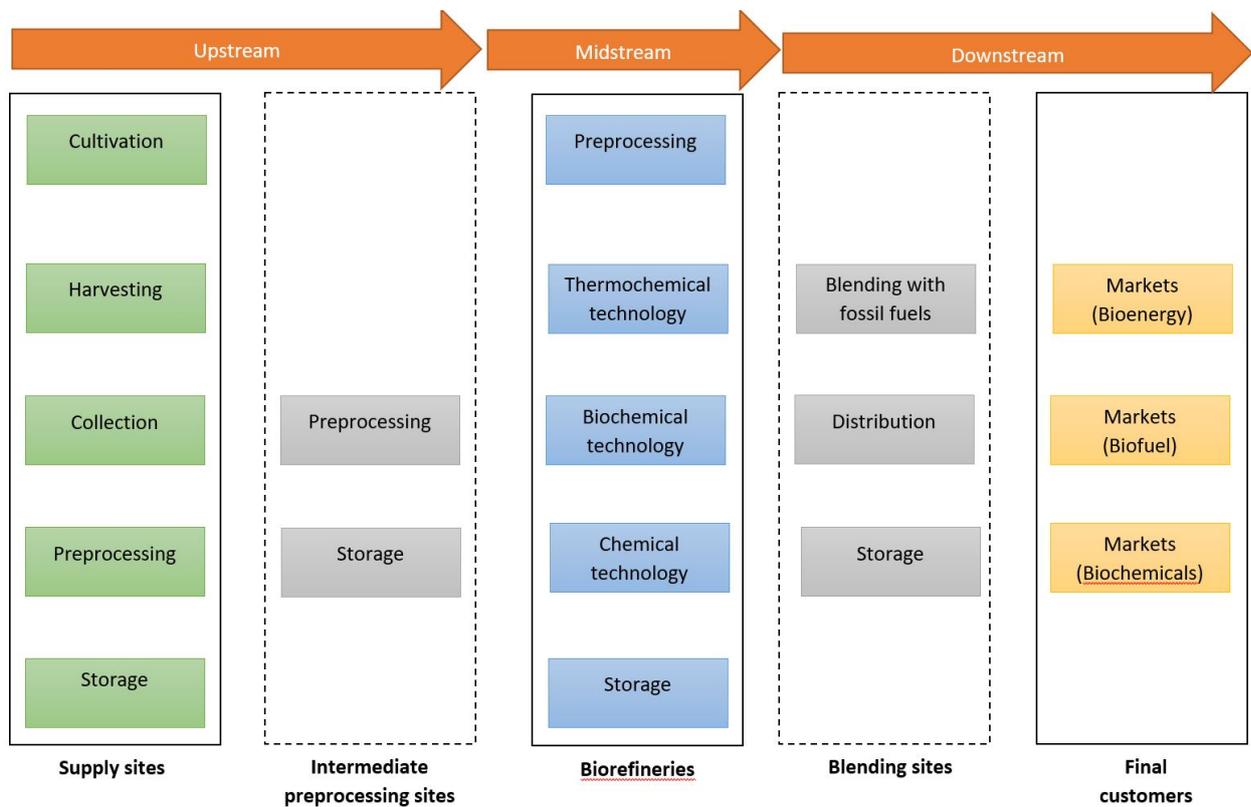


Figure 1.1 – Supply chain activities

## 1.2.2 The bioenergy facilities (technologies)

In bioenergy supply chain, there are facilities that can convert raw material (biomass) to different products: i) bioenergy such as heat and electricity; ii) biofuel such as bioethanol and biodiesel; and iii) biobased products such as plastics, chemicals. There are three main categories for these facilities, thermochemical, chemical, biochemical. (Demirbaş [2001], Frombo et al. [2009]). The generated products are sent to customers through the grid, network or channels of distributors, wholesalers and retailers (Yue et al. [2014]). Figure 1.2 shows different types of facilities (technologies) that can be used in the biorefineries (Adams et al. [2018], Fiorentino et al. [2017], McKendry [2002b,a], Naik et al. [2010], Patel et al. [2016], Patel et al. [2016]).

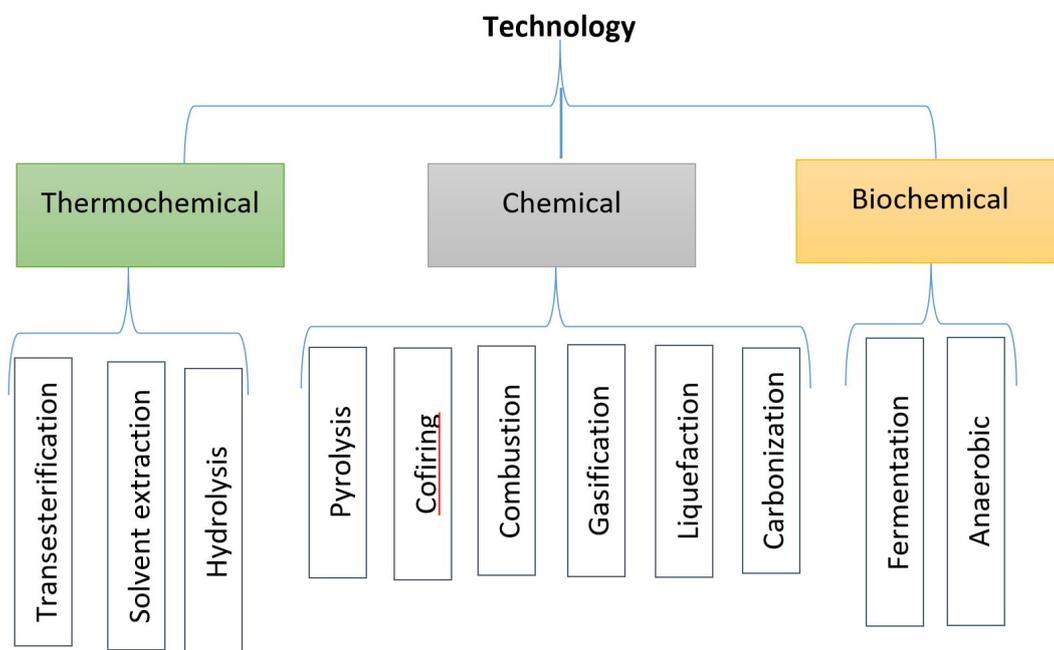


Figure 1.2 – Technologies

## 1.3 Sustainable development

Sustainable development aims to ensure two main elements. First, it is necessary that humans be able to meet their basic needs as well as to support continued development. Material, human, ecological, and social resources are adequately necessary to achieve this goal. Second, the future generation and current generation must have equal access to these resources.

Material resources consist in nonrenewable resources. Human resources refer to health, freedom, knowledge, human rights, and opportunity for applying the knowledge. Ecological resources include renewable resources (e.g., timber or food) and services (e.g., protection against ultraviolet solar radiation) that healthy natural ecosystems can provide. Social resources refer to trust, reciprocity norms, equity, and other conditions that help coordination and cooperation of mutual benefits (Rodriguez et al. [2002], Gray [2010]).

Human activities have caused environmental problems, so this is a motivation for scientists to pay more attention to sustainable development. These days environmental problems are not only local issues but also national issues. The interdependency of environmental effects with macro issues such as policy, development, society, economy, and culture leads environmental problems to be considered in a larger scale, and considered as a global issue. Therefore, the massive environmental problems can be categorized into following classes, global warming (greenhouse effects), freshwater scarcity, acid rain and air pollution, ozone layer depletion, biodiversity destruction, disposal of toxic waste, and loss of fertile soil (Hollander [2003]).

A prerequisite of a dynamic and healthy society as well as a vital element of sustainable development is a healthy human. Nevertheless, lots of people are not able to pay for basic health services, so the human health and development processes are at risk. In addition, unemployment, poverty, as well as unequal opportunities to work based on gender, age, and geographical locations are other critical social concerns.

Therefore, these social and environmental concerns have gotten more attention, and led to international summits. Finally, they introduced "sustainable development" paradigm. There are some definitions for sustainable development. The world commission on environment and development (WCED) made a definition for sustainable development that have been widely accepted. The commission defined sustainable development (in the published report) (Imperatives [1987]) as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". According to the definition, the objectives of a sustainable development must be set based on social, environmental, and economic decisions which are also called pillars of sustainability. Figure 1.3 shows these three pillars by providing:

- Sustainable growth of the economy
- The natural resources and the environment are effective protected
- Satisfying all individual's needs by social growth

Incorporating three sustainable aspects should be insured into supply chain network,

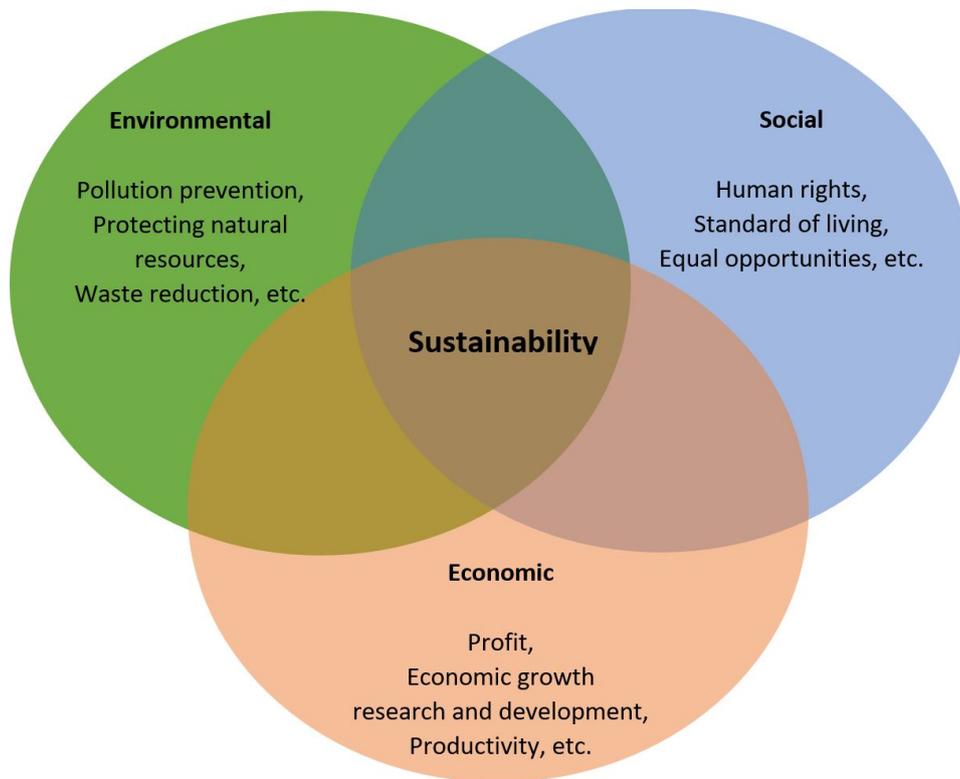


Figure 1.3 – Different aspects of sustainability

and not be limited into one business and corporation's boundary. Bioenergy can be used as a sustainable alternative to fossil fuels. In order to insure this alternative, the social, environmental, and economic aspects of the bioenergy supply chains must be incorporating in the design and planning of bioenergy sectors. In recent years, sustainability has gotten more attentions in literature related to the bioenergy supply chains.

### 1.3.1 Sustainable development in bioenergy supply chain

The increase in greenhouse gas (GHG) emissions has led to an abnormal increase of the earth's temperature, to climate changes, and, subsequently, to an increase in natural disasters. The photographs sent by emission measurement satellites have shown increasing greenhouse gas emissions and have provoked considerable concern. It caused the representatives of more than 100 countries participating in the 2015 United Nations Climate Change Conference in Paris to sign the Paris Agreement with the aim of reducing these emissions. The concerns were related to energy demand, and the environmental, economic, and social problems generated by using fossil fuels. These issues have led researchers to

consider the sources of renewable energy, which can lead to regional development, and protect the environment while still meeting the energy demand. Renewable energies -the bioenergy (heat and electricity) and biofuel (bioethanol, bio-oil, biodiesel, pellets)- can be obtained through biomass. The bioenergy and biofuel can be used as substitutes for fossil fuels. They can decrease greenhouse gas (GHG) emissions, and create new jobs and more vitality in the considered regions (d'Amore and Bezzo [2016], Shavazipour et al. [2020]).

One source of biomass is the feedstocks coming from agricultural and forest residues. For example, forest residues could be: a) shavings, sawdust, hog fuel, chips (from sawmill wastes); b) branches, leaves, tree tops, non-merchantable stems emanating from forest operations (Razm et al. [2019b]). The agricultural residues could be wheat straw, sugarcane bagasse, corn stover, etc., which are not used as food, and originate from the agricultural wastes (Razm et al. [2019a], Yue et al. [2014]). Bioenergy, biofuel, and other bio-based products (chemicals, plastics, etc.) can be generated through three basic conversion processes, biochemical, chemical, and thermochemical process (Demirbas et al. [2009], McKendry [2002b], Campbell [2007]). Two of them can be used for the forest and agricultural biomass to generate bioenergy and biofuel: i) thermochemical (combustion, pyrolysis, and gasification), ii) and biochemical (producing ethanol through hydrolysis and fermentation) (McKendry [2002b], McKendry [2002b]).

In order to optimally convert biomass to bioenergy, it is necessary to design an optimal supply chain for that. In recent years, the importance of the design, implementation, and management of bioenergy SC has increased. The most significant obstacle to development of a bioenergy sector is the cost of the supply network. For instance, high costs could be incurred by supplying biomass to the biorefinery due to the economic and environmental implications of gathering and transporting biomass feedstock from the biomass supply site. Designing supply chain is fundamental in terms of reducing costs and GHG emissions (e.g. due to transportation). In addition, the location of the biorefinery is important, because it can generate new jobs and sustainable development in the considering area (You et al. [2012]).

### 1.3.2 Policies and Regulations (RED)

In the literature, there are different policies and regulations related to bioenergy. In addition, there are different names/categories for different types of biomass that have links with the policies. One category for biomass is edible feedstock, such as soybeans, rapeseeds, sugarcane, maize /corn grains, animal fats, can be converted to the biofuels (first generation) through the processes such as transesterification (producing biodiesel) and fermentation (producing bioethanol) (Sharma et al. [2013b]). Other category is non-edible feedstock (lignocellulosic biomass) which can be classified in agricultural residues such as wheat straw, corn stover, bagasse, rice straw; and forest residues such as tree tops, wood chips, branches, hog fuel, sawdust, and bark. The processes of thermochemical (pyrolysis, combustion, and gasification) and Biochemical (fermentation and hydrolysis) can convert lignocellulosic biomass to the bio-energies and biofuels (second generation) (Mahjoub et al. [2020], Razm et al. [2019b]). This second category is also named advanced bioenergy/biofuel ([www.etipbioenergy.eu](http://www.etipbioenergy.eu)).

The importance of climate change and security of energy supply has led to a series of regulatory policies in the industrial countries. In the European Union (EU), the orientation of energy regulations shows the importance of the issue. For example, the EU Directive 2009/28/EC (Renewable Energy Directive-RED) is the core of European biofuels regulations. It introduced a mandatory share of 10% for renewable energy in the EU transport sector (Gamborg et al. [2014]).

Moving towards development of the EU energy for future, the EU defined its mid-term and long-term targets (Mandley et al. [2020]). The mid-term targets: i) the efficiency improvement in the energy consumption at least 32.5%, ii) at least 40% cuts in GHG emissions from 1990 levels (the basic year for emissions that also used in the UNFCCC and Kyoto Protocol), are considered for period 2021-2030 ([www.ec.europa.eu/2030](http://www.ec.europa.eu/2030)). The long-term target, keeping the global temperature increase between 1.5-2°C is considered by 2050 ([www.ec.europa.eu/2050](http://www.ec.europa.eu/2050)). This long-term target is also in line with the Paris Agreement objective ([www.ec.europa.eu/clean-energy-all-europeans](http://www.ec.europa.eu/clean-energy-all-europeans)). Biofuel regulations was first introduced in EU in 1997 to help biofuel industry development (Prussi et al. [2019]). In 2009, European Parliament and Council targeted a 10% limit on the first generation biofuels (the crop-base biofuels) by 2020 in Renewable Energy Directive (RED) (Directive 2009/28/EC of 23 April). In September 2013, the 10% limit reduced to 6%, and also European Parliament and Council forced a 2.5% target for the advanced biofuels (made of non-edible material) by 2020 (Directive 98/70/EC).

### 1.3.3 Policies and Regulations (RED II)

Nevertheless, in June 2014, a new agreement proposed by the European Union energy ministers was quite different. It suggested that there is no need for an obligatory target for the advanced biofuels, as well as suggested the 6% limit has to increase to 7% for the crop-based biofuels (Doumax-Tagliavini and Sarasa [2018]). In 2016 (fall), the 2009 Renewable Energy Directive was revised by European Union commission in order to make the new goals for renewable transportation fuels, renewable energy and energy efficiency for the period from 2021 to 2030. These revisions had two objectives: i) using a binding mandate to boost the advanced biofuels, ii) considering a cap for using the crop-based biofuels, a 3.8% incorporation rate in road transport. This bunch of suggestions is known as RED II or post-2020 European Union Renewable Energy Directive. However, the new direction (RED II) made by European Union Commission implied a considerable slowing of using biofuel in some states. Next, in January 2018, some of these proposals have been amended by Members of the European Parliament (Union [2009]). Therefore, by 2021, a 1.5% binding mandate is considered for the advanced biofuels, and then it could increase to 10% by 2030. The crop-based biofuels are fixed in a 7% cap by 2030.

It should be mentioned that in the Renewable Energy Directive (2009), there was not any mandatory objective for the advanced biofuels. The governments would have only encouraged producing the advanced biofuels, and considering the 0.5% incorporation rate (the advanced biofuels) in the road transport. The fears related to the biofuel industry of European Union and its profitability in the long term period had led to such those lower ambitions. However, a growth in the advanced biofuels and not from edible crops is a clear message from the recent negotiations to the biofuel industry of European Union (Doumax and Sarasa, 2018). Figure 1.4 summarize the most common policies and regulations related to the bioenergy supply chains.

## 1.4 Biomass: types and sources

Any living or recently living biological material generated on our planet by the process of photosynthesis can be considered as biomass (Allen et al. [1998]). Note that, it may go into some cycles (e.g., first as food, then it converts to biomass). Biomass can include a wide variety of sources such as agricultural and forest sources, industrial and municipal bio-degradable waste, and animal excrement (An et al. [2011]).

Although the cultivating/collection, transportation, and conversion of biomass lead to

air pollution (Hall and Scrase [1998]), there is a significant potential for saving green house gas (GHG) emissions when the generated bioenergy is substituted to fossil fuels (even negative emissions) (Ahtikoski et al. [2008]). According to International Energy Agency, transforming biomass to biofuel under appropriate and sustainable manner can lead to neutralize carbon generation. The life cycle of biofuel shows that the amount of CO<sub>2</sub> generated by consuming biomass is equal to amount of CO<sub>2</sub> taken from atmosphere by plant during growing stage (Saidur et al. [2011]).

Comparing with other renewable sources such as solar or wind, biomass is a flexible source of energy to generate heat, electricity, biofuel and bioenergy, because it can be stored and used in demand (Demirbaş [2001]).

As mentioned, a wide variety of materials can be considered as biomass to generate bioenergy and biofuel. For example, first, forest residues: a) branches, leaves, tree tops, non merchantable stems emanating from forest operations; b) sawmill wastes: shavings, sawdust, hog fuel, chips (Cambero et al. [2015]). Second, agricultural residues: wheat straw, sugarcane bagasse, corn stover, etc., which are not used as food, and originate from the wastes made from agriculture (Yue et al. [2014]). Third, energy crops such as switchgrass, jatropha (Osmani and Zhang [2013]). Forth, different types of algae (Mohseni et al. [2016]).

The above mentioned biomass are more known and common in the literature, although there are more types of biomass. Figure 1.5 shows the different type of biomass.

The regulation	Explanation	References
1 Crop cap	Maximum market share quota for the crop-based biofuels/bioenergy	(Prussi et al., 2019)
2 Minimum quota	Minimum market share quota for the advanced biofuels	(Mandley et al., 2020)
3 FQD	Sustainability criteria introduced by the Directive on Fuel Quality Standards (FQD) which regulate the green-house intensity generated by fuels used in road transport and non-road mobile machinery (heat, electricity). The overall target can change in each country (e.g., in France, overall target is 10% GHG reduction in fuels by December 2020)	(Wetterlund et al., 2013; Doumax and Sarasa, 2018)
4 ILUC	Sustainability criteria related to the Indirect Land Used Changes (ILUC). ILUC means changing the use of the existed agricultural land to generate bioenergy	(Gamborg et al., 2014; Strapasson et al., 2020)
5 DLUC	Sustainability criteria related to the Direct Land Used Changes (DLUC). DLUC means changing of non-agricultural land to use for generating bioenergy.	(Van Dam et al., 2008; Drews et al., 2020)
6 Total quota	Total market share quota for biofuels/bioenergy	(Giarola et al., 2012; Mikova et al., 2019)
7 Multiple counting	Double counting of the advance biofuels in calculating of this quota (Total market share quota)	(Mazetto et al., 2015)
8 Feed-in tariffs	Supporting schemes to accelerate investment in renewable energy technologies by offering long-term contracts to renewable energy producers. For example, the fixed electricity prices that are paid to renewable energy producers for each unit of energy produced and injected into the electricity grid.	(Schmidt et al., 2011b)
9 Pellet subsidies	Subsidies are granted for wood heating systems.	(Schmidt et al., 2011b)
10 Tax incentives	Tax incentives for biofuels (the blends). For example, in 2022, E5 is taxed at 77.8€/hl, whereas E85 is taxed at 18.95€/100 L in France)	(www.epure.org/media; Strapasson et al., 2020)

Figure 1.4 – Regulations

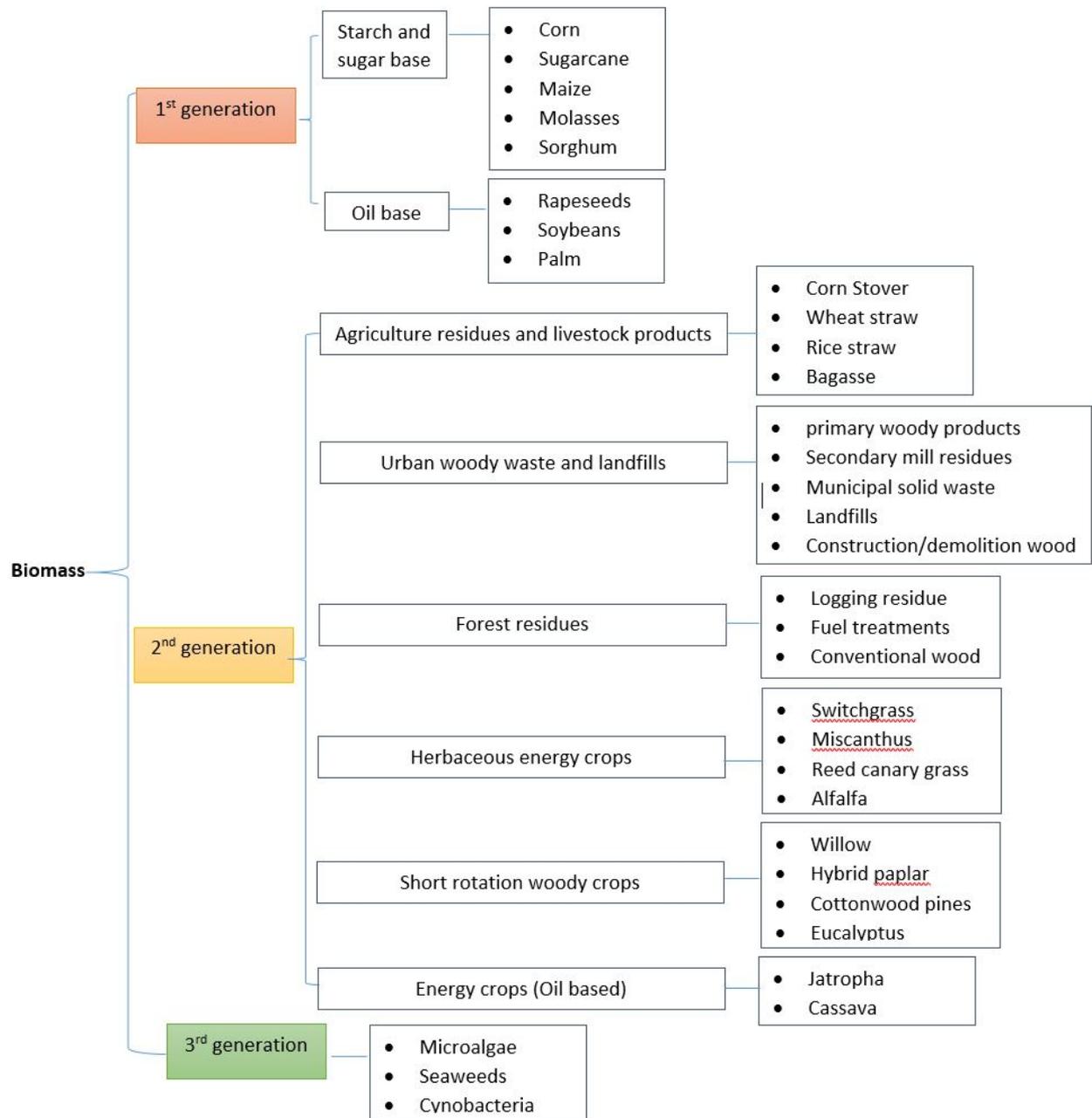


Figure 1.5 – Different types of biomass, inspired by (Sharma et al. 2013b)

## **1.5 Bioenergy Generation**

The literature also named different generation for bioenergy according to the consumed biomass. In this section, the advantages and disadvantages of each generation are discussed under three headlines: a) water, land, and nutrient requirements, b) competition with production of food, and c) production cost and commercialization. These are important issues in bioenergy production systems specially in the large-scale production.

### **1.5.1 Water, land, and nutrient requirements**

The first generation of bioenergy drives from food crops that require a large amount of water and agricultural lands and other inputs. Energy crops need less water, land, and fertilizer requirements compared to food crops. The reason is that energy crops have potential to grow on marginal lands, better water use efficiency, and more tolerant to nutrient deprivation (Mehmood et al. [2017]). Note that energy crops need less fertilizers, soil quality and availability of water. If they are cultivated on arable lands, their productivity can significantly improve with enough water and fertilizer (Heaton et al. [2004], Smith and Slater [2010]).

Compared to energy crops and food crops that are cultivated in marginal or arable lands, crop residue does not need extra land, it dose not compete for land, so landuse changes does not happen (Carriquiry et al. [2011]). Nevertheless, excessive removal of residues has some negative effects such as fluctuation in soil erosion and global climate change, degradation in soil organic carbon pool, quality reduction of soil (Lal [2005]). Microalgae is another types of biomass that needs less land for cultivating. However, the life cycle usage of water, phosphate, and nitrogen are high (Yang et al. [2011]).

### **1.5.2 Competition with production of food**

The first generation of bionenergy is directly produced from food crops. Large production of food crop to use as biomass leads to the diversion of large amounts of crops from food markets to bioeneregy market, so it leads to the food security reduction and the food price increase (Rulli et al. [2016]).

The second generation of bioenergy come from nonfood feedstocks (e.g., organic resides and energy crops). However, they could not entirely resolve the food versus fuel conflict. In large scale production of energy crops, the additional demand for inputs (e.g., fertilizer,

land, and water) cases increasing in their price. In addition, widespread adoption of energy crops leads to reallocation of fertilizer, equipment, capital, labor, and other inputs from agricultural to bioenergy production. This negatively influences the food price and production, and it can be responsible for negative competition between food and energy (Thompson and Tyner [2014]).

Macroalgae do not need a large lands to grow and can be cultivated in marginal lands without competing with agricultural land. On the other hand, it requires a large amount of water and nutrient. Large-scale production of microalgae might compete with production of food for water and fertilizers. Consequently, it can increase the pressure on food price and water resources.

### **1.5.3 Production cost and commercialization**

For many years, first generation of bioenergy is used in a large scale around the world. The technologies adopted to convert food crops to bioenergy have reached to good level of maturity, so it made first generation of bioenergy competitive with fossil fuels.

Even though the cost of production depends on the crop type and geographic region, the cost of production of first generation of bioenergy is close to fossil fuel. Considerable progress has been made in improving the technical performance of the first generation of bioenergy. However, the second and third generation of bioenergy production has some challenges such as: 1) high production costs (Carrquiry et al. [2011]), 2) in some biorefinery, the technology is not enough mature (Bairamzadeh et al. [2015]), and 3) microalgae needs more processes and technological efforts to accelerate transition in large scale production (Mohseni et al. [2016]). Figure 1.6 summarizes the disadvantages and advantages of the three generations.

## **1.6 Storing biomass and bioenergy**

Availability of biomass can change because of different reasons (e.g., climate conditions), storing of biomass is one way to solve this problem. In addition, storing of bioenergy after generation is a challenge for biorefineries. It is not economy storing energy. These two kind of storage are explained in more details in the following.

### 1.6.1 Biomass storage and perishability

The biomass storage can be in supply sites (on the fields), in the biorefineries, or in the intermediate sites. This thesis defines biomass yield as the bioenergy and/or biofuel output over the amount of input biomass. Perishability is defined as a decrease in biomass yield over time. In other words it is a consequence of the *aging* of biomass in storage. When a new lot of the biomass arrives to the warehouse, it is considered as fresh with an age  $a = 0$ . Then, the biomass is sent to biomass storage. The age of the biomass increases and its yield  $\alpha_{ba}^F$  decreases in the biomass warehouse.

The *perishability rate* (the speed at which perishability takes place) differs from one biomass to another. It happens mainly because of chemical reactions. Hence, there is difference between the initial yield corresponding to that of fresh (zero age) biomass and the yield of "old" biomass at the beginning of each period. Again, this initial yield differs from one biomass to another.

### 1.6.2 Energy storage

According to the European Commission ([www.ec.europa.eu](http://www.ec.europa.eu)), consumption of energy has to match its generation. This balance is essential to maintain a safe and stable supply of energy. Some studies introduced different methods and technologies to store energy. For instance: 1) using different kinds of battery (e.g., flow battery, lithium battery) (Kousksou et al. 2014; Wichmann et al. 2019); 2) using the compressed air storage system (He et al. 2021); 3) using thermochemical energy storage system (Wu et al. 2021); 4) using superconducting magnetic energy storage (Diezmartínez 2021). Some studies introduced biofuel as one way to store energy (Ma 2021). Nevertheless they did not have mathematical models in their studies. This thesis appropriately defines and incorporates energy storage into the mathematical model and analysis the effects of that. Energy is stored in the form of biofuel, then, it will be converted into bioenergy inside the biorefinery later. Biofuel storage allows more flexibility on when to generate bioenergy and therefore helps to match energy supply with demand.

## 1.7 Biomass and bioenergy related challenges

Although using biomass to generate bioenergy has advantages, there are some barriers in its efficient utilization. Availability of biomass, quality and cost of biomass, perishable

nature of biomass, transportation costs, logistics efficiency. For example, forest biomass is bulky material with low density (Demirbaş [2001]). Biomass quality is important in the conversion process (Rentizelas et al. [2009]). Collecting, transporting, handling and storing low density materials is not easy. In some cases, transportation of biomass can cost half of the total biomass cost (Allen et al. [1998]). Instead of being concentrated like fossil fuel, biomass is usually spread over large area. In addition, it may need a large amount of equipment and different transportation modes (Hall and Scrase [1998]). Although, the demand for energy is high during the year, availability of biomass can vary in some months during the year. Consequently, biomass storage is suggested. However, biomass storage can affect the biomass quality because of perishability (Fuller [1985]), thus, the conversion process is impacted.

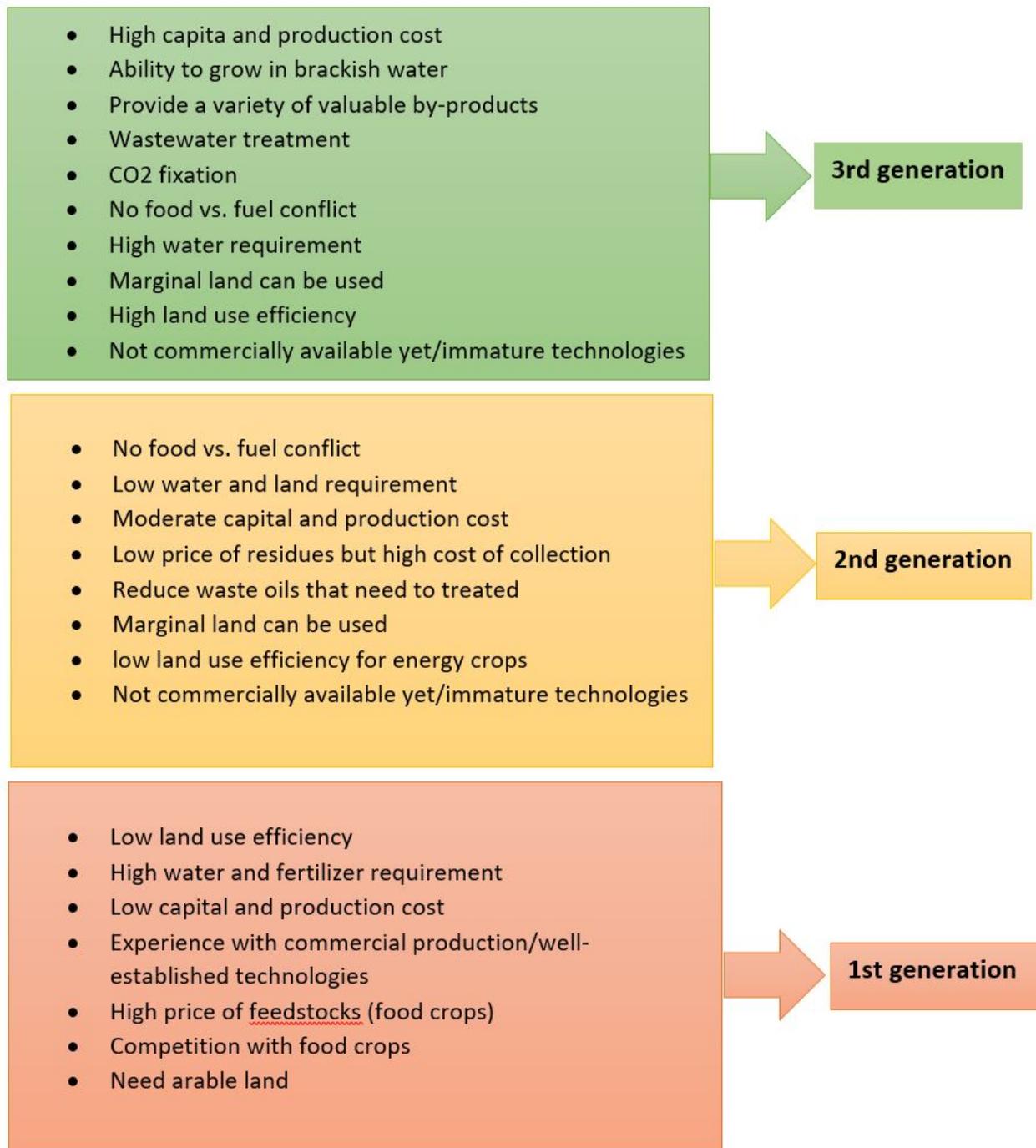


Figure 1.6 – Three generations



# STATE OF THE ART OF MODELING AND OPTIMIZATION OF BIOENERGY SUPPLY CHAINS

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## 2.1 Introduction

This part of the thesis divided into three main parts. First, a general literature review for bioenergy supply chains is proposed. Second, a specific literature review is proposed for production planning in bioenergy supply chains. finally, another literature review for uncertainty is proposed that is related to the production planning in bioenergy supply chains

## 2.2 The general literature for bioenergy supply chains

Cost of bioenergy supply chain is the most important barrier in designing a bioenergy sector comparing with other sources of energy (e.g., fossil fuel). One way to deal with this challenge is to use the advanced technology to improve the quality of raw material and efficiency of the system. A complementary approach is to improve the bioenergy supply chain by optimizing its design and production planning (Shmulsky and Jones [2019]).

A supply chain model helps manage the supply chain with more efficiency. Operations research and mathematical programming are tools used for this mission. If all parts of the supply chain are taken into account (depends on planning level) and are integrated, mathematical modeling would be effective. According to Shmulsky and Jones [2019], the performance of the bioenergy supply chain can be improved using optimization technique, so bioenergy can be economically viable.

### 2.2.1 Modeling and optimization of bioenergy supply chains

Modeling and optimization of bioenergy supply chains (SCs) have been attracting a great deal of attention from researchers recently. In bioenergy SC literature, from one point of view, many models only considered the economic aspect of the SC when designing the network. For instance, in the studies based on agricultural and forest (AF) biomass, some researchers focused on geographical dispersion to find the sources and supply capacities (Nguyen and Chen [2018], Arabani and Farahani [2012], Soren and Shastri [2019]). Others worked on decisions related to the locations of biorefinery and production capacity (Schmidt et al. [2010] ), and another group concentrated on the design of the supply chain (network) that generates biofuel from various types of AF biomass (Razm et al. [2019a], Marvin et al. [2012], Vikash and Shastri [2019]).

Bairamzadeh et al. [2018b] investigated the strategic and tactical decision levels of the biofuel supply chain based on AF biomass. The authors considered agricultural residues such as corn stover, wheat straw, barley straw and rice straw as feedstock biomass and proposed an MILP model to minimize the total cost of the SC by selecting the capacity, location, and technology of the biorefineries, as well as the amounts of production, inventory, allocation, and transportation. A hybrid robust optimization approach was suggested to cope with the uncertainties. Santibañez-Aguilar et al. [2019] proposed an approach for optimal planning of the biomass residues obtained from crops such as sugar cane, corn, agave, paly rice in a processing system. The authors suggested a mathematical programming model involving mass balances to achieve the interconnections among different nodes of the supply chain. They considered constraints for the technologies in terms of capital investment and cost of production. The objective was to maximize the annual profit obtained from the revenue of selling products, minus the transportation cost, manufacturing cost, and raw material cost. They did not consider the related uncertainties in the model that may lead to a design for the SC network which is not feasible.

Mohseni et al. [2016] developed a mixed-integer linear programming model (MILP) to minimize the total cost of the biodiesel supply chain. The study focused on third generation biofuel, so the proposed mathematical model and approach are specific to a microalgae biomass supply chain. These studies only considered economic aspects of the supply chain, and social concerns or the concepts of sustainability related to the microalgae-based biodiesel SC were not investigated.

## 2.2.2 Sustainable development

In terms of sustainable development, Rabbani et al. [2018] proposed an MILP model to design a sustainable bioenergy supply chain network for switchgrass based biomass. The model included economic, environmental and social objectives and aimed to find the maximum capacity in the biomass centers, the location and capacity of the power plants, and the amount of the collected and stored switchgrass. The authors used a hybrid method involving augmented  $\epsilon$  constraint and TOPSIS approach to consider preferences of decision makers. The study did not consider any uncertainty.

According to (Bairamzadeh et al. [2015]), designing a new biofuel supply chain can create jobs for local people in the area and protect the environment (d'Amore and Bezzo [2016]). However, in the bioenergy supply chain literature, most of the studies just considered economic aspects of the supply chain, and less attention was given to the sustainability of the bioenergy SC, especially social aspects.

Nevertheless, it is crucial to consider sustainability when designing bioenergy supply chains. Thus, there is a gap in the literature and a need to take into account, at the design stage, sustainability aspects, along side economic effects (Ghaderi et al. [2016]). Considering social criteria, in the article (Bairamzadeh et al. [2015]), the authors designed a bioethanol supply chain network using corn stover and wheat straw (lignocellulosic biomass). They considered job opportunities as a social objective in a multi-objective MILP model to determine the location and capacity level of the facilities used in the biorefineries, inventory levels, and material flows. There are other studies in the literature which considered social aspects (Carter and Rogers [2008], Bijarchiyan et al. [2020]). Bijarchiyan et al. [2020] used the Guidelines for the Social Life Cycle Assessment of a Product (GSLCAP) method to find the social impact of a bioenergy supply chain network, and (Carter and Rogers [2008]) introduced job creation as a social objective.

## 2.2.3 Large scale design

When a large geographic area is considered for a bioenergy SC network, identifying the locations where the bio-refineries may be installed is very important, because the network structure, costs, social performance, and environment are affected by these decisions. The methods used in the existing publications are not always clearly out. For instance, some researchers considered sets of locations which were as large as possible, covering most of the desired territory, to obtain more opportunities.

Some others considered a continuous territory in their facility location models by assuming that the facilities could be placed anywhere (Arabani and Farahani [2012]). These methods present some problems such as: 1) they cannot guarantee that optimal places are chosen in the whole of the desired territory, 2) those that considered continuous territory in their facility location models (Arabani and Farahani [2012]) usually restricted their models to a limited number of levels and parts, 3) also when the planning space increases, not only the computational complexity is significantly increased, but functionality is also severely limited (Melo et al. [2009]).

The conventional agricultural and forest (AF) biomass SC models (Schmidt et al. [2010], Murillo-Alvarado et al. [2015], Ahmed and Sarkar [2018]) usually focused on limited and predetermined candidate locations. In this case, simultaneously considering geographical information and social sustainability of the wide geographical territory is very important to select such candidate locations. Nevertheless, the existing models usually did not take them into account. By embracing the Geographic Information System (GIS) and the sustainability as well as by using the multi criteria decision making techniques, it is possible to determine more appropriate places for bio-refineries.

## **2.2.4 Stochastic programming and robust optimization**

Stochastic programming is one approach to handle uncertainty. It models uncertain parameters as a multidimensional random variable with a known probability distribution. Optimizing the expected value of the objective function over all possible realizations of the random variable is the goal of the stochastic programming.

In real world environments, stochastic programming suffer from two major draw backs, even though it was widely used in theoretical supply chain problems to tackle uncertainty. First, it needs the probability distribution information for values of the parameters under uncertainty, but in real life, it is not usually possible to determine this distribution accurately because of the shortage of historical data. Second, it generally leads to complexity in the computations for models in real world problems because it needs many scenarios to model uncertainties (Pishvae et al. [2011]). Conversely, RO, which is capable of preserving the primary model's computational tractability (Li et al. [2011]), is a free distribution method aimed at finding the solution (worst case) according to a set of uncertainties. It could be used to prevent input data uncertainty in the problem, and stays robust against any perturbations.

The interval uncertainty in robust optimization was first presented in (Soyster [1973]).

The author considered all the uncertain parameter values in the worst case to provide maximum protection against uncertainties. Nevertheless, this is not realistic, because at the same time the whole set of uncertain parameters may result in the worst value, so the idea was excessively over-conservative. This theory was then developed in (Ben-Tal and Nemirovski [2000], El Ghaoui et al. [1998]) and, under an ellipsoid uncertainty set, a robust counterpart formulation to control the solution's conservatism level was presented. The authors developed a robust optimization methodology in which the linear program (LP) is changed to a convex nonlinear program (NLP), which is more complicated as regards the computations. Next, in (Bertsimas and Sim [2004b]) an approach was developed that can control the conservatism level and preserve the linearity of the model as well.

### **2.2.5 Uncertainty in bioenergy supply chains**

There are some factors that lead to uncertain conditions in bioenergy supply chain, for example, climate changes, market instability, policy and regulations, natural disasters, and nature of industry (biomass quality and perishability). These uncertainties expose the bioenergy production systems at risk, so providing an appropriate planning under these conditions is difficult.

Uncertainty is one of the most important factors affecting the performance of the bioenergy production systems. Ignoring uncertainty leads to the model generating decisions which are infeasible or suboptimal (Shabani and Sowlati [2016]). There are different sources of uncertainty in the bioenergy production systems. For example, biomass production is impacted by weather and climate conditions. Supplying of biomass varies from one season to another season, from supply site to another supply site, and from one year to another year. (Poudel et al. [2016]).

Biomass price, biomass storage, biomass transportations are other uncertainties related to the biomass supply. Technology uncertainty, capital and operation cost, yield of the conversion process are uncertainties inside the biorefinery (Yue et al. [2014]). In the bioenergy market which is sensitive to economic and financial fluctuations, there are demand and price uncertainties. Furthermore, besides the operational uncertainty, there are other disruption risks made by human or natural disasters (droughts, floods, earthquakes, terrorist attacks) that impact the structure and operation of the bioenergy production system.

### ***Preprocessing plants under uncertainty***

Zamar et al. [2017] proposed a stochastic programming model to address uncertainty related to the biomass supply and biomass demand in a preprocessing site that supplies biomass for other biorefineries. They used forest residues as biomass for feeding biorefineries generating power. Flow of biomass was the main decision in their study. Ahmadvand and Sowlati [2022] proposed a production planning model for existing biorefineries under uncertainty. The biomass is forest biomass, and syngas is final product (biofuel). Intermediate storage between supply sites and biorefinery is considered in a form of open-pile storage. Amount of biomass transferring from supply sites to the intermediate storage sites, from intermediate storage to biorefinery, and from supply sites directly to biorefinery as well as the amount of stored biomass are the main decisions in the study. Available biomass, cost of biomass, demand for biomass from biorefineries are the uncertain parameters. They used robust optimization to tackle the uncertainty (the row-wise robust optimization). In storage of biomass, they considered a percentage of biomass as waste in each period.

### ***Network design under uncertainty***

In designing a new bioenergy network, stochastic programming (two-stage) has been used in a large number of models. For example, a stochastic MILP model was proposed by (Dal-Mas et al. [2011]) to design a biofuel SC under uncertainties related to the product price and cost of the feedstocks. The authors considered the net present value and the conditional value at risk as two objective functions in their model. Finding the optimal locations of biorefineries and supply sites is the main goal in the study. A stochastic programming model under price and demand uncertainties which was solved by simulation and a Benders decomposition algorithm was proposed in (Awudu and Zhang [2013]) for the planning of a biofuel SC. A bioethanol SC considering demand as uncertainty was modeled by a stochastic MILP and solved with two-stage method in (Kostin et al. [2012]). The sample average approximation method was used in that study in order to provide a set of configurations for facing uncertainty.

Chen and Fan [2012] presented a stochastic programming (two stage) model for resource allocation and strategic planning of a biofuel SC under uncertainty related to demand and supply. The authors solved it by using a decomposition algorithm based on Lagrange relaxation. In order to maximize the profit and decrease the carbon emissions with price, demand and supply uncertainties in a bioethanol supply chain, a two-stage stochastic MILP was also proposed by (Osmani and Zhang [2014]). In these studies, they were looking the

locations to install bio-refineries.

### ***Existing biorefineries under uncertainty***

There are few studies that focusing on production planning under uncertainty for existing biorefineries. (Tay et al. [2013]) proposed a scenario base stochastic optimization approach to determine the optimal production planning to generate syngas from forest residues biomass, selecting the type of technology and the flow of biomass are the decision in their study. Biomass supply and demand are uncertain parameters in their study. Production planning is explained in the existing biorefinery (under uncertainty) in more details in the following chapters.

## **2.2.6 Conclusion for the general literature review**

Figure 2.1 shows the outcomes of the literature review (Dal-Mas et al. [2011], Gonela et al. [2015], Kostin et al. [2012], Saghaei et al. [2020], Balaman and Selim [2015], Awudu and Zhang [2013], Santibañez-Aguilar et al. [2019], Mohseni et al. [2016], Chen and Fan [2012], Marvin et al. [2012], Razm et al. [2019b], Osmani and Zhang [2013], Khishtandar [2019]) concerning the bioenergy SC problems. It shows that there is an research gap to optimize bioenergy supply chains by considering a two-phase sequential approach containing the geographical information, sustainability, multi criteria decision making techniques, and uncertainty conditions. Note that the research gaps are explained in more details the related chapters.

This study vs. the bio-energy supply chain literature.

Article	Approach (Modeling)		Geographical information	Objective function	Decisions (Strategic)			Decisions (Tactical)			Social sustainability	MCDM techniques	Uncertain parameters			Uncertainty modelling approach	Final products		
	MoMILP	MILP			MINLP	Sourcing	Facilities		Biomass allocation	Biomass production			Transportation	Inventory planning	Biomass supply		Demand of products	Price of products	Costs
			Location	Capacity			Technology												
(Dal-Mas et al., 2011)	X			X	X	X	X	X	X	X	X	X						X	
(Gonela et al., 2015)	X			2	X	X	X	X	X	X	X	X						X	
(Kostin et al., 2012)	X			3,4	X	X	X	X	X	X	X	X						X	
(Saghaei et al., 2020)			X	1	X	X	X	X	X	X	X	X						X	
(Balamani and Selim, 2015)	X			2-7	X	X	X	X	X	X	X	X						X	
(Awudu and Zhang, 2013)	X			2	X	X	X	X	X	X	X	X						X	
(Santibañez-Aguilar et al., 2019)			X	2	X	X	X	X	X	X	X	X						X	
(Mohseni et al., 2016)	X		X	1	X	X	X	X	X	X	X	X						X	
(Chen and Fan, 2012)	X		X	1	X	X	X	X	X	X	X	X						X	
(Marvin et al., 2012)	X		X	3	X	X	X	X	X	X	X	X						X	
(Razm et al., 2019b)	X			3	X	X	X	X	X	X	X	X						X	
(Osmani and Zhang, 2013)	X			2	X	X	X	X	X	X	X	X						X	
(Khishtandar, 2019)			X	1	X													X	
<b>Proposed model</b>	X		X	1	X	X	X	X	X	X	X	X						X	

1= minimizing (expected) total cost/annual cost/unit cost. 2= maximizing (expected) total profit/annual income/net cash. 3= maximizing (expected) net present value. 4=minimizing expected (conditional) value at risk/investment financial risk. 5=minimizing investment cost. 6= minimizing annual transportation cost. 7= minimizing annual purchasing cost. 8= minimizing annual operational cost.

Figure 2.1 – Literature

## **2.3 Literature review for production planning in bioenergy supply chains**

The relevant studies can be classified into three categories. First, the studies that focused on production planning of the pre-processing plants producing the processed biomass for other biorefineries. Second, the studies that focused on designing a new network for producing bioenergy and/or biofuel from biomass. Their goal is to find the locations of the biorefineries (the suppliers and distribution centers) (Rentizelas and Tatsiopoulos 2010). Third, the studies that focused on production planning of an existing biorefinery. There are few studies in the third category.

### **2.3.1 Production planning in the preprocessing plants**

Eriksson and Björheden [1989] proposed a production planning model used for one pre-processing center to supply feedstocks for one biorefinery. The amount of biomass transported from different suppliers (forest regions), amount of stored biomass, and amount of chips production were the main decisions. However, the authors did not address the important features of the biomass like perishability and its effect on the output of the process.

Some studies considered the intermediate terminals where biomass quality (initial yield) is improved before delivering it to the biorefinery. Gunnarsson et al. [2004] and Gautam et al. [2017] proposed production planning models for the intermediate terminals supplying the feedstocks for the existing biorefineries. The models determine the amount of biomass to chip, store, and transport. The intermediate terminal was used for preprocessing, handling, and storage of biomass for a long time. Nonetheless, according to Kanzian et al. [2009], storing biomass in the intermediate site leads to increasing the total costs of supplying biomass for the biorefineries, because of more transportation, loading, and unloading of the biomass.

According to Gunnarsson et al. [2004] the stored biomass feedstocks have to be protected against rain, and also storing biomass feedstocks deteriorates the energy value of the biomass. Consequently, Gautam et al. [2017] considered two types of biomass storage at the intermediate terminals, storage under a shed and open-air storage. They assumed that the quality of the biomass feedstocks was more affected in the open-air storage. Unlike Kanzian et al. [2009], Gautam et al. [2017] highlighted that intermediate terminals have advantages in terms of reducing the costs of supplying biomass for the biorefinery. They

asserted that the intermediate terminal, using storage of biomass under shed (comparing with open-air storage), leads to more control on the quality of biomass. Therefore, the costs may be saved because of the biomass quality improvement. Although these studies considered quality of biomass, they focused on the decisions related to supplying biomass for other biorefineries rather than bioenergy production in the biorefinery. In other words, they focused on the flow of biomass feedstocks to the gate of the biorefineries.

### **2.3.2 Network desing in biorefineies**

A GIS (Geographic Information System) approach combined with a Mixed Integer Non-Linear Programming (MINLP) model was developed by Santibañez-Aguilar et al. [2019] for production planning of several biorefineries. Different agricultural biomass was used for biofuel and bioenergy production. The amount of biomass acquisition in one year, the amount of biofuel and bioenergy production, and the amount of storing and selling biofuel were determined in the production planning model. In this study, biomass quality and biomass storage were not considered, although the authors used the perishable biomass which is available at specific season.

Some studies considered a deterioration rate as biomass waste, and some others did not consider storage to prevent this biomass deterioration. Bairamzadeh et al. [2018b] proposed a production planning model for different biorefineries using agricultural biomass feedstocks. Unlike the former model (Santibañez-Aguilar et al. [2019]), Bairamzadeh et al. [2018b] considered biomass storage and biomass deterioration. They used a constant parameter (in the inventory constraint) as the deterioration rate of biomass in each period in the warehouse. It means that a percentage of the stored biomass is thrown away from the warehouse each month. Cambero et al. [2015] proposed an optimization model to generate bioenergy and biofuel from forest residues. The production planning was defined for several biorefineries. The model optimized the decisions such as the amount of purchased and assigned biomass, the amount of bioenergy and biofuel production, and the amount of biofuel storage. Non-merchantable logs, harvesting residues, wood chips, hog fuel, shavings, and sawdust were considered the biomass feedstocks. They announced that in order to prevent the deterioration of biomass, biomass storage is not considered in the study.

Note that biomass quality (different initial yield) and production planning are the links among three mentioned categories (Subsections 2.3.1, 2.3.2, 2.3.3).

Miret et al. [2016] and Zhang et al. [2016] also considered biomass deterioration in their models. Their production planning models involved storage biomass to generate bioethanol.

One year is considered as the length of the planning horizon and each month as one period. They considered a constant biomass deterioration rate during the storage. A percentage of stored biomass is considered as waste in each period.

The form of collecting biomass could affect the deterioration rate of the biomass and the costs of the production planning. Three forms of collecting switchgrass such as loose chop, square bales, and round bales were considered by Zhang et al. [2013] Figure 2.2 and 2.3 showshow the square and round bale of wheat straw. The loose chop was sent to the intermediate facilities for densification. Two other collecting forms of biomass, the square and round bales, could be stored at the farms (the biomass supply sites). Then, they directly are sent to the biorefineries. Although the loose chop created more transportation costs (not directly sent to the biorefineries), the model chooses the loose chop as the best harvesting way. They asserted that after preprocessing (creating more density), the dry matter loss decreases. In the same way, two forms of collecting biomass were considered by Larson et al. [2015]. They suggested the collection of biomass in the form of square bales is better, because it efficiently occupies the space of the warehouse, and also it is easier for transportation. Therefore, the square bale form was considered as more economical in their research, although they announced that the square bale form has more dry matter losses comparing with the round bale.



Figure 2.2 – Wheat straw round bale

Two studies, Castillo-Villar et al. [2017], Nur et al. [2021], incorporated the quality-related costs into a two-stage stochastic model. The quality costs impacted the decisions made in production planning. They considered biomass with different characteristics (moisture and ash content) coming from the suppliers (with different deterioration rates). Nur



Figure 2.3 – Wheat straw square bale

et al. [2021] suggested densification and preprocessing of biomass in the depots before converting the biomass into biofuel. They asserted densification and preprocessing of biomass can impact the biomass conversion process as well as the biomass transportation cost. They considered the distance between the suppliers and biorefineries to reduce the biomass quality loss over time. The amount of the purchased, stored, used biomass, and amount of the bioethanol production are the main decisions in the production planning model of this study.

In the literature related to bioenergy/biofuel production, the perishability of biomass was not very well applied into the production planning models. Most relevant works only considered a constant deterioration rate in the inventory constraint. It means that each period a percentage of the biomass is thrown away as waste. Nonetheless, the biomass perishability can affect the amount of biofuel obtained from the conversion process (Fuller 1985), and also the amount of bioenergy obtained from the conversion process (yield of biomass conversion) (Shabani and Sowlati 2013).

### **2.3.3 Production planning in existing biorefineries**

Shabani and Sowlati [2013], proposed an optimization model to maximize the total

profit of an existing biorefinery. Forest residues were considered as input biomass. One-year production planning with monthly periods was considered. The model involves procurement of biomass, storage, power production, and ash management (extra costs for removing ash after combustion process). The effect of biomass quality on the amount of generated electricity was considered in the model. In the power production constraint, they considered a static parameter (Quality Reduction Factor only at the specific conditions) that is multiplied by a binary variable and the variable of consumed biomass. They linked the binary variable to biomass storage. They assumed that the binary variable is equal to one if the storage level is lower than the storage lower limit in one period. It means that the biomass is kept in the smaller pile. This causes generating insufficient internal heat in the pile, so the quality reduction occurs (low temperature and wet environment).

However, according to Fuller [1985] the deterioration of biomass is a complex process that depends on many factors, and it does not happen only in the low temperature. The chemical reactions continuously occur and lead to losses of the valuable materials in the biomass over storage time.

In terms of energy storage, some studies introduced different methods and technologies to store energy. For instance: 1) using different kinds of battery (e.g., flow battery, lithium battery) (Kousksou et al. 2014; Wichmann et al. 2019); 2) using the compressed air storage system (He et al. 2021); 3) using thermochemical energy storage system (Wu et al. 2021); 4) using superconducting magnetic energy storage (Diezmartínez 2021). Some studies introduced biofuel as one way to store energy (Ma 2021). In contrast, to the best of my knowledge, no previous study considered biofuel as a way of storing energy in the production planning model for converting biomass-to-bioenergy and/or biofuel.

Note that the output gaps from this part (Literature review for production planning in bioenergy supply chains) are explain in more details in Chapters 3 and 4. The summary table for this part (Literature review for production planning in bioenergy supply chains) is proposed in Chapter 4.

## **2.4 Literature review for uncertainty in the production planning of bioenergy supply chains**

This part classifies relevant literature into the three classes. First, production planning in the preprocessing plants under uncertainty. These plants supply the processed feedstocks for other biorefineries. Second, a new network design for biorefineries under uncertainty. Find-

ing the locations of biorefineries (the distribution centers and suppliers) is the main goal in these studies. Third, production planning for an existing biorefinery under uncertainty. This one includes few studies. Note that production planning, biomass quality (initial yield) and uncertainty are the links among three classes (Subsections 2.4.1, 2.4.2, and 2.4.3).

### **2.4.1 Production planning in the preprocessing plants under uncertainty,**

One preprocessing center producing biomass for one biorefinery is considered in the study done by Eriksson and Björheden 1989. The main decisions in this study were the amount of transported biomass from different biomass sites, the biomass storage, and the amount of chips production in the preprocessing center. Nevertheless, they did not consider two important issues, perishable nature of biomass and uncertain conditions.

Intermediate terminals introduced by some studies (Gunnarsson et al. 2004, Gautam et al. 2017) to improve biomass quality (initial yield) instead of directly transferring the biomass to the biorefineries. However, according to Kanzian et al. 2009, because of more loading and unloading of the biomass and more transportation, storing biomass in intermediate centers increases the total costs in biomass supplying for biorefineries. The stored biomass must be protected against rain, as well as biomass storage deteriorates the energy value of the biomass (Gunnarsson et al. 2004). As a result, two methods for storing biomass at the intermediate terminals were considered by Gautam et al. 2017, open-air storage and storage under a shed. Unlike Kanzian et al. 2009, Gautam et al. 2017 asserted that intermediate terminals in which biomass is stored under shed (comparing with open-air storage) can reduce the total costs of supplying the biomass, due to more quality control on biomass. Even though biomass quality was taken into account, they only focused on decisions related to the flow of biomass to the gate of biorefineries (not inside the biorefinery). In addition, uncertainty is not considered in these studies.

Sharma et al. [2013b] proposed a scenario optimization model for a preprocessing site supplying biomass for other biorefineries under different weather scenarios. They used switchgrass as biomass feedstock, the objective function was minimizing the different costs for procuring of biomass, storage, rented and purchased equipment, transportation. They considered the effects of rainfall, temperature and daylight on the available working hours. Two methods for biomass storage methods were considered, unprotected bales on the ground and trapped bales on gravel. A constant percentage was considered as dry matter loss in each period. (Zamar et al. 2017) proposed a stochastic programming model to address

uncertainty related to the biomass supply and biomass demand in the preprocessing site that supplies biomass for other biorefineries. They used forest residues as biomass for feeding biorefineries generating power. Flow of biomass was the main decision in their study.

(Ahmadvand and Sowlati 2022) proposed a mathematical model to optimize the total cost of a biomass preprocessing site under uncertainty. It supplies forest biomass for biorefineries generating syngas. They considered intermediate storage in the supply chain in the form of open-pile storage. Biomass can be transferred from biomass sites to the intermediate sites, or can be directly transferred to preprocessing site. The flows of biomass as well as establishing intermediate storage are the main decisions in their study. Available biomass, cost of biomass, and demand for the processed biomass are the uncertain parameters. They used robust optimization to tackle the uncertainty (the row-wise robust optimization). They considered a percentage of biomass as waste in each period for biomass storage.

## **2.4.2 Network design in biorefineries under uncertainty**

Santibañez-Aguilar et al. 2019 proposed a GIS (Geographic Information System) approach combined with a Mixed Integer Non-Linear Programming (MINLP) model for production planning of several biorefineries. The amount of biomass obtained in one year, the amount of biofuel and bioenergy production were the main decisions. They used agricultural biomass that is perishable and available at specific season. However, they did not consider biomass quality, storage or uncertainty in their model.

In the literature, some study did not consider storage to prevent the biomass deterioration. Cambero et al. 2015 proposed an optimization model to generate biofuel and bioenergy from forest residues. The production planning was considered for several biorefineries with different capacities using hog fuel, sawdust, harvesting residues, non-merchantable logs, shavings, and wood chips. They asserted that biomass storage is not considered to prevent biomass deterioration. Some studies considered a deterioration rate as biomass waste. For example, (Miret et al. 2016, Zhang et al. 2016) consider biofuel production planning models including biomass storage and biomass deterioration over one year planning horizon with monthly time periods. A constant biomass deterioration rate during the storage (a percentage as waste) in each period was considered.

The collected biomass form can impact on the biomass deterioration rate, and production planning costs. Zhang et al. [2013] proposed three forms of biomass collection, round bales, square bales, and loose chop. Switchgrass with square bales and round bales were

stored at the farm, and then were directly sent to the biorefinery. However, the loose chop switchgrass was sent to the preprocessing site, and then it was sent to biorefinery (indirectly). The loose chop form was chosen as best way while it led to more transportation costs. They argued that the dry matter loss decreases after preprocessing (creating more density). Larson et al. [2015] also considered two forms of collecting biomass, square bales and round bales. Although the square bale form has more dry matter loss, their reason was that the square form is easier for transportation, as well as it efficiently occupies the space of the warehouse. These studies did not consider any uncertainty in the models.

Castillo-Villar et al. [2017] and Nur et al. [2021] incorporated the quality costs (affecting production planning decisions) into the two-stage stochastic model. Available biomass was considered as uncertainty parameter by defining different scenarios for that. They considered candidate locations for suppliers, biorefineries, and depots to design a bioenergy network. Biomass can be supplied by different suppliers and with different characteristics (moisture and ash content) to convert into bioethanol. Deterioration rate was considered as biomass waste for different types of biomass. Biomass preprocessing and densification were suggested by Nur et al. [2021] in depot sites to prevent losing the biomass as waste. In designing the biofuel network, they considered the distance between suppliers and biorefineries to reduce biomass quality loss over time. The main production planning decisions in this study are the amount of purchased, stored, and converted biomass to bioethanol.

Bairamzadeh et al. [2018a] proposed a hybrid robust optimization model for production planning of different biorefineries under uncertainty. They used agricultural biomass to generate bioethanol, mixed alcohols, electricity. Biomass storage with a deterioration rate- a constant parameter in the inventory constraint for each period-is considered. This study used a row-wise optimization method for demand uncertainty that is not appropriate method for such a uncertain parameter.

A two-stage stochastic MILP model was proposed by Osmani and Zhang [2013] to maximize the profit and minimize the carbon emissions. In this study, switchgrass is converted into bioethanol. Demand and price are uncertain parameters. Amount of switchgrass per hectare depends on average annual rainfall. They used annual data to define a regression model to predict the amount of switchgrass during planning horizon. They did not consider biomass storage.

The amount of biofuel and bioenergy obtained from conversion process (yield of biomass conversion) can be impacted by perishability (Fuller 1985, Shabani and Sowlati 2013). However, in the literature related to production planning for biofuel and/or bioenergy,

biomass perishability was not very well applied into the mathematical models. Most of the studies considered a constant rate for deterioration in the inventory constraint meaning that a percentage of biomass is throw away as waste.

### **2.4.3 Production planning in existing biorefineries under uncertainty**

An optimization model for one-year production planning with monthly periods was proposed by Shabani and Sowlati [2013] to maximize the total profit of an existing biorefinery. Forest residues were considered as input biomass for this biorefinery. They considered biomass procurement, biomass storage, production of power, and ash management (after combustion process, extra costs considered for ash cleaning). The amount of bioenergy obtained from the converting process can be impacted by biomass quality. They defined a static parameter (Quality Reduction Factor only at the specific conditions) in the power production constraint that is multiply by the variable of consumed biomass and a binary variable . The binary variable is linked to biomass storage. It was assumed that the binary variable is equal to one if the storage level is lower than the storage lower limit. This means that the biomass is kept in the smaller pile. This causes generating insufficient internal heat in the pile, so the quality reduction occurs (low temperature and wet environment). Shabani and Sowlati 2013 was extend by Shabani et al. 2014 by introducing available biomass as uncertain parameter, then they used two-stage stochastic programming by defining different scenarios for available biomass. Shabani et al. 2014 was extended by Shabani and Sowlati 2016 by introducing conversion yield as second uncertain parameter when storage is lower than the storage lower limit. They used robust optimization to tackle the second uncertainty (a row-wise robust optimization approach). In Shabani et al. 2014 and Shabani and Sowlati 2016, the quality reduction occur only at the specific conditions.

Nevertheless, the biomass deterioration is a complex process that depends on many factors, and it does not happen only in the low temperature according to Fuller [1985]. Over storage time, the chemical reactions continuously occur and cause losing the valuable materials of the biomass.

In terms of energy storage, different methods and technologies were introduced to store energy in the literature. For example: 1) using the compressed air storage system (He et al. 2021); 2) using different kinds of battery (e.g., flow battery, lithium battery) (Kousksou et al. 2014; Wichmann et al. 2019); 4) using superconducting magnetic energy storage (Diezmartínez 2021); 3) using thermochemical energy storage system (Wu et al. 2021).

Some studies introduced biofuel as one way to store energy (Ma 2021). Nevertheless, there is no previous study to the best of my knowledge that considers biofuel as a way of storing energy in the production planning model for converting biomass-to-biofuel and/or bioenergy.

Note that the output gaps from this part (Literature review for uncertainty related to the production planning in bioenergy supply chains) are explained in more details in Chapter 5. In addition, a summary table for this part (Literature review for uncertainty related to the production planning in bioenergy supply chains) is proposed in Chapter 5.

# A MULTI-PERIOD BIOENERGY PRODUCTION PLANNING MODEL WITH PERISHABLE BIOMASS

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## 3.1 Introduction

Biomass, the clean feedstock for generating energy, has gotten attention compared to fossil fuels in recent years. This valuable material has some features affecting the total supply chain. Biomass availability and biomass perishability are two challenges for biorefineries in their production planning. One way to tackle the biomass availability problem (in the different sessions) is biomass storage. However, biomass is a perishable feedstock (Tavanandi et al. [2018], Castillo-Villar et al. [2017]). Storage of biomass for a long time has an impact on its quality. This is due to some chemical reactions that occur during storage (Fuller [1985], Kenney et al. [2013]). Biomass quality plays a prominent role in the production process (Rentizelas et al. [2009]), so it influences the production planning of the biorefineries.

In this study, a multi-period production planning model is proposed for the biorefineries to maximize their total profit. The following decisions can be optimally made by the model.

- How much biomass should be purchased, stored, assigned, and converted?
- How much biofuel and bioenergy should be generated?
- How much bioenergy and biofuel should be sold to the customers in each period?

It is obvious that classical production planning models that consider perishability are limited and this can result in generating suboptimal or even infeasible solutions. Therefore, in this study the contributions are as follows:

- For production planning of the bio-refineries, a mathematical model is developed.
- The issue of the perishability of biomass is incorporated in the model of production planning.

The structure of this chapter is as follows: Section 2 presents the problem statement. Section 3 describes the model formulation. Section 4 describes the implementation and evaluation of the introduced model. Finally, in addition to the conclusion, some future studies to extend this study are suggested in Section 5.

## 3.2 Problem definition

The framework of the supply chain is illustrated in Figure 3.1. Existence of the conversion technologies and warehouses are usually common in the biorefineries. In Figure 3.1 , different kinds of biomass feedstock are shown by B. The age of biomass is shown by A. The different period is presented by T. Biofuel is shown by F. Bioenergy is presented by E. More explanation is represented by the superscripts in the notations, although the indices presented in the subscripts (e.g., t in  $F_t^C$ ). This model considers one single biorefinery but it can be easily extended to the multiple-refinery case. Biomass feedstocks (which are fresh) such as forest residues, agricultural residues, and crop-based biomass are purchased for biorefinery ( $X_{b,0,t}$ ) (Kusumastuti et al. [2016], Razm et al. [2021b]). The biomass feedstocks, which are perishable materials ( $I_{b,a,t}^B$ ) (Tavanandi et al. [2018]), are stored in the warehouse. Keeping biomass feedstock in the warehouse leads to aging of the biomass. The longer the biomass is stored in the warehouse, the more perishability (more chemical reactions) will occur (Fuller [1985]). As a result, the biomass quality decreases. This change could affect the conversion process of the biomass (Kenney et al. [2013], Nur et al. [2021]).

Then as shown in Figure 3.1, the biomass feedstocks are assigned to the technologies. The first kind of technology can transform the biomass ( $X_{b,a,t}^E$ ) to electricity and heat as bioenergy. The second kind of technology can transform the assigned biomass ( $X_{b,a,t}^F$ ) to biodiesel and bioethanol as biofuel. The generated biofuel ( $F_t$ ) can be stored in the warehouse (the biofuel storage) then it will be sold to the customer. However, the heat or electricity generated from biomass is immediately sold to the customer ( $E_t^B$ ).

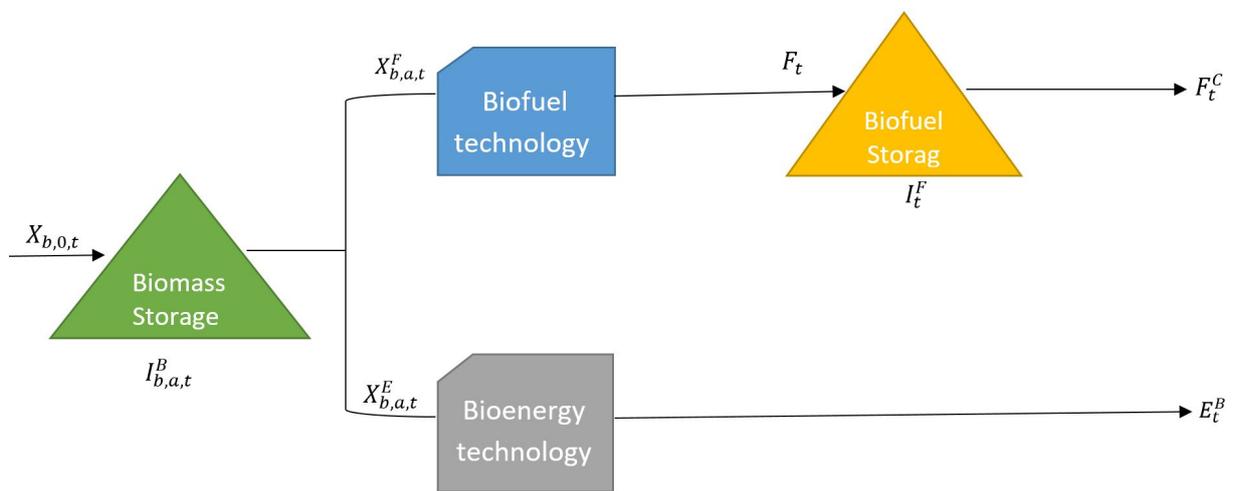


Figure 3.1 – Framework of the bioenergy production system

Table 3.1 – Mathematical notations of the model

Symbol Definition	
$B$	Set of biomass feedstock types; index $b \in B$
$A$	Set of biomass age; index $a \in A$
$T$	Set of periods; index $t \in T$
Parameter	
$p^F$	Biofuel selling price (\$/unit of product)
$p^E$	Bioenergy selling price (\$/MWh)
$c_{b,t}^B$	Cost of purchasing <i>fresh</i> biomass $b$ in period $t$ (\$/t)
$c_{b,t}^{BF}$	Cost of converting biomass $b$ to biofuel in period $t$ (\$/t)
$c_{b,t}^{BE}$	Cost of converting biomass $b$ to bioenergy during period $t$ (\$/t)
$h_b^B$	Cost of holding biomass $b$ (\$/t)
$h^F$	Cost of holding biofuel (\$/unit of product)
$\omega_{b,t}$	Available biomass $b$ at the supply sites in period $t$ (tonne)
$\alpha_{b,a}^F$	The yield of biofuel when using the biomass with age $a$ (unit of product output/tonne of biomass input).
$\alpha_{b,a}^E$	The yield of bioenergy when using the biomass with age $a$ (unit of product output/tonne of biomass input).
$D_t^{Fmax}$	Maximum demand for biofuel (unit of product)
$D_t^{Emax}$	Maximum demand for bioenergy (MWh)
Decision variable	
$F_t$	The total amount of biofuel produced in period $t$ (unit of product)
$F_t^C$	Amount of biofuel sent directly to the customers in period $t$ (unit of product)
$E_t^B$	Amount of bioenergy obtained from converting biomass ( MWh )
$X_{b,a,t}$	Amount of purchased biomass $b$ with age $a$ in period $t$ (t)
$X_{b,a,t}^F$	Amount of biomass $b$ with age $a$ that is used as input for biofuel technology in period $t$ (t)
$X_{b,a,t}^E$	Amount of biomass $b$ with age $a$ that is used as input for bioenergy technology in period $t$ (t)
$I_{b,a,t}^B$	Amount of biomass $b$ with age $a$ stored in the biomass storage in period $t$ (t)
$I_t^F$	Amount of biofuel stored in the biofuel storage in period $t$ (unit of product).

### 3.3 Mathematical model

This study proposes a linear mathematical programming model for the optimal planning of the biorefineries generating biofuel and bioenergy from (perishable) biomass. The developed model is formulated as follows (considering symbols defined in Table 3.1).

The objective function is to maximize the total profit of the biorefinery corresponding to the total revenues (selling bioenergy and biofuel) minus total costs. The total costs refer to costs of: 1) supplying the biomass feedstock(fresh), 2) production or process of transforming biomass to biofuel, 3) transforming biomass to bioenergy, 4) biomass inventory (biomass storage), and 5) biofuel inventory (biofuel storage).

$$\begin{aligned} \text{Maximize } & \sum_t (p^F \cdot F_t^C + p^E \cdot E_t^B) - \sum_b \sum_a \sum_t (c_{b,t}^B \cdot X_{b,a,t} + c_{b,t}^{BF} X_{b,a,t}^F + c_{b,t}^{BE} X_{b,a,t}^E) \\ & - \sum_b \sum_a \sum_t h_b^B \cdot I_{b,a,t}^B - \sum_t h^F \cdot I_t^F \end{aligned} \quad (3.1)$$

$$X_{b,0,t} \leq \omega_{b,t} \quad \forall b, t \quad (3.2)$$

$$I_{b,0,0}^B = 0 \quad \forall b \quad (3.3)$$

$$X_{b,0,t} = I_{b,0,t}^B + X_{b,0,t}^F + X_{b,0,t}^E \quad a = 0, \forall b, t \quad (3.4)$$

$$I_{b,a-1,t-1}^B = I_{b,a,t}^B + X_{b,a,t}^F + X_{b,a,t}^E \quad \forall b, t, a \in A \setminus \{0\} \quad (3.5)$$

$$I_0^F = 0 \quad (3.6)$$

$$I_{t-1}^F + F_t = I_t^F + F_t^C + F_t^E \quad \forall b, t \quad (3.7)$$

$$\sum_b \sum_a \alpha_{b,a}^F \cdot X_{b,a,t}^F = F_t \quad \forall t \quad (3.8)$$

$$\sum_b \sum_a \alpha_{b,a}^E \cdot X_{b,a,t}^E = E_t^B \quad \forall t \quad (3.9)$$

$$F_t^C \leq D_t^{Fmax} \quad \forall t \quad (3.10)$$

$$E_t^B \leq D_t^{Emax} \quad \forall t \quad (3.11)$$

$$X_{b,a,t}, X_{b,a,t}^F, X_{b,a,t}^E, F_t, F_t^C, E_t^B, I_t^F, I_{b,a,t}^B \geq 0 \quad \forall b, a, t \quad (3.12)$$

Constraints (3.2) represent the limitation of biomass availability. Constraints (3.3)-(3.5) indicate that in each period, the inventory of biomass should be balanced. Constraints (3.3) ensure that at the beginning of the planning horizon the biomass warehouse is empty. This involves all kinds of biomass. Constraints (3.4) are for fresh biomass that ensure the

amount of biomass assigned to the technology for transforming biomass to bioenergy, plus the amount of biomass assigned to the technology for transforming biomass to biofuel, plus inventory biomass must be equal to the amount of biomass supplied for the biorefinery. Constraints (3.5) are for old biomass that ensure the amount of biomass assigned to the technology for converting biomass to bioenergy, plus the amount of biomass to assigned to the technology for converting biomass to biofuel plus biomass inventory at period  $t$  have to be equal to the inventory of biomass at period  $t-1$ .

Constraints (3.6) ensure that at the beginning of the planning horizon the biofuel warehouse is empty. Constraints (3.7) guarantee that the amount of biofuel is directly sold to the customer, plus the inventory of biofuel at period  $t$  have to be equal to the amount of biofuel generated at period  $t$ , plus the inventory of biofuel at period  $t-1$ .

Constraints (3.8) and (3.9) are related to the effect of perishability on the production. Constraints (3.8) ensure that amount of production yield of biomass (to biofuel) is related to the quality of biomass (in case of using fresh biomass or old biomass). The yields obtained from the fresh/old biomass must be equal to the total generated biofuel in the biorefinery. Constraints (3.9) ensure that amount of production yield of biomass (to bioenergy) is related to the quality of biomass (in case of using fresh biomass or old biomass). These yields obtained from the fresh/old of biomass have to be equal to the total generated bioenergy in the biorefinery.

Constraints (3.10) ensure that amount of biofuel to sell to the customer could not be more than the maximum demand of the biofuel. Constraints (3.11) ensure that amount of bioenergy to sell to the customer could not be more than the maximum demand of the bioenergy. Constraints (3.12) guarantee that the decision variables in this model have to be non-negativity.

## 3.4 Results

Using an Intel Core i7, 2.11 GHz processor with 32 GB of RAM the model was implemented. All codes and experiments were done in GAMS 24 using CPLEX solver. The results of the experiments are as follows.

### 3.4.1 The biomass perishability effects

The goal here is to show how biomass perishability impacts the production planning of the biorefinery. Two types of biomass in terms of biomass perishability exist in the study

(biomass which is old or fresh). Four ages for biomass are considered in this study. The ages start from zero to 3. Biomass with an age more than zero is considered as old biomass, and the age of fresh biomass is equal to zero. The old biomass with different ages has a different quality, so the production yield of biomass is different for each age. The production yield of biomass is calculated using  $\alpha_{ba}^F = \alpha_{b,0}^F \times (1 - m \times \lambda\%)$ , where  $\lambda$  is the effect of biomass perishability on the yield. The specific age of biomass is represented by  $m$ . In other words, since each age is equal to one period,  $\lambda$  is the perishability rate (%) of biomass in each period.

According to the experts' opinion ([www.satba.gov.ir](http://www.satba.gov.ir)), in each month the perishability of biomass could have 5% effects on the biomass yield. Accordingly, using a base case, the model is run considering the effect of biomass perishability is 5%. The results of this experiment under the base case (four ages, and 5% effect of perishability) are shown in Table 3.2.

Table 3.2 – The optimal solution of the base case

The total profit (\$)	9.94E+07
The total revenue (\$)	3.42E+08
The total costs (\$)	2.42E+08
The fresh stored biomass (in the different periods) (t)	315797

### 3.4.2 The perishable biomass analysis

In this part, in order to analyze the effect of perishability, the model has been run several times, in each time the perishability rate has been changed in a range between zero and one hundred. The total profit of the biorefinery and biomass inventory is considered as outputs of this experiment. Figure 3.4 shows the total profit of the biorefinery is decreased by about 13% when the perishability rate is increased by 50%. The 50% is an important point. After that, the profit of the biorefinery does not change anymore. It means after 50%, the perishability of biomass could not affect the biorefinery.

One important note here is that the biomass price is considered constant (as an assumption), even when the perishability rate of biomass increases. Increasing the perishability rate (from 0% to 50%) leads to reducing the production yield (in the next period or after one age). It should be mentioned that at the beginning the feedstock is fresh. As a result, the total profit decreases. After 50%, it does not matter for the biorefinery to buy biomass

which has a high level or low level of perishability rate (see figures 3.2 and 3.3, since both kinds of biomass lead to the same profit.

Now in this part, it is assumed that the purchasing price of biomass can change by changing the quality of biomass. Under this condition, the model is run. In other words, it is assumed that if the biorefinery buys biomass with a low level of perishability (e.g., 50%), it must pay more costs than buying biomass with a high level of perishability (e.g., perishability rate is 100%). When the perishability rate is 100%, it means that the biomass will be considered as waste in the next period if it is not immediately used in the first period.

In this condition, it is reasonable that the manager of biorefinery purchases the biomass which can be used in the other periods, because it makes more opportunities for the biorefinery. In other words, it is not a good idea that the manager purchases the biomass which must be immediately consumed in the first period (i.e., the biomass with 100% perishability rate).

Nevertheless, after running the model, the obtained results were not what had been expected. The results were surprising. From 50% to 100%, the profit of biorefinery got started to grow. This means buying biomass with a high perishability rate is better for biorefinery. The results were deeply surveyed once again to understanding this behavior of the model. Biomass storage is the answer. The model decides to empty the warehouse after 50% perishability rate. Therefore, the biorefinery prefers to purchase cheaper biomass. In other words, the biorefinery does not store the purchased biomass (after 50%), so the perishability does not affect the yield. Consequently, the yields are identical. As a result, the biorefinery selects the biomass which has a high perishability rate and low price to obtain more profit.

## 3.5 Conclusion

This chapter proposed a production planning model for biorefineries converting different kinds of biomass to biofuel and bioenergy. One processing unit, in which biofuel storage and biomass storage are allowed, was considered. Over different periods, the production planning problem was modeled and solved. The perishability of biomass which was not enough considered in the literature was incorporated in the model. Then, the effects of perishability on the profit of the biorefinery were studied. The proposed model had one main feature. It could control the inventory of biomass in terms of perishability when the

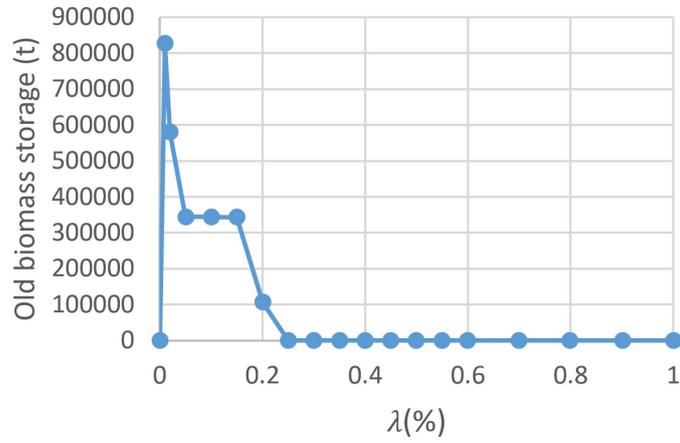


Figure 3.2 – Old biomass storage under perishability

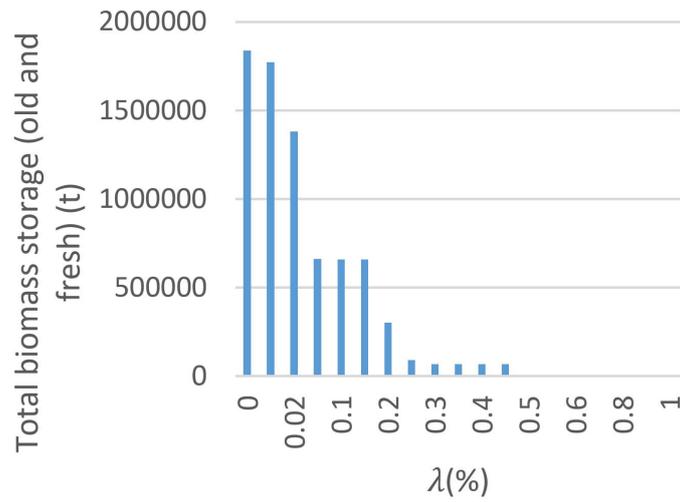


Figure 3.3 – Total biomass storage under perishability

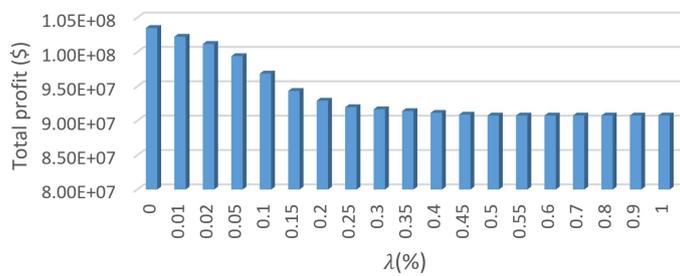


Figure 3.4 – Total profit under perishability

biomass could have different ages in the warehouse. After solving the model, the results showed that the total profit of the biorefinery is significantly changed under the effects of perishability. This demonstrates the importance of perishability in the production planning problem. This study could be extended in some ways. First, incorporating sustainability in the model. For example, taking into account the carbon policy which the biorefinery has to follow. Second, incorporating international logistics in the study. Finally, incorporating the model with the value of money over the planning horizon, in terms of financial calculations.

# A PRODUCTION PLANNING MODEL FOR BIOREFINERIES WITH BIOMASS PERISHABILITY AND BIOFUEL TRANSFORMATION

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## 4.1 Introduction

The increasing concerns related to the energy demand and environmental problems made by using fossil fuels have led scientists to think about renewable energy as a clean alternative. In particular, bioenergy and biofuel have become very attractive due to the large diversity of resources available for such energies (Sharma et al. 2013b; Razm et al. 2021a). Different categories of biomass feedstocks can be converted to bioenergy/or biofuel using different technologies (Yue et al. 2014; Ben Daya and Nourelfath 2019). This study can be adapted to any biomass category and technology, producing bioenergies and biofuels.

Although using biomass has advantages in generating energy compared with fossil fuels, there are some barriers to its utilization. Such barriers include uncertainty and seasonality of available biomass in addition to its perishability (Rentizelas et al. 2009) that impact the performance of the bioenergy production process. Here This study defines biomass yield as the bioenergy and/or biofuel output over the amount of input biomass. Perishability is defined as a decrease in biomass yield over time. In other words it is a consequence of the *aging* of biomass in storage. The *perishability rate* (the speed at which perishability takes place) differs from one biomass to another. It happens mainly because of chemical reactions. Hence, This study distinguishes between the initial yield corresponding to that of fresh (zero age) biomass and the yield of "old" biomass at the beginning of each period. Again, this initial yield differs from one biomass to another.

In this study, a mathematical model is proposed to optimize the bioenergy production

system. The objective is to maximize the profit of the biorefinery. The model optimizes the following decisions:

1. The quantity of purchased, stored, assigned, and converted biomass (into bioenergy or biofuel).
2. The amount of generated bioenergy and biofuel as well as the amount of stored biofuel.
3. The amount of bioenergy and biofuel to sell.

This model has two main features. First, controlling biomass perishability by monitoring the age of biomass. Second, storing energy in the form of non-perishable biofuel which can be kept in the warehouse and converted into bioenergy whenever required. The energy storage has two advantages: i) Matching the supply of bioenergy with the dynamic demand; ii) Tackling the issue of storage limitation of biomass due to perishability or storage capacity.

Effective management and planning of the biorefinery have a prominent impact on decreasing production costs and making biomass a valuable source of energy. Operations research and mathematical modeling can be used to accomplish that. Different models have been developed to optimize the production planning of the biorefineries (Cambero et al. 2015; Santibañez-Aguilar et al. 2019; Uhlemair et al. 2014; Palak et al. 2014 ). However, the effect of biomass perishability is not effectively incorporated in most of these models. Storing energy is another challenge in production planning, because it is not economic on a large scale or not technically feasible. According to the European Commission ([www.ec.europa.eu](http://www.ec.europa.eu)), consumption of energy has to match its generation. This balance is essential to maintain a safe and stable supply of energy. Biofuel storage allows more flexibility on when to generate bioenergy and therefore helps to match energy supply with demand. In the literature related to the production planning of bioenergy from biomass, energy storage is rarely considered.

The related literature is proposed in Chapter 2 in Section 2.3. Figure 4.1 shows the results of the literature review. In Figure 4.1, the generic type of feedstock means using more than one type of biomass (e.g. forest residues as well edible biomass). Monitoring the age of biomass means controlling the time length of storing fresh biomass. Biomass loss means throwing biomass away from the warehouse as waste. Static quality reduction means reducing (not continuously) the biomass quality (the valuable materials) only at specific conditions (e.g. low temperature). Dynamic quality reduction means reducing (continuously) the biomass quality based on biomass aging. Energy storage in the form of biofuel

means storing the biofuel which will be converted into bioenergy inside the biorefinery later. Of course, other papers considered biofuel storage, but our main interest here is in the conversion of biofuel into bioenergy inside the biorefinery and the integration of this decision into the biorefinery production planning model. The yield of biomass conversion impacted by biomass quality means changing the amount of output by changing the quality of input (biomass). The planning horizon is divided into three columns: i) continuous-time horizon; ii) discrete-time horizon (e.g., one year with weekly periods); iii) single period. Both the continuous and discrete-time horizons are multi-period.

As shown in Table 4.1, there is a research gap in production planning for a biorefinery using perishable biomass. The perishability of biomass and energy storage need to be incorporated in the production planning models. This study tries to fill this gap.

In this chapter, one existing biorefinery is considered. A planning horizon of 1 year divided into time periods is considered, one period is equal to one month. a dynamic biomass quality reduction (based on the age of biomass) is considered over storage time and this impacts the yield of the biomass conversion. It means that the yield of biomass conversion is dynamically reduced over time, because perishability is a dynamic process. Note that the applicability of the proposed model is general, and it can also be applied for two other cases (the static quality reduction and the biomass loss (Shabani and Sowlati 2013, Bairamzadeh et al. 2018b)). Moreover, in this study, biofuel is considered as a method to store energy that can be converted to bioenergy later inside the biorefinery.

Accordingly, the contributions of this study are as follows:

1. Developing a mathematical model for production planning of biorefineries.
2. Incorporating dynamic perishability of biomass into the production planning model.
3. Biomass can be transformed into either bioenergy or biofuel, which in turn can be stored and then transformed into bioenergy.
4. Incorporating energy storage (through biofuel storage) into the production planning model to match supply with demand.
5. Monitoring the biomass age to manage biomass perishability and biorefinery profitability.

The optimization model is developed and numerical experiments are conducted to derive managerial insights. Some of the results suggest that.

1. There is a threshold value on the perishability rate above which perishability does not have any longer impact on the profit. In this case, the manager should buy the

less expensive biomass regardless of its perishability rate.

2. Energy storage under the form of biofuel results in considerable increase in profit and smoother production at the facility even when there is a high fluctuation in price and demand.
3. The decision maker could choose to impose a maximum age (maximum storage time) of the biomass to enhance quality and reduce health risks. In this case, the model provides guidelines for this choice with the least significant impact on profit.

The remainder of the article is structured as follows: The problem definition is presented in Section 4.2. In Section 4.3, the model formulation is presented. The case study is described in Section 4.4. This study conducts the experiments in Section 4.5 and drive insights. In Section 4.6, the conclusions and the future research directions are proposed.

Article	Feedstock	Inventory planning			Perishability (in the stor-age)			Conversion technology			Energy storage	The yield of biomass conversion	Planning horizon		
		Biomass storage	Monitoring the biomass age	Biofuel storage	Biomass loss	Static quality reduction	Dynamic quality reduction	Biomass preprocessing	Biomass to biofuel	Biomass to bioenergy			In the form of biofuel	Impacted by biomass quality	Continuous (multi-period)
Eriksson and Björheden (1989)	Specific/Generic	X						X				X			
Gunnarsson et al. (2004)	S	X						X					X		
Kazian et al. (2009)	S	X						X					X		
Zhang et al. (2013)	S	X				X		X					X		
Larson et al. (2015)	S	X				X		X					X		
Shabani and Sowlati (2013)	S	X											X		
Akhtari et al. (2014)	S	X								X			X		
Dansereau et al. (2014)	S	X								X			X		
Cambero et al. (2015)	S			X				X	X	X			X		
Miret et al. (2016)	G	X		X			X	X	X	X			X		
Zhang et al. (2016)	S	X					X	X	X	X			X		
Gautam et al. (2017)	S	X								X			X		
Castillo-Villar et al. (2017)	S									X			X		
Bairamzadeh et al. (2018)	S	X		X			X	X	X	X			X		
Santibañez-Aguilar et al. (2019)	G			X						X				X	
Nur et al. (2021)	G	X				X		X	X	X			X		
<b>Proposed model</b>	G	X	X	X	X	X	X	X	X	X	X		X	X	

Figure 4.1 – Literature2

## 4.2 Problem definition

The general structure of a bioenergy production system is shown in Figure 4.2. In one biorefinery, there are usually some conversion technologies (Cheng and Anderson 2017) and warehouses as shown in Figure 4.2. In this Figure,  $B$  is a type of biomass (as feedstock), and  $A$  is the age of biomass.  $T$  represents periods,  $F$  shows biofuel, and  $E$  means bioenergy. In this study, the subscripts represent the indices (not superscripts). The superscript in the notation is only used for more description of the notation (e.g., in  $E_t^B$ ,  $B$  is not an index). Only one biorefinery is considered in the example of bioenergy production system, although more than one biorefinery can be also used.

Different kinds of fresh biomass (e.g., crop-based biomass, agricultural wastes, forest residues, etc.) are brought to the biorefinery ( $X_{b,0,t}$ ) (Kusumastuti et al. 2016). The biomass, the perishable product (Tavanandi et al. 2018), is stored in the biomass warehouse ( $I_{b,a,t}^B$ ). The more time for storing biomass, the more age it has. The more age, the more perishability. Thus, the quality of the biomass will change. The biomass quality can impact the biomass conversion process (Kenney et al. 2013; Nur et al. 2021).

In the next stage, the biomass is assigned to two types of conversion technology. The first type of technology converts the biomass ( $X_{b,a,t}^F$ ) to the biofuel such as bioethanol, biodiesel, pellet. The second one converts the biomass ( $X_{b,a,t}^E$ ) to the bioenergy such as heat and electricity (Razm et al. 2021b). The heat or electricity made from biomass is immediately sold after generating ( $E_t^B$ ). However, the generated biofuel ( $F_t$ ) is stored in the biofuel warehouse. The stored biofuel ( $I_t^F$ ) can be sold as biofuel or bioenergy (as stored energy). It means there are two ways for selling the stored biofuel. First, biofuel can be directly sold to the customer as biofuel ( $F_t^C$ ). Second, biofuel can be assigned to the technology ( $F_t^E$ ) to convert to bioenergy, then the bioenergy made from the biofuel ( $E_t^F$ ) will be sold to the customer. Consequently, in the second way, the biofuel can be stored in the biofuel storage for a long time, so the bioenergy which will be made from it also can be stored for a long time.

Unlike the basic bioenergy production systems (without energy storage), the proposed bioenergy production system (with energy storage) can store bioenergy for a long time. Energy storage is one of the challenges that the basic bioenergy production systems (without energy storage) are facing with. In planning for the biorefinery production, when consumption of energy does not match the generation of that (because of fluctuation in demand, price, available biomass, etc.), the energy storage can make the required balance for smoother production to provide a safe and stable supply of energy ([www.ec.europa.eu](http://www.ec.europa.eu)).

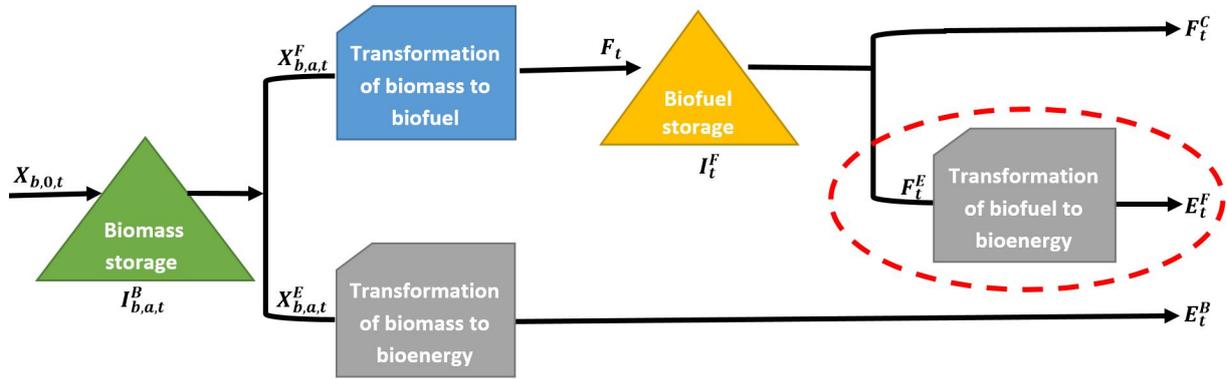


Figure 4.2 – Illustrative figure of the bioenergy production system.

In terms of the energy storage application, the difference between the basic bioenergy production systems (without energy storage) and the proposed bioenergy production system (with energy storage) is shown by the red ellipse in Figure 4.2, and it can be easily applied to the basic bioenergy production systems (without energy storage).

### 4.3 Model formulation

In this study, a multi-period linear programming mathematical model is developed for the optimal planning and operation of the bioenergy production systems. Before formulating the problem, the verbal description of the bioenergy production system is presented to better understand the mathematical model:

$$\text{Maximize profit} = \quad [\text{Biofuel revenue} + \text{Bioenergy revenue}] \\ - [\text{Biomass costs} + \text{Production costs} + \text{Inventory costs}]$$

Subject to :

- Biomass availability constraints
- Biomass inventory balance equations
- Biofuel inventory balance equations
- Demand constraints
- Production (conversion) equations

Table 4.1 presents the notations which will be used in the mathematical model.

Table 4.1 – Decision variables, parameters, and sets of the model

Symbol Definition	
$B$	Set of biomass feedstock types; index $b \in B$
$A$	Set of biomass age; index $a \in A$
$T$	Set of periods; index $t \in T$
Parameter	
$p^F$	Biofuel selling price (\$/unit of product)
$p^E$	Bioenergy selling price (\$/MWh)
$c_{b,t}^B$	Cost of purchasing <i>fresh</i> biomass $b$ in period $t$ (\$/t)
$c_{b,t}^{BF}$	Cost of converting biomass $b$ to biofuel in period $t$ (\$/t)
$c_{b,t}^{BE}$	Cost of converting biomass $b$ to bioenergy during period $t$ (\$/t)
$c_t^{FE}$	Cost of converting biofuel to bioenergy during period $t$ (\$/unit of product)
$h_b^B$	Cost of holding biomass $b$ (\$/t)
$h^F$	Cost of holding biofuel (\$/unit of product)
$\omega_{b,t}$	Available biomass $b$ at the supply sites in period $t$ (tonne)
$\alpha_{b,a}^F$	The yield of biofuel when using the biomass with age $a$ (unit of product output/tonne of biomass input).
$\alpha_{b,a}^E$	The yield of bioenergy when using the biomass with age $a$ (unit of product output/tonne of biomass input).
$\eta^{FE}$	The yield of bioenergy when using the biofuel (unit of product output/unit of product input)
$D_t^{Fmax}$	Maximum demand for biofuel (unit of product)
$D_t^{Emax}$	Maximum demand for bioenergy (MWh)
Decision variable	
$F_t$	The total amount of biofuel produced in period $t$ ( $F_t = F_t^C + F_t^E$ ), (unit of product)
$F_t^C$	Amount of biofuel sent directly to the customers in period $t$ (unit of product)
$F_t^E$	Amount of biofuel used as input for the technology converting biofuel to bioenergy in period $t$ (unit of product)
$E_t^F$	Amount of bioenergy obtained from converting biofuel ( MWh )
$E_t^B$	Amount of bioenergy obtained from converting biomass ( MWh )
$X_{b,a,t}$	Amount of purchased biomass $b$ with age $a$ in period $t$ (t)
$X_{b,a,t}^F$	Amount of biomass $b$ with age $a$ that is used as input for biofuel technology in period $t$ (t)
$X_{b,a,t}^E$	Amount of biomass $b$ with age $a$ that is used as input for bioenergy technology in period $t$ (t)
$I_{b,a,t}^B$	Amount of biomass $b$ with age $a$ stored in the biomass storage in period $t$ (t)
$I_t^F$	Amount of biofuel stored in the biofuel storage in period $t$ (unit of product).

### 4.3.1 Objective function:

The objective function (4.1) in the proposed model maximizes the total profit (the total revenues minus total costs). The total revenues include the revenues obtained from: 1) selling biofuel directly to the customer; 2) selling bioenergy that is generated from biomass; 3) selling bioenergy that is generated from biofuel. The total costs include the costs enforced by: 1) purchasing the fresh biomass; 2) converting biomass to biofuel (production costs); 3) converting biomass to bioenergy; 4) converting biofuel to bioenergy; 5) the inventory holding of biomass; and 6) the inventory holding of biofuel.

$$\begin{aligned} \text{Maximize } & \sum_t \left( p^F \cdot F_t^C + p^E \left( E_t^B + E_t^F \right) \right) - \sum_b \sum_a \sum_t \left( c_{b,t}^B \cdot X_{b,a,t} + c_{b,t}^{BF} X_{b,a,t}^F + c_{b,t}^{BE} X_{b,a,t}^E \right) \\ & - \sum_t c_t^{FE} \cdot F_t^E - \sum_b \sum_a \sum_t h_b^B \cdot I_{b,a,t}^B - \sum_t h^F \cdot I_t^F \end{aligned} \quad (4.1)$$

### 4.3.2 Constraints:

Constraints (4.2) ensure that amount of the biomass  $b$  with age  $a=0$  (fresh biomass) coming from the suppliers could not be more than the available biomass in each period.

$$X_{b,0,t} \leq \omega_{b,t} \quad \forall b, t \quad (4.2)$$

Constraints (4.3)-(4.5) ensure the mass balances of biomass feedstocks (the fresh or aged biomass) in each period. In constraints (4.3), the amount of the fresh biomass coming from suppliers (i.e.  $X_{b, a=0,t}$ ) are equal to the amount of the fresh biomass inventory (i.e.  $I_{b,a=0,t}^B$ ), plus the amount of fresh biomass assigned to the biofuel technology (i.e.  $X_{b,a=0,t}^F$ ), plus the amount of fresh biomass assigned to the bioenergy technology (i.e.  $X_{b,a,t}^E$ ). Constraints (4.3) are corresponding to the fresh biomass ( $a = 0$ ).

Constraints (4.4) ensure that the inventory of each type of biomass with age  $a-1$  at the end of period  $t-1$  (i.e.  $I_{b,a-1,t-1}^B$ ) has to be equal to the inventory of old biomass with age  $a$  at the end of the period  $t$  (i.e.  $I_{b,a,t}^B$ ), plus the amount of old biomass assigned to the biofuel technology (i.e.  $X_{b,a,t}^F$ ), plus the amount of old biomass assigned to the bioenergy technology (i.e.  $X_{b,a,t}^E$ ). Constraints (4.4) are corresponding to the old biomass ( $a \in A \setminus \{0\}$ ).

Constraints (4.5) guarantee that the inventory for each kind of biomass with each age

(fresh) is zero at the beginning of the planning horizon.

$$X_{b,0,t} = I_{b,0,t}^B + X_{b,0,t}^F + X_{b,0,t}^E \quad a = 0, \forall b, t \quad (4.3)$$

$$I_{b,a-1,t-1}^B = I_{b,a,t}^B + X_{b,a,t}^F + X_{b,a,t}^E \quad \forall b, t, a \in A \setminus \{0\} \quad (4.4)$$

$$I_{b,0,0}^B = 0 \quad \forall b \quad (4.5)$$

Constraints (4.6) ensure that the amount of biofuel generated by biofuel technology (i.e.  $F_t$ ), plus the biofuel inventory at the end of period  $t-1$  (i.e.  $I_{t-1}^F$ ) have to be equal to the biofuel inventory at the end of the period  $t$  (i.e.  $I_t^F$ ), plus the amount of biofuel that is directly sold to the customer (i.e.  $F_t^C$ ), plus the amount of biofuel assigned to the technology to generate bioenergy (i.e.  $F_t^E$ ).

Constraint (4.7) guarantee that the inventory of the biofuel is zero at the beginning of the planning horizon.

$$I_{t-1}^F + F_t = I_t^F + F_t^C + F_t^E \quad \forall b, t \quad (4.6)$$

$$I_0^F = 0 \quad (4.7)$$

Constraints (4.8) and (4.9) show the maximum demand limitations for biofuel and bioenergy. The demand for bioenergy could be satisfied by the bioenergy obtained from biomass, and/or by the bioenergy obtained from biofuel.

$$F_t^C \leq D_t^{Fmax} \quad \forall t \quad (4.8)$$

$$E_t^F + E_t^B \leq D_t^{Emax} \quad \forall t \quad (4.9)$$

Constraints (4.10) guarantee that the amount of biofuel produced by the technology is equal to the amount of biomass multiplied by the conversion efficiency (production yields) concerning the biomass quality whether is fresh ( $a=0$ ) or old ( $a \neq 0$ ).

$$\sum_b \sum_a \alpha_{b,a}^F \cdot X_{b,a,t}^F = F_t \quad \forall t \quad (4.10)$$

Constraints (4.11) guarantee that the amount of bioenergy produced by the technology is equal to the amount of biomass multiplied by the conversion efficiency (production yields) considering the fresh biomass ( $a=0$ ) or old biomass ( $a \neq 0$ ). Constraints (4.10) and (4.11)

represent the conversion of biomass which is perishable.

$$\sum_b \sum_a \alpha_{b,a}^E \cdot X_{b,a,t}^E = E_t^B \quad \forall t \quad (4.11)$$

Constraints (4.12) are related to the conversion efficiency (production yields) of the process of generating bioenergy from biofuel.

$$\eta^{FE} \cdot F_t^E = E_t^F \quad \forall t \quad (4.12)$$

Constraints (4.13), are non-negativity constraints of the model.

$$X_{b,a,t}, X_{b,a,t}^F, X_{b,a,t}^E, F_t, F_t^C, F_t^E, E_t^F, E_t^B, I_t^F, I_{b,a,t}^B \geq 0 \quad \forall b, a, t \quad (4.13)$$

### 4.3.3 Note on the yield and perishability rate

When a new lot of the biomass arrives to the warehouse, it is considered as fresh with an age  $a = 0$ . As the biomass is carried into inventory, its age increases and its yield  $\alpha_{ba}^F$  decreases based on the following formula (equation (4.14)),

$$\alpha_{ba}^F = \alpha_{b,0}^F \times (1 - a \times \xi\%) \quad (4.14)$$

where  $\xi$  shows the perishability rate of the biomass and  $a$  its age.

For example, the yield of the fresh corn stover (the biomass of type  $b = 1$ ) is  $\alpha_{1,0}^F = 0.272$  (Bairamzadeh et al. 2015). If it is assumed that perishability rate is 5%, i.e. the yield decreases by 5% each month, the yield of corn stover ( $m^3/t$ ) after one month becomes  $\alpha_{1,1}^F = 0.2584$ . Similarly  $\alpha_{1,2}^F = 0.2448$ ,  $\alpha_{1,3}^F = 0.2312$  is gotten, and  $\alpha_{1,11}^F = 0.1224$ . Notice that if  $\xi \geq 50\%$ , the biomass cannot be stored more than one period of time. Hence, in this case,  $\alpha_{ba}^F = 0, \forall a \geq 2$ .

## 4.4 Base case data

The proposed model was applied to a base case with data compiled from different sources. Five kinds of biomass are considered: corn stover, wheat straw, switchgrass, forest residues, and sawmill wastes. The availability of the different types of biomass varies over the year and from one region to another. There were attempts to estimate such availability (e.g. [www.bioenergyeurope.org](http://www.bioenergyeurope.org)). For instance, Figure 4.3 shows biomass availability in a given country. This thesis used this data of biomass availability, knowing that the proposed model is generic and can be applied to other distributions.

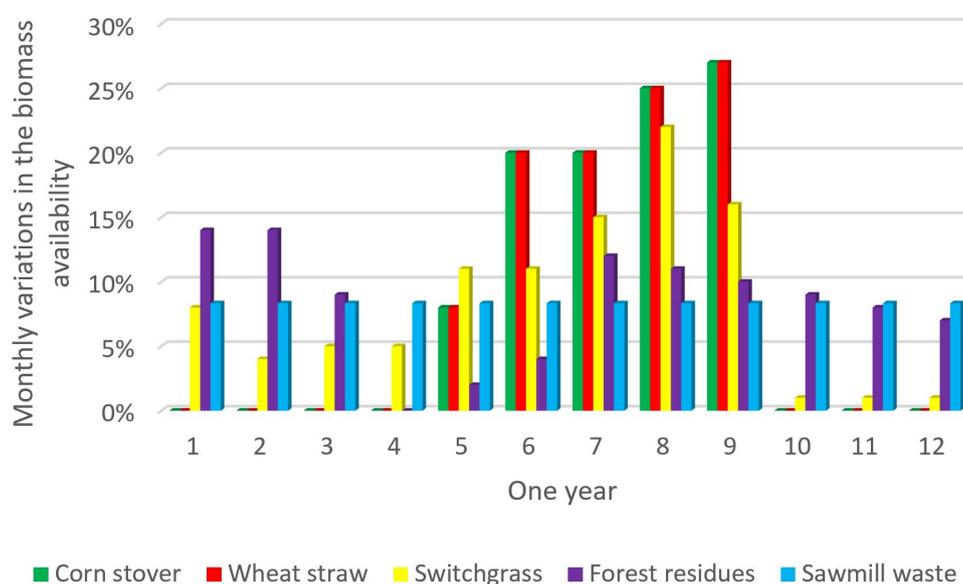


Figure 4.3 – Biomass availability

Other important biomass characteristics such as moisture content, energy content, and purchase prices are presented in Table 7 in Appendix C. In this study, it is supposed that the bioethanol (as biofuel) generated from the different biomass can also be used as input for generating the bioenergy. The associated energy content and corresponding references are shown in Appendix C.

In the biorefinery, there are two kinds of technology. First, using a biochemical conversion process (Fermentation technology), the biorefinery converts corn stover, wheat straw, and switchgrass to bioethanol. Second, the thermochemical conversion process (Combustion technology) is used. Forest residues, sawmill waste, and bioethanol can be used as input feedstocks to be burnt to generate bioenergy. The assigned technology, the value of the processing cost, and the yield of the fresh biomass when it is converted by the different

technologies are given in Appendix D, in Table 8.

The yields in Table 8 can vary with the change of the biomass quality. It is worth noting that the yield of the bioenergy can also be obtained by (4.15) (Akhtari et al. 2018, Kenney et al. 2013, Nur et al. 2021). It indicates that the yield in Megawatt-hour per tonne (MWh/t) is a function of the energy content in Gigajoule per tonne (GJ//t), the coefficient of technology efficiency and a constant of 3.6 to convert GJ to MWh (1MWh = 3.6 GJ). Note that the values of "energy content" in Table 7 are used as inputs for (4.15), and then, the results are shown in Table 8 as inputs for the model.

$$\text{Bioenergy product Yield} \left( \frac{MWh}{t} \right) = \frac{\text{Energy content} \left( \frac{GJ}{t} \right) \times \text{Efficiency of bioenergy technology}}{3.6 \left( \frac{GJ}{MWh} \right)} \quad (4.15)$$

Two final products are considered in this study; Bioethanol as biofuel, and electricity as bioenergy. In addition, bioethanol can also be used as input feedstock to be burnt for generating electricity. The maximum demand for products can vary over time (e.g. [www.niordc.ir](http://www.niordc.ir); Hemingway and Prime 2013). The maximum annual demand of the products, the price of selling each cubic meter ( $m^3$ ) of biofuel, the price of selling each Megawatt hour (MWh) of bioenergy, the holding cost of each tonne of biomass, and the holding cost of each cubic meter of biofuel are shown in Table 9 (Appendix E).

## 4.5 Numerical Experiments

The proposed model was coded in GAMS 24.1.2 and solved using CPLEX solver (version 20.1). The model was implemented on an Intel Core i7, 2.11 GHz processor with 32 GB of RAM. This study conducts a numerical analysis to derive a series of insights into the optimization of operations and profitability of the biorefinery. The results are presented in this section as follows: 1) the optimal solution of the base case is described in Subsection 6.1; 2) the biomass perishability is analyzed in Subsection 6.2; 3) the maximum age of biomass and the restrictions of storing perishable biomass are discussed in Subsection 6.3; 4) the interest of storing biofuel to transform it later to bioenergy is discussed in Subsection 6.4; 5) a sensitivity analysis is performed in Subsection 6.5.

### 4.5.1 Optimal solution of the base case

In this this part, This study uses the base case data explained in Section 4.4, and sets the value of the perishability rate (see equation (4.12) ) to 5%. Then, the model was run. Table 4.2 and Figure 4.4 show the optimal solution. In Table 4.2, the column named the fresh stored biomass shows summation of the stored biomass with age equal to zero ( $a = 0$ ) in all periods. The column that is named the old stored biomass shows summation of the stored bioamss with age more than one ( $a \geq 1$ ) in all periods. Table 4.2 also shows the optimal profit and the total corresponding revenue and cost over the planning horizon. Table 4.4 shows the optimal biomass storage over the planning horizon in more details. For example, 2899 tonne of biomass type 5 with age 6 is stored in period 7. The total biomass type 5 with age 6 over the planning horizon is equal to 5798 tonne. Theses results are shown in last row of Figure 4.4. Therefore, the proposed model helps to manage biomass perishability by monitoring the age of biomass over the planning horizon.

Table 4.2 – Decomposition of the optimal solution value for the base case

Profit (\$)	Revenue (\$)	Costs (\$)	The fresh stored biomass (t)	The old stored biomass (t)
$2.32E + 08$	$8.89E + 08$	$6.57E + 08$	553883	1977693

		T										
Biomass Type	Age	Storage	1	2	3	4	5	6	7	8	Total inventory of age $a$	
$b = 4$	$a = 0$	$I_{b=4,a=0,t}^B$	116200	116200	116200				99600	91300	539500	
	$a = 1$	$I_{b=4,a=1,t}^B$		116200	116200	116200				99600	448200	
	$a = 2$	$I_{b=4,a=2,t}^B$			107309	116200	116200					339709
	$a = 3$	$I_{b=4,a=3,t}^B$				95249	116200	116200				327649
	$a = 4$	$I_{b=4,a=4,t}^B$					82435	116200	116200			314835
	$a = 5$	$I_{b=4,a=5,t}^B$						68767	116200	116200		301167
	$a = 6$	$I_{b=4,a=6,t}^B$							54122	116200	170322	
	$a = 7$	$I_{b=4,a=7,t}^B$								38352	38352	
$b = 5$	$a = 0$	$I_{b=5,a=0,t}^B$	2787	2899	2899				2899	2899	11484	
	$a = 1$	$I_{b=5,a=1,t}^B$		2669	2899	2899				2899	11366	
	$a = 2$	$I_{b=5,a=2,t}^B$				2899	2899				5798	
	$a = 3$	$I_{b=5,a=3,t}^B$					2899	2899			5798	
	$a = 4$	$I_{b=5,a=4,t}^B$						2899	2899		5798	
	$a = 5$	$I_{b=5,a=5,t}^B$							2899	2899	5798	
	$a = 6$	$I_{b=5,a=6,t}^B$							2899	2899	5798	

Figure 4.4 – Amounts of inventory with different ages in the optimal solution of the base case

## 4.5.2 The effects of biomass perishability

The effects of perishability on the total profit and the biomass storage are shown in Figure 4.5. Here, using equation (4.14), the rate of perishability ( $\xi$ ) has been changed in the interval [0%-100%]. When the rate of perishability is increased to 50%, the total profit decreases by about 12%. After the threshold point of 50% perishability rate, the profit remains constant.

The initial assumption in this study is that the purchasing price of biomass ( $c_{b,t}^B$ ) is independent of  $\xi$ . Buying biomass with low perishability rate, gives more flexibility to the manager to store this biomass over longer time periods without big losses in the yield. If the perishability rate is larger than 50%, the biomass can be stored at most for one period before its yield becomes zero. The yield in the second period of the stored biomass decreases as the perishability rate increases. The best solution in this case consists in avoiding storage of biomass at all, which results in the same profit for  $\xi$  values between 50% and 100%. Maximum period for storing the biomass will be discussed in more details in Subsection 5.5.3.

In Figure 4.6, the same analysis is carried out, but it is assumed that the price of the biomass is a function of its perishability rate, which is more realistic. In this case the purchasing price ( $c_{b,t}^B$ ) is decreasing when  $\xi$  is increasing in [0%, 100%]. For the purpose of this experiment,  $c_{b,t}^B$  will decrease with 1% for each 5% increase in the perishability rate in the interval  $\xi \in [0\%, 100\%]$ .

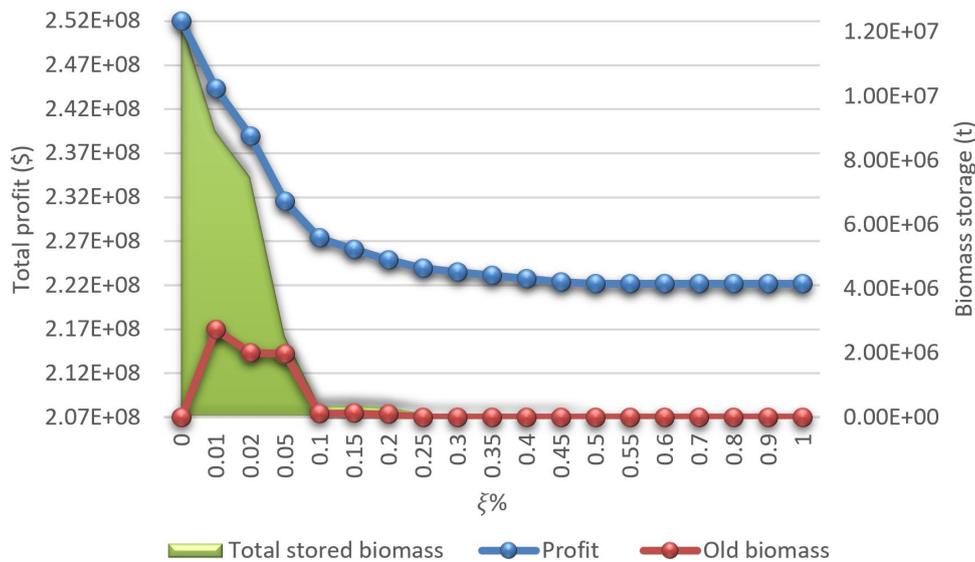


Figure 4.5 – Effect of biomass perishability rate on profit and amount of stored biomass.

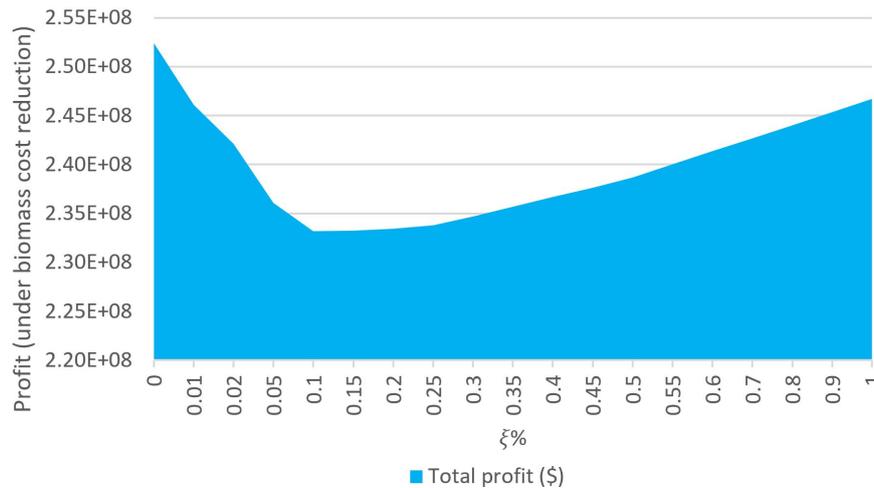


Figure 4.6 – Effect of biomass perishability on the total profit: Biomass price decreases with 1% for each 5% increase in  $\xi$ .

While, one could expect that manager prefers biomass with lower perishability rates as it provides him/her with higher flexibility, the results on Figure 4.6 show something quite different. When the biomass price is not constant, there is a trade-off between savings on the raw material cost and storage flexibility. Figure 4.6 shows that the total profit increases for the values of  $\xi$  above 10%. In the range from 10% to 45% the amount of stored biomass is very low compared with  $\xi = 0\%$ . In this case, the price of biomass has more impact on the profit than the perishability rate. In the range [50%, 100%], the biorefinery does not stock any biomass to avoid perishability. However, it still takes advantage of the lower prices of such high perishability biomass.

### 4.5.3 The effects of the maximum age of biomass

The perishability rate is an indicator of the maximum amount of time biomass can be stored before its yield becomes zero. However, in practice, the manager should have the flexibility to decide on the maximum amount of time to store the biomass even if it still has a positive yield. For example, the manager might be concerned about health and safety problems made by storing the perishable biomass for long time, such as fungal (fungus) /spore formation (Rentizelas et al. 2009), or spontaneous ignition (Torrent et al. 2015) due to exothermic microbial degradation. Hence, the maximum age of biomass, here, means that the maximum number of time periods that biomass is allowed to be stored in a warehouse.

The effects of the maximum age of the biomass is analyzed using the default value of perishability rate ( $\xi = \%5$ ). In this experiment, the maximum allowed age of the biomass is decreased from 11 to 0 time periods. Figure 4.7 shows the results of the tests. In each maximum age of biomass, the summation of all old/fresh biomass are considered that are stored in different periods.

The main insights from Figure 4.7 can be summarized in the following three points. First, when the maximum age of biomass increases from 0 to 2 periods, the profit significantly increases. This means that considering biomass storage is so important for managers, because they can significantly increase their profit compared with the case in which the maximum age is set to 0 that storage is not allowed for neither old biomass nor fresh biomass. Second, the curve is almost flat on ranges [2, 5] and [8, 11]. The profit stays almost constant. In this case, the decision maker might prefer to set the maximum to the lowest value

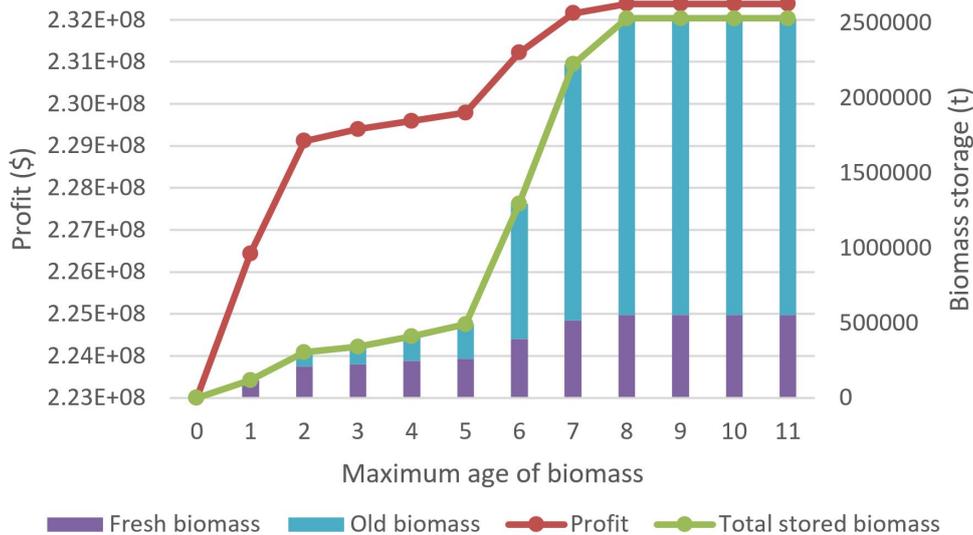


Figure 4.7 – Maximum age of biomass

of the range (2 or 8) considering that the small loss in profit (between 2 and 5 periods maximum age) is offset by the health benefits incurred.

Third, in the range from 5 to 8, a trade-off is shown between the extra costs for longer time storage (perishable biomass) and the profit, so the manager can use this trade-off to determine the best maximum age. As a last note, beyond a certain value (here 8 periods), the total profit remains unchanged. This threshold value depends mostly on the inventory holding costs.

#### 4.5.4 The value of energy storage

This part shows the advantages of energy storage application in the bioenergy production system, and compares the proposed model (with energy storage) with the existing models. The proposed model considers two types of outputs (bioenergy and biofuel). Unlike bioenergy, biofuel can be stored. This is called "Energy Storage", because (unlike the existing models) it can be converted to bioenergy later inside the biorefinery. Therefore, biofuel storage can be used to match supply with demand. Inventory plays an important role in the proposed model since it may be interesting to transform a large quantity of biomass to avoid perishability which is possible only when the output product can be stored since, otherwise, production will be lost.

Although the existing models in the literature considered biofuel storage, they did not convert the stored biofuel into the bioenergy inside the biorefinery. They sell biofuel directly to the customers. This part of converting stored biofuel (energy storage) to bioenergy is shown by a red ellipse in Figure 4.2. Now, this part is removed from the proposed model (with energy storage) to obtain a basic model without energy storage. If the value of  $\eta^{FE}$  is set to 0 in constraint (4.12), the proposed model (with energy storage) is equivalent to the basic model (without energy storage). Table 5.6 shows the optimal solutions of two models ( $\xi = 5\%$ ). It shows the advantages of the proposed model. When energy storage is considered, the profit increases by more than 2.2% comparing with the basic model (without energy storage). In addition, the amount of biofuel used for converting to bioenergy increases from 0 to  $0.109 \times 10^7 m^3$ . The biofuel storage is increased up to 19.6%. The amount of sold bioenergy is significantly increased. However, the amount of the purchased and stored biomass stay constant. As a result, the manager of biorefinery could obtain more profit from the same amount of purchased biomass.

In the next step, the difference between the two models under different perishability rates is shown. Both models are run when the perishability rate changes from 0% to 100%. Figure 4.8 shows the results. First, the proposed model (with energy storage) has always superiority over the basic model (without energy storage) under different perishability rates. Second, perishability also has a high negative impact on the basic model (without energy storage). It can reduce the profit by 10.5% when the perishability rate increase from zero. This shows the importance of considering perishability even in basic models (without energy storage). Third, above 50% in both models, biomass is not stored to avoid high perishability. Therefore, both models have a constant profit.

Now, it is determined that which parameters in the proposed model (with energy stor-

Table 4.3 – Optimal solution of the bioenergy production system ( $\times 10^7$ )

	Basic model (without energy storage)	the proposed model (with energy storage)
Profit (\$)	22.70	<b>23.19</b>
Biofuel storage ( $m^3$ )	0.1268	0.1516
Biomass storage (t)	0.2531	0.2531
Revenues (\$)	86.66	88.87
Costs(\$)	63.96	65.68
Purchased biomass (t)	1.373	1.373
Biofuel sold ( $m^3$ )	0.3975	0.2914
Bioenergy sold (MWh)	0.068	0.363
The biofuel used for bioenergy ( $m^3$ )	0	0.106

age) lead to its superiority compared with the basic model (without energy storage). To do so, some parameters which have more potential to affect the performance (of the biorefinery with energy storage) are investigated. These parameters are: 1) price of biofuel; 2) price of bioenergy; 3) biomass holding cost; 4) biofuel holding costs. Then, the values of these parameters are changed ( $\pm 20\%$ ) from their base case values (nominal value) to see their impact on the profit of both models: the proposed model and the basic models (without energy storage). The output (fluctuation in the profit) is also calculated as a percentage by comparing with the base case. Table 4.4 presents the results. First, in both models the impact of the biofuel holding cost fluctuation ( $\pm 20\%$ ) on the profit is more than that of the biomass holding cost. This is more obvious in the proposed model (with energy storage). According to Table 5.6, the proposed model (with energy storage) stores more biofuel than the basic model (without energy storage), because the proposed model (with energy storage) stores more biofuel to be used in two ways, directly to sell to the customer, or to convert it to bioenergy to be sold later. As a result, the biofuel holding cost fluctuation has more impact in the proposed model (with energy storage). Once again, in the basic model (without energy storage), there is also biofuel storage, but it does not convert biofuel to bioenergy inside the biorefinery.

Second, the biofuel price has more effect on the profit of the basic model (without energy storage) than the proposed model (with energy storage). However, the bioenergy price has more impact on the proposed model (with energy storage) compared with the basic model

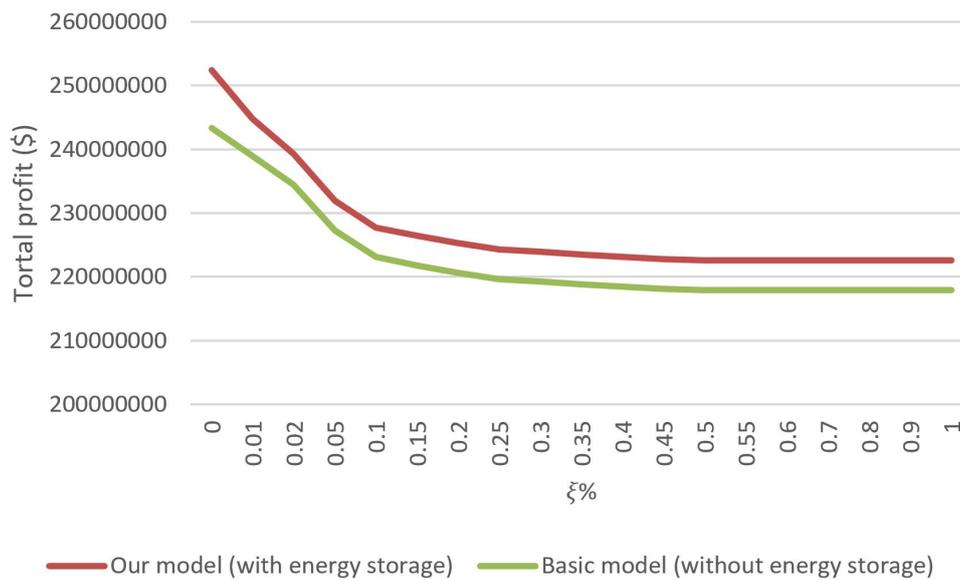


Figure 4.8 – Profit of the proposed model (with energy storage) and the basic model (without energy storage) models under different perishability rates

(without energy storage). The amount of biofuel sold in the basic model (without energy storage) is more than the proposed model (with energy storage). However, the amount of bioenergy sold in the proposed model (with energy storage) is more than the basic model (without energy storage). This confirms the previous results (see Table 5.6).

Third, in the proposed model (with energy storage), the profit can be more impacted by the positive changes than negative changes. In other word, the proposed model (with energy storage) is resilient to the negative changes. The reason of this superiority (compared with the basic model (without energy storage)) is the flexibility of the proposed model (with energy storage) under negative changes. For example, when the price of bioenergy/biofuel decreases, since the model is looking for maximizing the profit, the proposed model (with energy storage) switches to sell more biofuel/bioenergy which still has a high price, so that more profit (or less loss) is obtained. It means, the proposed model (with energy storage) tries to neutralize the negative impact of the parameter (resiliency) by using other opportunities that are still available. Therefore, the model is resilient to fluctuation in the price of biofuel and bioenergy, as it adjusts the production quantity of each final product to maintain the profit. This is an interesting feature of the proposed model (with energy storage).

Table 4.4 – Percent changes in profit as function of parameter change (-20%, +20%)

Parameter	Percent change in parameter value of the models			
	-20%		+20%	
	Basic model	the proposed model	Basic model	the proposed model
Bioenergy price	-4.910%	-6.743%	4.910%	33.314%
Biofuel price	-71.440%	-44.257%	71.440%	67.821%
Biofuel holding cost	0.590%	0.691%	-0.590%	-0.599%
Bioamss holding cost	0.008%	0.008%	-0.008%	-0.007%

### 4.5.5 Sensitivity analysis

In this part, a sensitivity analysis is performed to find the effect of the following parameters on the profit (compared with the base case that this study used in Section 5.4) : (a) production costs; (b) maximum demand; (c) availability of biomass; (d) holding costs; (e) conversion rate; (f) price of products; (g) cost of purchasing biomass. The values of these parameters are changed over a reasonable range (-20% to +20%) to see the variation of the profit. Figure 4.9 shows the results. First, the model is highly sensitive to the conversion rate. This shows the importance of perishability. Note that the prices of all products (all products at the same time) are changed here . Second, the proposed model is not sensitive to demand. The reason is that the proposed model in this study includes powerful tools such as biomass storage, biofuel storage, converting biofuel to bioenergy, energy storage, etc. All these tools help smoother production even with highly fluctuating demand.

## 4.6 Conclusion

This study developed and solved a multi-period production planning model for a biorefinery that transforms different types of biomasses into either bioenergy or biofuel. The biomass can be stored but its quality is deteriorated over time, which incurs a lower yield. The biofuel can also be stored to be transformed later to bioenergy. The applicability of the developed model was illustrated by a case study. Extensive numerical experiments were performed to understand the behavior of the model and derive managerial insights. The results showed that the higher the biomass perishability rate the lower the profitability

The percentage of variation in the total profit with respect to base case solution.

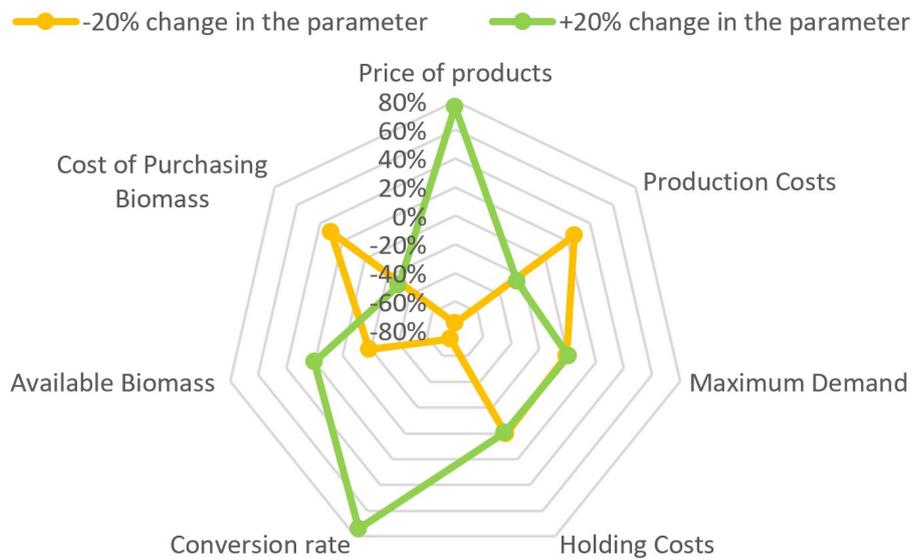


Figure 4.9 – Sensitivity analysis with respect to the base case scenario

of the biorefinery, but there is a threshold value on the biomass perishability rate above which perishability does not have any more impact on the profit. The biofuel storage is an important feature of the proposed model. While bioenergy cannot be stored and biomass storage leads to reducing its quality, the biofuel can be stored and transformed later into bioenergy to match supply with demand. This study showed that this results in considerable profit increase and smoother production at the facility even under a high fluctuation in bioenergy selling price and demand.

the proposed modeling framework comes with limitations that offer avenues for future work directions. First, it is interesting to consider the uncertainty on the supply of biomass and evaluate its impact on production strategy and profit. Second, bioenergy price and demand uncertainties could also be incorporated into the model. Finally, applying the proposed model to a real case study would certainly require to make some adjustments in the modeling framework and constraints.

# A PRODUCTION PLANNING MODEL FOR BIO-REFINERIES UNDER UNCERTAINTY

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## 5.1 Introduction

Increasing demand and environmental problems of using fossil fuels have led scientists to think about renewable energy as a clean alternative. Among different types of renewable energy, bioenergy and biofuel made from biomass have become more attractive, because of the great diversity of biomass resources (Machani et al. 2015, Razm et al. 2021a). However, there are some barriers for the bioenergy production systems that affect their performance and profit. For example, first, unpredictable climatic conditions can impact the availability of biomass, the feedstock of the biorefineries (Langholtz et al. 2014, Sharma et al. 2013b).

Second, factors such as fluctuating market price, and correlation between the price of biofuel and the price of other sources (e.g., Natural gas, crude oil), etc. can impact the biofuel selling price (Osmani and Zhang 2013, Kim et al. 2011).

Under the uncertain conditions caused by the above factors, a deterministic mathematical model can not help the manager of biorefinery make the optimal decisions in the real world. In other words, there is a need to incorporating the above-mentioned uncertainties into the production planning of the biorefineries. If these uncertainties are ignored in the production planning of the biorefineries, the decisions made by the mathematical models will not be trustworthy nor feasible.

The third barrier of bioenergy production systems is related to the perishable nature of biomass. The chemical reactions during biomass storage lead to continuous loss of the valuable materials in the biomass (higher heating value and oil yield) (Shabani and Sowlati 2016, Fuller 1985). Forth, storing energy is another challenge which the bioenergy production systems are facing with. Generation of energy must match its sales. According to the European Commission ([www.ec.europa.eu](http://www.ec.europa.eu)), this balance is necessary to maintain a safe and stable supply of energy. Nonetheless, storing energy is the solution although it is not

economic

The related literature is proposed in Chapter 2 in Section 2.4. Table 5.1 shows the results of the literature review. In Table 5.1, Changing the amount of output by changing the quality of input (biomass) is the definition of *The yield of biomass conversion impacted by biomass quality*. Storing the biofuel which will be converted into bioenergy inside the biorefinery later is the definition of *Energy storage in the form of biofuel*.

Of course that biofuel storage was considered in other studies, but our main interest here is in the conversion of biofuel into bioenergy inside the biorefinery and the integration of this decision into the biorefinery production planning model. Biomass quality reduction that occurs (continuously) based on biomass aging is the definition of *Dynamic quality reduction*. Biomass quality reduction that occurs (not continuously) only at the specific conditions (e.g. low temperature) is the definition of *Static quality reduction*. Throwing the biomass away from the warehouse as waste is the definition of *Biomass loss*. Controlling the time length of storing fresh biomass is the definition of *Monitoring the age of biomass*. Using more than one type of biomass (e.g. forest residues as well edible biomass) is the definition of *Generic feedstock*.

When we have more than one uncertain parameter in each constraint (row), we must use *Row-wise robust optimization*. When we have only one uncertain parameter in each constraint (row), we must use *Column-wise robust optimization*. The reason is that when we have only one uncertain parameter in each row, if we use Row-wise RO, the decision maker could not have control over the different conservation levels, based on the definition of the uncertainty budget ( $\Gamma_i$ ) by Bertsimas and Sim [2004a]. Appendix A and B explain these methods in more detail.

There is a research gap in production planning for a biorefinery using perishable biomass under weather and price uncertainty as shown in Figure 5.1. Weather uncertainty, biomass perishability, energy storage, and price uncertainty that are important challenges for biorefineries need to be incorporated into the production planning model to help manager of biorefineries make reliable decisions in the real world. This chapter tries to fill this gap.

This chapter proposes a production planning model for one biorefinery generating biofuel and bioenergy from different types of biomass under uncertainty. Unpredictable climatic conditions impact the availability of biomass. Three criteria are defined: i) rainfall, ii) temperature, iii) sunshine to model the climatic conditions. Based on these criteria, the new uncertain parameter in the model is defined that represents weather uncertainty. For storing perishable biomass, a dynamic biomass quality reduction is considered in the

biomass warehouse. This dynamically affects the yield of the biomass conversion, since perishability is a dynamic process. Furthermore, biofuel is considered as a method to store energy that can be converted to bioenergy later inside the biorefinery, and this decision is integrated into the production planning model. In addition, fluctuating market price leads to price uncertainty. A hybrid model, a row and column wise robust optimization model, is proposed to attack uncertainty.

In other words, this study proposes a multi-period production planning model for the biorefinery converting perishable biomass to biofuel and bioenergy under uncertain conditions, the price and weather uncertainty. The objective of the model is to maximize the total profit of the biorefinery. The following decisions are optimally made by the model:

1. The amount of biomass that is purchased, stored, assigned, and converted
2. The amount of biofuel and bioenergy that must be generated, and amount of biofuel that must be stored.
3. The amount of bioenergy and biofuel that must be sold during the planning horizon.

The proposed model includes three main features: i) incorporating the age of stored biomass to control the biomass perishability, and ii) biomass is converted to either bioenergy or biofuel, which in turn can be stored and then converted to bioenergy. iii) it is robust against unpredictable climate conditions and price uncertainty.

Effective managing and planning of the biorefinery can lead to reduction in the production costs, and make biomass a valuable source of energy. Mathematical modeling and operations research can be applied to accomplish that. They are different models in the literature related to production planning for the biomass-to-bioenergy systems (Cambero et al. 2015, Santibañez-Aguilar et al. 2019). Nevertheless, the effect of weather, price uncertainty, biomass perishability, and energy storage are not efficiently considered in these studies.

Therefore, the contributions of this study are as follows:

1. Proposing a mathematical model for production planning of biorefineries.
2. Modeling the weather conditions and incorporating them into the production planning of biorefineries.
3. Incorporating the effects of biomass perishability and energy storage (under uncertain conditions) into the mathematical model.
4. incorporating the weather and price uncertainty into the production planning of biorefineries.

5. Proposing a row and column-wise robust optimization approach to tackle uncertainty.
6. Providing managerial insights based on the effects of the uncertain parameters.

The organization of this chapter is as follows: Section 5.2 is problem definition. Section 5.3 is mathematical formulation. Section 5.4 is case study. Section 5.5 is experiments and results. Section 5.6 is conclude and the suggestions for future research.

Article	Feedstock		Inventory planning			Perishability (in the storage)			Conversion technology			Energy storage	The yield of biomass conversion	Uncertain parameter		Factors affecting supply uncertainty			Uncertainty Modeling approach			
	Specific/Generic	Biomass storage	Monitoring the biomass age	Biofuel storage	Biomass loss	Static quality reduction	Dynamic quality reduction	Biomass preprocessing	Biomass to biofuel	Biomass to bioenergy	In the form of biofuel	Impacted by biomass quality	Available biomass (supply uncertainty)	Price of final product	Rainfall	Temperature	Daylight	Scenario-based SP	Continuous SP	Row-wise RO	Column-wise RO	
Eriksson and Björheden, 1989	S	X						X														
Gunnarsson et al., 2004	S	X						X											X			
Mohseni et al., 2016	S			X					X													
Kanzian et al., 2009	G	X		X	X			X	X													
Mahjoub et al., 2020	S	X		X	X			X	X													
Zhang et al., 2013	S	X			X			X	X													
Larson et al., 2013	S	X			X			X	X													
Saghaei et al., 2020	S	X							X													
Shabani et al., 2016	S	X				X			X													
Akhari et al., 2014	S	X						X														
Dansereau et al., 2014	S	X						X	X													
Cambero et al., 2015	S			X				X	X													
Miret et al., 2016	G	X		X	X			X	X													
Zhang et al., 2016	S	X			X			X	X													
Gautam et al., 2017	S	X						X														
Castillo et al., 2017	S							X														
Bairamzadeh et al., 2018	S	X		X	X			X	X													
Santibañez-Aguilar et al., 2019	G			X				X	X													
Nur et al., 2021	G	X			X			X	X													
Sharma et al., 2013	S	X			X			X	X													
Shabani et al., 2013	S	X			X			X	X													
Shabani et al., 2014	S	X						X	X													
Osmani and Zhang, 2013	S							X														
Kim et al., 2011	S							X														
Sahar Ahmadvand, 2022	S	X			X			X														
<b>Proposed model</b>	G	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	

Figure 5.1 – The literature review

## 5.2 Problem definition

In this study, one installed biorefinery is considered that converts different types of biomass to bioenergy and biofuel. Both biomass and biofuel can be stored. Figure 5.2 shows the framework of the bioenergy production system. Different types of biomass are shown by  $B$ , and the age of biomass is represented by  $A$ .  $T$  shows the periods, biofuel is shown by  $F$ , and  $E$  means bioenergy. Under weather uncertainty in different seasons, different types of the fresh biomass are collected and brought into the biorefinery ( $X_{b,0,t}$ ). Note that biomass collection needs appropriate weather conditions (e.g., it is not possible in rainy days) (Sharma et al. 2013a; Borodin et al. 2015). Weather uncertainty is explained in more details in Section 5.3.3. The biomass, a perishable product (Tavanandi et al. [2018]), is stored in the biomass warehouse ( $I_{b,a,t}^B$ ). The biomass gets more age (old biomass) if it is stored for a longer time. The more age, the more decomposition (the quality of biomass changes). The biomass quality can affect the process of biomass transformation (Kenney et al. [2013], Nur et al. [2021]). In next step, biomass is assigned to two technologies. First, transformation of biomass to biofuel ( $X_{b,a,t}^F$ ). Second, transformation of biomass to bioenergy ( $X_{b,a,t}^E$ ).

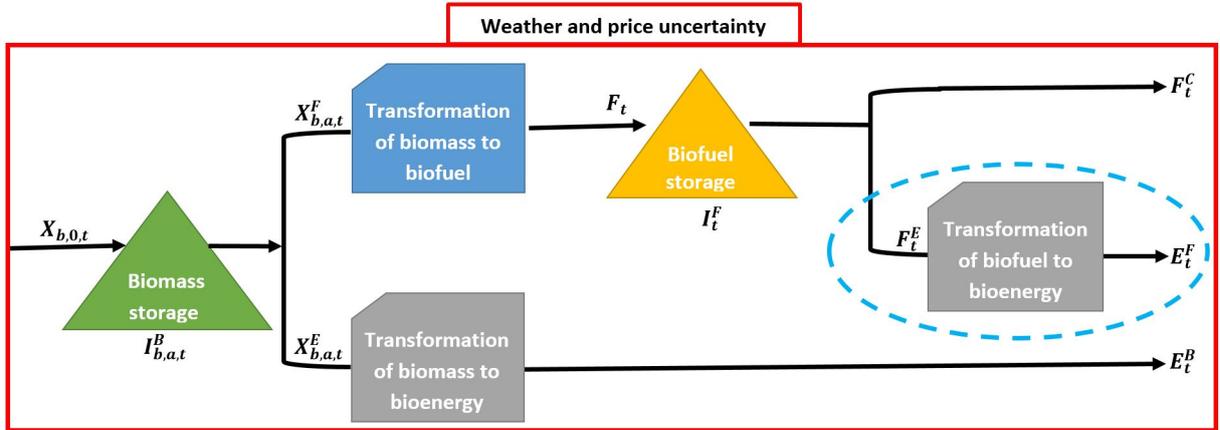


Figure 5.2 – Framework of the bioenergy production system

The bioenergy made from biomass is immediately sold after generating ( $E_t^B$ ). Nonetheless, the biofuel ( $F_t$ ) is stored in the biofuel warehouse. The stored biofuel ( $I_t^F$ ) can be sold as biofuel ( $F_t^C$ ) or bioenergy (as stored energy). In other words, instead of directly selling the biofuel, it is assigned to the technology ( $F_t^E$ ) to transform into bioenergy ( $E_t^F$ ). This part is demonstrated by the blue ellipse in Figure (5.2). Therefore, the biofuel can be stored for a long time, so the bioenergy generated from that also can be stored for a

long time (energy storage). Although this study considers one biorefinery, more than one biorefinery can also be applied. Price of biofuel can be affected by fluctuating market price as well as correlation between the price of biofuel and the price of other sources, so the price of biofuel is considered as uncertain parameter in this study.

### 5.3 Model formulation

A multi-period linear programming mathematical model is proposed in this study to optimize the planning and operation of the bioenergy production system under uncertainty. First, the verbal description of the model is presented to better understanding the mathematical formulation. Then, the mathematical formulation for deterministic model is presented. After that, the mathematical formulation of the robust model is presented.

$$\begin{aligned}
 &\text{Maximize} && [\text{Biofuel revenue} + \text{Bioenergy revenue}] \\
 &\text{profit} = && \\
 &&& -[\text{Biomass costs} + \text{Production costs} + \text{Inventory costs}] \\
 &\text{Subject to :} && \\
 &&& \text{Biomass availability constraints} \\
 &&& \text{Biomass inventory balance equations} \\
 &&& \text{Biofuel inventory balance equations} \\
 &&& \text{Demand constraints} \\
 &&& \text{Production (conversion) equations}
 \end{aligned}$$

The notations of the mathematical formulation are presented in Table 5.1.

#### 5.3.1 Deterministic model

Now using Table 5.1, the mathematical formulation for deterministic model is presented as follows:

$$\begin{aligned}
 \text{Maximize} \quad & \sum_t \left( \tilde{p}_t^F \cdot F_t^C + p_t^E (E_t^B + E_t^F) \right) - \sum_b \sum_a \sum_t (c_{b,t}^B \cdot X_{b,a,t} + c_{b,t}^{BF} X_{b,a,t}^F + c_{b,t}^{BE} X_{b,a,t}^E) \\
 & - \sum_t c_t^{FE} \cdot F_t^E - \sum_b \sum_a \sum_t h_b^B \cdot I_{b,a,t}^B - \sum_t h^F \cdot I_t^F
 \end{aligned} \tag{5.1}$$

$$X_{b,0,t} \leq \tilde{\psi}_{b,t} \quad \forall b, t \quad (5.2)$$

$$X_{b,0,t} = I_{b,0,t}^B + X_{b,0,t}^F + X_{b,0,t}^E \quad a = 0, \forall b, t \quad (5.3)$$

$$I_{b,a-1,t-1}^B = I_{b,a,t}^B + X_{b,a,t}^F + X_{b,a,t}^E \quad \forall b, t, a \in A \setminus \{0\} \quad (5.4)$$

$$I_{b,0,0}^B = 0 \quad \forall b \quad (5.5)$$

$$I_{t-1}^F + F_t = I_t^F + F_t^C + F_t^E \quad \forall b, t \quad (5.6)$$

$$I_0^F = 0 \quad (5.7)$$

$$F_t^C \leq D_t^{Fmax} \quad \forall t \quad (5.8)$$

$$E_t^F + E_t^B \leq D_t^{Emax} \quad \forall t \quad (5.9)$$

$$\sum_b \sum_a \alpha_b^F \times X_{b,a,t}^F = F_t \quad \forall t \quad (5.10)$$

$$\sum_b \sum_a \alpha_b^E \times X_{b,a,t}^E = E_t^B \quad \forall t \quad (5.11)$$

$$\eta^{FE} \cdot F_t^E = E_t^F \quad \forall t \quad (5.12)$$

$$X_{b,a,t}^F, X_{b,a,t}^E, X_{b,a,t}^B, F_t, F_t^C, F_t^E, E_t^F, E_t^B, I_t^F, I_{b,a,t}^B \geq 0 \quad \forall b, a, t \quad (5.13)$$

In the objective function, the total profit of the biorfinery is maximized that include total revenues minus total costs. The total revenues are obtained by selling biofuel, bioenergy generated by biomass, and bioenergy generated by biofuel. The total costs are incurred by biomass purchasing (fresh biomass), transforming biomass (to biofuel and bioenergy), transforming biofuel (to bioenergy), biomass holding cost, and biofuel holding cost. A tilde ( $\tilde{p}_t^F$ ) indicates the uncertain nature of the parameter.

Constraints (5.2) show that amount of the purchased fresh biomass ( $a = 0$ ) could not be more than available biomass. The available biomass that is an uncertainty parameter will be explained in more details in Section 5.3.2.

In each period, the mass balances of biomass feedstocks (the fresh or aged biomass) are guaranteed by constraints (5.3)-(5.5). Constraints (5.3) grantee that the amount of fresh biomass ( $a = 0$ ) coming from suppliers is equal to amount of fresh biomass that is stored in period t, plus amount of biomass assigned to the biofuel technology, and plus amount of biomass assigned to the bioenergy technology. Constraints (5.4) grantee that the amount of biomass inventory for old biomass ( $a \neq 0$ ) in period t-1 is equal to amount of biomass inventory (old biomass) in period t, plus the amount of old biomass that is assigned to the biofuel technology as well as to the bioenergy technology. Constraint (5.5) grantee that at

the beginning of the planning horizon, the inventory of the fresh biomass is zero.

Constraints (5.6) guarantee that amount of biofuel inventory in period  $t-1$  plus amount of generated biofuel must be equal to the amount of inventory in period  $t$  plus amount of biofuel directly is sold, plus amount of biofuel that is converted to bioenergy. Constraints (5.7) insure that at the beginning of the planning horizon, the biofuel inventory is zero.

Constraints (5.8) and (5.9) are demand constraints. Constraints (5.8) insure that amount of sold biofuel could not be more than maximum amount of biofuel demand. Constraint (5.9) insure that amount of bioenergy generated from biomass, plus amount of bioenergy generated from biofuel could not be more than the amount of maximum demand for bioenergy.

The amount of biofuel generated by the technology is equal to amount of input biomass multiplied by the conversion efficiency (production yields) considering whether the biomass is fresh ( $a = 0$ ) or old biomass ( $a \neq 0$ ). This is guaranteed by constraints (5.10).

The amount of bioenergy generated by the technology is equal to the amount of the conversion efficiency (production yields) considering whether the biomass is fresh ( $a = 0$ ) or old ( $a \neq 0$ ) multiplied by input biomass. This is guaranteed by constraints (5.11). Constraints (5.10) and (5.11) represent the conversion of perishable biomass.

The conversion efficiency (production yields) of the technology transforming biofuel to bioenergy is guaranteed by constraints (5.12). Constraint (5.13) is related to the non-negativity variables of the model.

### 5.3.2 Perishability rate and production yield

When a new lot of the biomass arrives to the warehouse, it is considered as fresh with an age  $a = 0$ . Then, the biomass is sent to biomass storage. The age of the biomass increases and its yield  $\alpha_{ba}^F$  decreases in the biomass warehouse. The following formula (equation (5.14)) show these changes.

$$\alpha_{ba}^F = \alpha_{b,0}^F \times (1 - a \times \xi\%) \quad (5.14)$$

Where  $a$  is the age of biomass and  $\xi$  is the perishability rate of biomass.

For instance, according to (Bairamzadeh et al. 2015), the yield of the fresh corn stover (the biomass of type  $b = 1$ ) is  $\alpha_{1,0}^F = 0.272$ . If it is assumed that perishability rate is 5%, i.e. the yield decreases by 5% each month, the yield of corn stover ( $m^3/t$ ) after one month

becomes  $\alpha_{1,1}^F = 0.2584$ .

Similarly we can get  $\alpha_{1,2}^F = 0.2448$ ,  $\alpha_{1,3}^F = 0.2312$ , and  $\alpha_{1,11}^F = 0.1224$ . Note that the biomass cannot be stored more than one period of time when  $\xi \geq 50\%$ . In this case,  $\alpha_{ba}^F = 0, \forall a \geq 2$ .

Table 5.1 – Sets, parameters, and decision variables of the model

Symbol Definition	
$B$	Biomass type; index $b \in B$
$A$	Biomass age; index $a \in A$
$T$	Periods; index $t \in T$
Parameter	
$p^F$	Biofuel price (\$/unit of product)
$p^E$	Bioenergy price (\$/MWh)
$c_{b,t}^B$	The purchasing cost of biomass $b$ in period $t$ (\$/t)
$c_{b,t}^{BF}$	Cost of biomass transformation to biofuel in period $t$ (\$/t)
$c_{b,t}^{BE}$	Cost of biomass transformation to bioenergy in period $t$ (\$/t)
$c_t^{FE}$	Cost of biofuel transformation to bioenergy in period $t$ (\$/unit of product)
$h_b^B$	Holding cost of biomass $b$ (\$/t)
$h^F$	Holding cost of biofuel (\$/unit of product)
$u_{b,t}$	Amount of biomass $b$ obtained from each hectare (t/hectare).
$\delta_{b,t}$	The biomass lost because of maturity (%)
$s_b$	Capacity of collecting unit to collect biomass $b$ (hectare/h)
$\psi_{b,t}$	Number of workdays/hours available for collecting biomass $b$ in period $t$ (h)
$\alpha_b^F$	The biofuel yield obtained from transformation of biomass $b$ (fresh biomass) (unit of product output/tonne of biomass input).
$\alpha_b^E$	The bioenergy yield obtained from transformation of biomass $b$ (fresh biomass) (unit of product output/tonne of biomass input).
$\eta^{FE}$	The bioenergy yield obtained from transformation of biofuel (unit of product output/ unit of product input)
$D_t^{Fmax}$	Maximum biofuel demand (unit of product)
$D_t^{Emax}$	Maximum bioenergy demand (MWh)
Decision variable	
$F_t$	Total biofuel generated in period $t$ ( $F_t = F_t^C + F_t^E$ ), (unit of product)
$F_t^C$	Amount of biofuel which is directly sold to the customers in period $t$ (unit of product)
$F_t^E$	Amount of biofuel for transformation to bioenergy in period $t$ (unit of product)
$E_t^F$	Amount of bioenergy generated from biofuel ( MWh )
$E_t^B$	Amount of bioenergy generated from biomass ( MWh )
$X_{b,a,t}$	Purchased biomass $b$ with age $a$ in period $t$ (t)
$X_{b,a,t}^F$	Amount of biomass that is used as input for biofuel technology (t)
$X_{b,a,t}^E$	Amount of biomass that is used as input for bioenergy technology (t)
$I_{b,a,t}^B$	Amount of stored biomass $b$ with age $a$ in period $t$ (t)
$I_t^F$	Biofuel storage in period $t$ (unit of product).

### 5.3.3 Weather uncertainty

Different types of biomass can be collected in different seasons. However, weather conditions impact on the amount of biomass that can be collected. The process of collecting biomass needs appropriate weather conditions. For example, collecting wheat straw is not possible in the rainy days (Borodin et al. 2015). According to the literature, this study takes three criteria into account to obtain appropriate weather conditions for collecting biomass in different seasons. In other words, the available time is considered for collecting biomass in each period by defining three criteria, rainfall, temperature, and daylight hours.

Now, weather uncertainty is explained in constraint (5.2) in more details.  $\tilde{\psi}_{b,t}$  is available biomass (an uncertain parameter) that depends on the weather conditions.

$$\tilde{\psi}_{b,t} = \text{Available working hours(h)} \times \text{Harvesting capacity (t/h)} \quad (5.15)$$

$$\text{Harvesting capacity (t/h)} = u_{b,t} \times (1 - \delta_{b,t}) \times \varsigma_b \quad (5.16)$$

The amount of biomass that can be obtained from each hectare ( $u_{b,t}$ ) is multiplied by one minus the biomass lost ( $\delta_{b,t}$ ) because of maturity (%), (e.g., 5% per month from one month after starting the collecting season (Epplin et al. 2007)). These two parameters are multiplied by capacity of the collecting unit that collects biomass  $b$ . These three parameters are multiplied by the available hours for collecting biomass  $b$  in period  $t$  ( $t/\text{hectare} \times \text{hectare}/h \times h$ ). This available working hours (the uncertain parameter) depends on the weather factors such as rainfall, temperature as well as daylight hours. In the following, each one is discussed.

**a. Rainfall criterion:** In order to estimate the number of workdays lost, the rainfall criterion is used (Borodin et al. 2015) considering five scenarios. Table 5.2 Shows the workdays lost given the amount of rainfall in different scenarios. For example, if the amount of rainfall is between 0.5 to 0.99 inches, collecting biomass is not possible in the next three days (Enz et al. 1991). If we have sequence rainy days, we consider the last day (assumption).

**b. Temperature criterion** If the minimum temperature in one day is above  $32^\circ\text{F} = 0^\circ\text{C}$ , the day is considered as a workday (Sharma et al. 2011), otherwise, non-workday.

**c. Daylight hours criterion** The available hours for collecting biomass in each day are calculated based on Daylight hours. It is assumed that 80% of the daylight hours in each day can be taken into account, because of unpredictable events such as unavailability

Table 5.2 – Unsuitable workdays

Rainfall range (inches)	0.00 - 0.05	0.06 - 0.19	0.20 - 0.49	0.50 - 0.99	$\geq 1$
Workdays lost (days)	0	1	2	3	4

of labor, machinery breakdown (Sharma et al. 2013a).

Now based on these criteria and using the weather data ([www.mesonet.org](http://www.mesonet.org)), a real lower and upper bonds of variation range base on the minimum and maximum value of the uncertain parameter ( $\tilde{\psi}_{b,t}$ ) can be extracted. Then, these intervals are used as input for the adjustable column-wise robust optimization model (See Appendix B) to tackle the uncertainty.

### 5.3.4 Robust model:

In this part, the robust model (the robust counterpart model) is proposed. The objective function of the deterministic model is reformulated into constraints (5.17)-(5.19). In addition, the first constraint of the deterministic model is reformulated into constraints (5.20)-(5.29). For more details, please see Appendix B. Consequently, the robust model is as follows:

$$\text{Maximize } Z \quad (5.17)$$

$$\begin{aligned} \sum_t (p_t^F \cdot F_t^C + p_t^E (E_t^B + E_t^F)) - \sum_b \sum_a \sum_t (c_{b,t}^B \cdot X_{b,a,t} + c_{b,t}^{BF} X_{b,a,t}^F + c_{b,t}^{BE} X_{b,a,t}^E) \\ - \sum_t c_t^{FE} \cdot F_t^E - \sum_b \sum_a \sum_t h_b^B \cdot I_{b,a,t}^B - \sum_t h^F \cdot I_t^F - \sum_t \lambda_t - \Gamma^z \cdot k^z \geq Z \end{aligned} \quad (5.18)$$

$$k^z + \lambda_t \geq \hat{p}_t^F \cdot F_t^C \quad \forall t \quad (5.19)$$

$$\sum_b \sum_t X_{b,0,t} \leq \sum_b \sum_t u_{b,t} \times \varsigma_b \times \psi_{b,t} - \Gamma \times O - \sum_b \sum_t P_{b,t} \quad (5.20)$$

$$O + P_{b,t} \geq u_{b,t} \times \varsigma_b \times \hat{\psi}_{b,t} \quad \forall b, t \quad (5.21)$$

$$X_{b,0,t} \leq u_{b,t} \times \varsigma_b \times \psi_{b,t} \quad \forall b, t \quad (5.22)$$

$$X_{b,0,t} \geq u_{b,t} \times \varsigma_b \times \psi_{b,t} - u_{b,t} \times \varsigma_b \times \hat{\psi}_{b,t} \quad \forall b, t \quad (5.23)$$

$$P_{b,t} \leq M \times Y_{b,t} \quad \forall b, t \quad (5.24)$$

$$\sum_b \sum_t Y_{b,t} \geq \Gamma \quad (5.25)$$

$$X_{b,0,t} \leq u_{b,t} \times \varsigma_b \times \psi_{b,t} - P_{b,t} - R_{b,t} \quad \forall b, t \quad (5.26)$$

$$R_{b,t} \leq N \times Y_{b,t} \quad \forall b, t \quad (5.27)$$

$$R_{b,t} \geq N \times (Y_{b,t} - 1) + O \quad \forall b, t \quad (5.28)$$

$$R_{b,t} \leq O \quad \forall b, t \quad (5.29)$$

$$X_{b,0,t} = I_{b,0,t}^B + X_{b,0,t}^F + X_{b,0,t}^E \quad a = 0, \forall b, t \quad (5.30)$$

$$I_{b,a-1,t-1}^B = I_{b,a,t}^B + X_{b,a,t}^F + X_{b,a,t}^E \quad \forall b, t, a \in A \setminus \{0\} \quad (5.31)$$

$$I_{b,0,0}^B = 0 \quad \forall b \quad (5.32)$$

$$I_{t-1}^F + F_t = I_t^F + F_t^C + F_t^E \quad \forall b, t \quad (5.33)$$

$$I_0^F = 0 \quad (5.34)$$

$$F_t^C \leq D_t^{Fmax} \quad \forall t \quad (5.35)$$

$$E_t^F + E_t^B \leq D_t^{Emax} \quad \forall t \quad (5.36)$$

$$\sum_b \sum_a \alpha_b^F \times X_{b,a,t}^F = F_t \quad \forall t \quad (5.37)$$

$$\sum_b \sum_a \alpha_b^E \times X_{b,a,t}^E = E_t^B \quad \forall t \quad (5.38)$$

$$\eta^{FE} \cdot F_t^E = E_t^F \quad \forall t \quad (5.39)$$

$$X_{b,a,t}, X_{b,a,t}^F, X_{b,a,t}^E, F_t, F_t^C, F_t^E, E_t^F, E_t^B, I_t^F, I_{b,a,t}^B, k^z, \lambda_t \geq 0 \quad \forall b, a, t \quad (5.40)$$

## 5.4 Base case data

Data for this study is collected from different sources. Sawmill wastes, forest residues, switchgrass, wheat straw, corn stover are different types of biomass that are used in this study. Table 7 in Appendix C presents purchase prices, energy content, moisture content of the biomass. The corresponding references and the associated energy content are shown in Appendix C. It is supposed that bioethanol (as biofuel) generated from the different biomass can also be used as input for generating bioenergy. There are two kinds of technology in the biorefinery. First, combustion technology (the thermochemical conversion process) is used. Sawmill waste, forest residues, and bioethanol can be used as input feedstocks to be burnt to generate bioenergy. Second, using the fermentation technology (biochemical conversion process), wheat straw, switchgrass, and corn stover are converted to bioethanol in the biorefinery. Table 8 in Appendix D shows The yield of the fresh biomass converted by the different technologies, the value of the processing cost, and the assigned technology.

Electricity as bioenergy and bioethanol as biofuel are the final products in this study, and bioethanol can also be used as input feedstock to be burnt for generating electricity.

According to differnt refrences (e.g. [www.niordc.ir](http://www.niordc.ir); Hemingway and Prime 2013), the maximum demand of biofuel and bioenergy can vary over planning horizon. Table 9 in Appendix E shows the maximum annual demand, the cost of holding each cubic meter of biofuel, the cost of holding each tonne of biomass, the selling price of each Megawatt hour (MWh) of bioenergy, and the selling price of each cubic meter ( $m^3$ ) of biofuel. Using the method introduced in Section 5.3.3, the interval of the uncertain parameter obtained from the method is shown Figure 5.3.

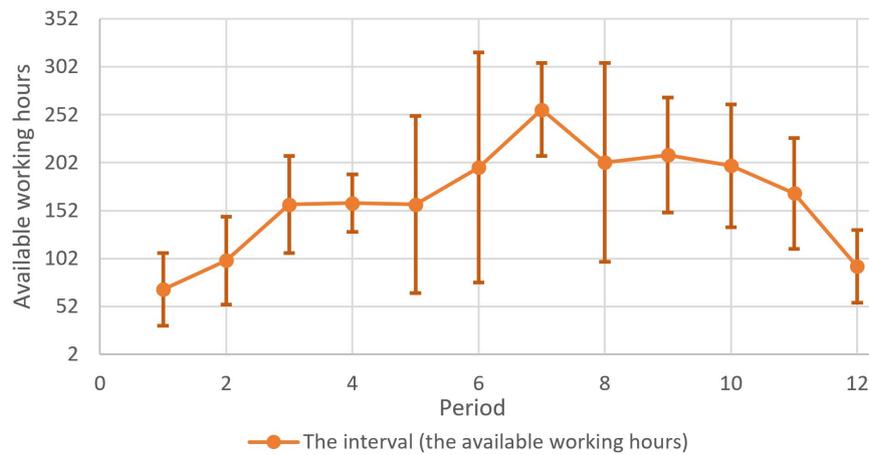


Figure 5.3 – The intervals (the available working hours)

## 5.5 Numerical Experiments

The models (the deterministic and robust models) were coded in GAMS 24.1.2 and solved using CPLEX solver (version 20.1). Using an Intel Core i7, 2.11 GHz processor with 32 GB of RAM, the models were implemented under the base case explained in Section 5.4. In order to extract a series of insights into optimization of operations and profitability of the biorefinery, a numerical analysis is conducted. The rest of this chapter is divided into the several subsections as follows: 1) The optimal solutions of the models (deterministic and robust) using the base case data are presented in Subsection 5.5.1. The effects of biomass perishability on the production planning are presented in Section 5.5.2. The effects of the maximum age of biomass are presented in Section 5.5.3. Energy storage is analyzed in Section 5.5.4. The effects of each uncertain parameter are separately studied in Section 5.5.5. In Section 5.5.6, the sensitivity analysis is presented. The robustness and the value of that are presented in section 5.5.7.

### 5.5.1 Optimal solution of the deterministic and robust model

In this section, the base case explained in Section 5.4 is used and the deterministic and robust model are run. Here, three protection/conservation levels (80%, 90%, and 99%) are defined that represent various risk preferences. Note that in the base case scenario, the conservation level is considered equal to 90%. Table 5.3 shows the results. The profit in robust model is less than the profit in the deterministic model because of costs incurred for improving the production planning stability. This can be more tangible when the level of conservatism increases. For instance, a risk averse version of the robust model (Protection level=99%) leads to 31% decrease in the total profit. Nevertheless, with lower uncertainty level, a trade-off can be made between robustness and its cost to increase the reliability of the solutions at a more reasonable cost.

Figure 5.4 shows the optimal biomass storage over the planning horizon in more details. For example, 5705.3 tonne of biomass type 4 with age 5 is stored in period 6. The total biomass type 4 with age 5 over the planning horizon is equal to 29941 tonne. These results are in sixth row of Figure 5.4. Consequently, the robust model (conservative level= 90%) helps manage biomass perishability by monitoring the age of biomass over the planning horizon under uncertain conditions.

Table 5.3 – Comparison of the deterministic and robust models under different conservation levels

		Deterministic	Robust (conservation level)		
			99%	90%	80%
Profit(\$)		47179784	32858960	32947541	33212489
The fresh stored biomass (t)		262878.268	199188.2682	201148.2682	209198.2682
The old stored biomass (t)		659957.905	509465.9175	522190.8826	553859.2927

## 5.5.2 Biomass perishability

In following parts, the effect of biomass perishability is investigated. To do this, we use equation (5.14) for deterministic model, and equation for robust model, and change the rate of perishability ( $\xi$ ) into the range 0% to 100%. Figure 5.5 and 5.6 show the results. In these Figures, the effect of perishability on the total profit and biomass storage is investigated. First, Figure 5.5 demonstrates that when the perishability rate increases the profit decreases by 26%, so this shows perishability is important. However, after 80% perishability rate, the profit stay fixed. The reason for this behaviour is that after 80% perishability level, it is not optimal decision to keep biomass in the storage. Therefore, there is nothing in the storage that can be affected by perishability.

Second, we expected more biomass storage under uncertain conditions, although according to Table 5.3 amount of biomass storage in deterministic model is more than than real world conditions (under uncertainty). I deeply review the results to understand this behaviour of the model. The answer is biomass perishability. When we do not consider perishability or consider a very low level of perishability, model chooses to store more biomass storage under uncertain conditions. However, when we consider perishability or high level of perishability, biomass storage decreases under uncertain conditions. This also can be seen in Figures 5.5 and 5.6.

The logic behind this behaviour links to strategy of the robust model. Under perishability of biomass, robust model prefers to convert biomass with high level of perishability to biofuel, and then keep it in biofuel storage to neutralize the effect of biomass perishability.

			T								
Biomass Type	Age	Storage	1	2	3	4	5	6	7	8	Total inventory of age $a$
$b = 4$	$a = 0$	$I_{b=4,a=0,t}^B$	51920	29040				20900	22990	10890	135740
$b = 4$	$a = 1$	$I_{b=4,a=1,t}^B$		51920	29040				20900	22990	124850
$b = 4$	$a = 2$	$I_{b=4,a=2,t}^B$			44247.2	29040			20900	22990	117177.2
$b = 4$	$a = 3$	$I_{b=4,a=3,t}^B$				32187.1	29040				61227.1
$b = 4$	$a = 4$	$I_{b=4,a=4,t}^B$					19373.3	29040			48413.3
$b = 4$	$a = 5$	$I_{b=4,a=5,t}^B$						5705.3	24235.7		29941
$b = 4$	$a = 6$	$I_{b=4,a=6,t}^B$								9591.3	9591.3
$b = 5$	$a = 0$	$I_{b=5,a=0,t}^B$	4088.2	3780	7560	10500	4620	13300	14630	6930	65408.2
$b = 5$	$a = 1$	$I_{b=5,a=1,t}^B$		3970.6	3780	7560	10500	4620	3780	14630	48840.6
$b = 5$	$a = 2$	$I_{b=5,a=2,t}^B$				3780	7560	10500	4620	13300	39760
$b = 5$	$a = 3$	$I_{b=5,a=3,t}^B$					3780	7560	10500	4620	26460
$b = 5$	$a = 4$	$I_{b=5,a=4,t}^B$						3780	7560	10500	21840
$b = 5$	$a = 5$	$I_{b=5,a=5,t}^B$								7560	7560

Figure 5.4 – Amounts of inventory in the robust model (conservative level=90%)

This can be seen in Figure 5.7.

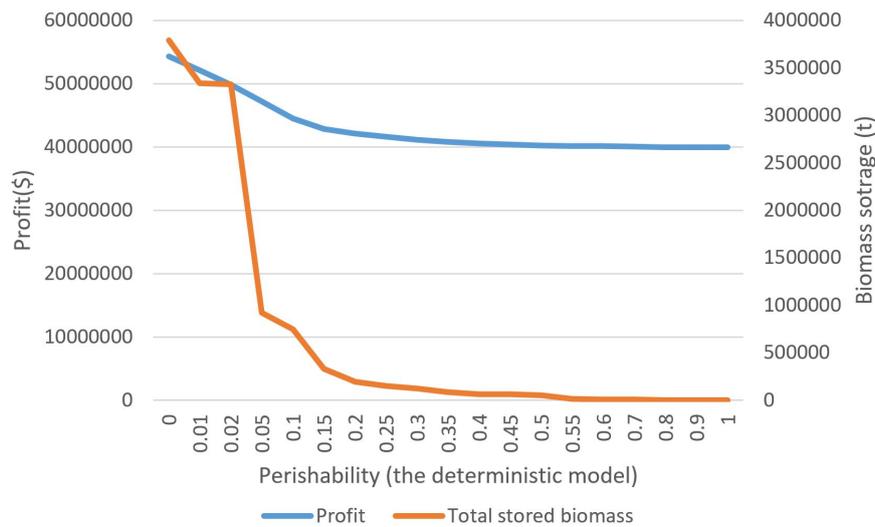


Figure 5.5 – Perishability (deterministic model)

### 5.5.3 The effects of the maximum age of biomass

In practice, it is necessary that the manager has flexibility to make decision for maximum amount of time to store the biomass, due to the different concerns. The healthy and safety problems made by storing biomass for long time are more common concerns. For instance, spore / fungal (fungus) formation (Rentizelas et al. 2009) or spontaneous ignition (Torrent et al. 2015), because of the exothermic microbial degradation.

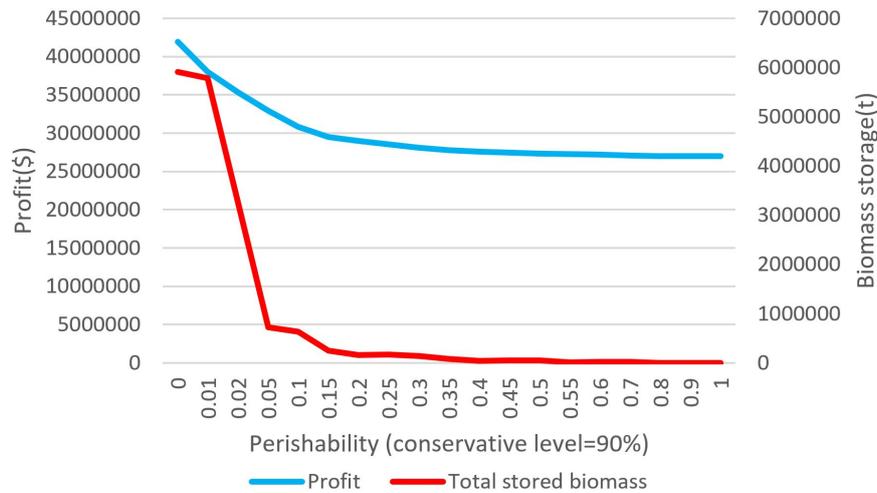


Figure 5.6 – Perishability (uncertainty model)

The maximum age of biomass is defined here, the maximum number of time periods in which biomass is allowed to be stored. In this subsection, the effects of maximum age of biomass on the biorefinery under uncertainty is analyzed. We use the default value of perishability rate which is equal to 5%, and set the conservative level equal to 90%. The maximum allowed age of the biomass is decreased from 11 to 0 time periods. The results of this test are shown in Figure 5.8. The main insights in this figure are as follows. First, the profit significantly increases when the maximum age of biomass increases from 0 to 2 periods. In other words, comparing with the case of not allowing the biomass storage (neither old biomass nor fresh biomass, Maximum Age=0), storing biomass is so important for the manager to increase the total profit.

Second, the profit stays constant (flat curve) on ranges [3, 4] and [7, 11]. The decision makers may prefer to set the maximum age to lowest value of the range (i.e., 7 or 3) to obtain the health benefits. Further more, beyond a certain value (here 7 periods), the profit remains unchangeable. Inventory holding costs highly affects this threshold value. Third, in the ranges [2, 3] and [4, 7], there is a trade-off between the profit and the extra costs for longer time storage (perishable biomass). Using this trade-off, the manger can determine the best maximum age.

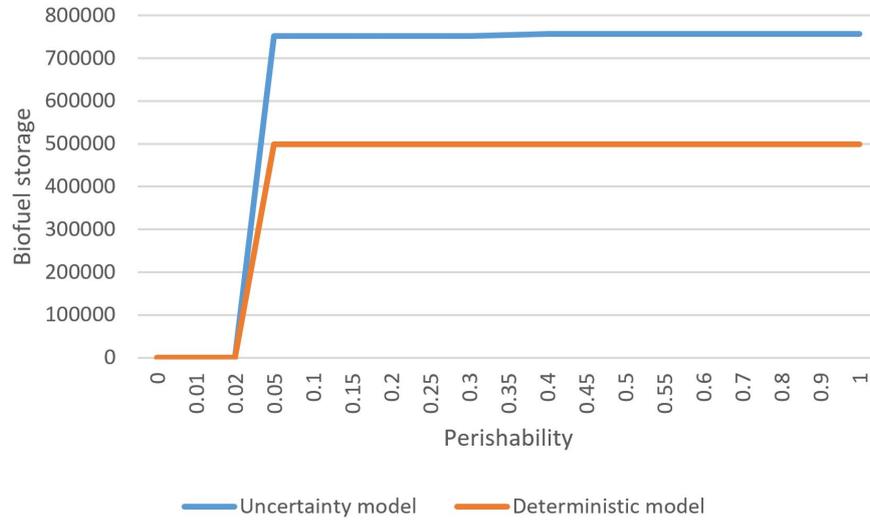


Figure 5.7 – Perishability and biofuel storage (uncertainty model)

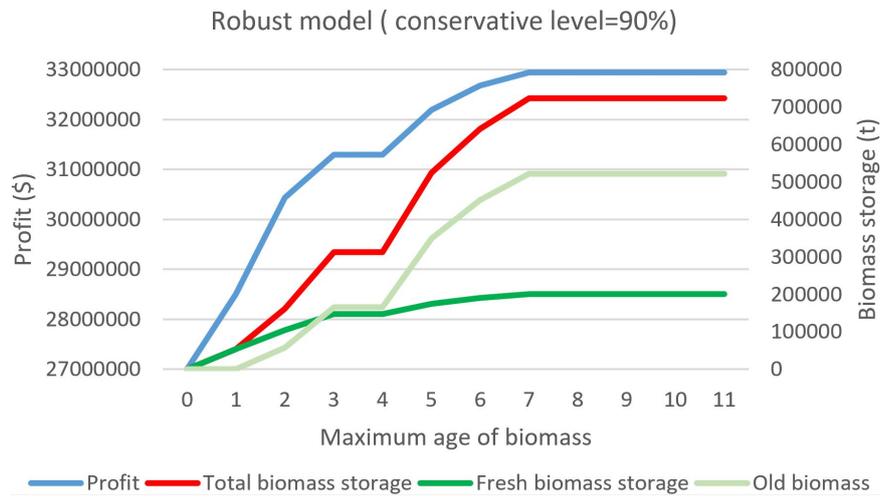


Figure 5.8 – Maximum age of biomass (Robust model, conservative level=90%)

### 5.5.4 Energy storage

Next, the superiority of the proposed model (with energy storage) over the basic model (without energy storage) is shown using two model, deterministic and uncertainty model (reliability=80%). The value of  $\eta^{FE}$  is set to zero to obtain the basic model (without energy storage). The results are shown in Table (5.9). It shows that the manager can obtain more profit from the same amount of biomass.

	BD (without E-storage)	OD (with)	BU (without)	OU (with)
Profit (\$)	46543660	47179780	29265964.19	32947541.45
Biofuel storage ( $m^3$ )	623168.36	499384.16	361387.20	752545.60
Biomass storage (t)	922836.17	922836.17	723339.15	723339.15
Purchased biomass (t)	2712610	2712610	2090070	2090070
Biofuel sold ( $m^3$ )	687877.93	564093.73	535777.99	137375.7
Bioenergy sold (MWh)	308759.76	652384.708	232273.49	1338238.266
The biofuel used for bioenergy ( $m^3$ )	0	123784.20	0	398402.29

Figure 5.9 – Optimal solution of the bioenergy production system

Figures 5.10 and 5.11 show the differences between basic model (without energy storage) and the proposed model in under two conditions, deterministic and uncertain. Given to the differences between two pairs of profits, Superiority of the proposed model will be more apparent when real world conditions (under uncertainty) are considered.

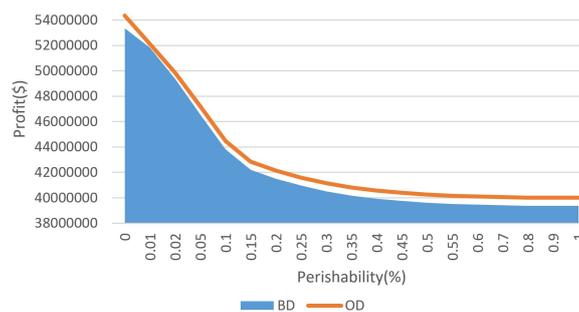


Figure 5.10 – Energy storage (Deterministic model)

### 5.5.5 The effect of each uncertainty

In this section, The effect of each uncertain parameter is investigated. First, the conservation budget related to the price uncertainty is set to zero, and the model is run for

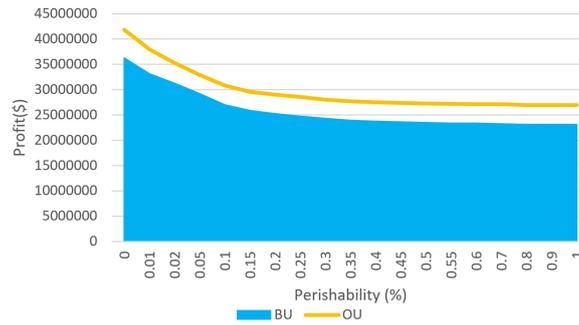


Figure 5.11 – Energy storage (Robust model)

different conservation budgets of supply uncertainty (weather uncertainty). Note that by adjusting the budget parameter, decision-makers can evaluate different scenarios of supply uncertainty. Increasing in the budget (protection /conservation level) leads to add perturbation values to their corresponding nominal values. In addition, system robustness is the percentage of fully covered perturbations of the uncertain parameter. The results related to supply uncertainty are shown in Figure 5.12 and Table 5.4. In the absence of protection levels (all budgets are equal to zero), the optimal value is equal to deterministic model (47179784\$) and the system robustness remains in its minimum state. The maximum protection level results in over-conservatism, and the profit dramatically decreases and reaches to 35927080\$. In this case, robustness reaches to its maximum state. Figure 5.12 shows increase in protection level leads to decrease in the profit, and Table 5.4 shows that by increasing the protection level the robustness increases. Note that robustness growing is desirable, although decrease in profit is not desirable. Reduction in Figure 5.12 and Table 5.4 is the difference between objective function in robust and deterministic model.

Weather uncertainty (supply uncertainty) can lead to about 23% reduction in the total profit. This shows the importance of considering weather uncertainty in bioenergy production planing in real life. Figure 5.12 shows that after point  $\Gamma^w = 39$ , the profit is not any more sensitive to weather conditions. The reason is that there are 39 months (different harvesting seasons) for collecting different types of biomass. Harvesting seasons.

Similarly, these experiments are implemented for price uncertainty. The results are shown in Figure 5.13 and Table 5.5. Increase in robustness leads to decrease in profit, and a maximum robustness state in price uncertainty lead to decrease in profit to 43506396\$. In Figure 5.13 after level 7 the profit is constant, the reason is that in this case study and under only price uncertainty, model choose to sell directly biofuel to the costumer in 7 months beside converting the biofuel to bioenergy. The results in Figure 5.12 and

5.13 indicate that weather uncertainty has more effect on the profit comparing with price uncertainty. Note that this is supply uncertainty, it has a big impact on the production planning. Therefore, manager must be careful about this kind of uncertainty. A trade-off is made between the cost of robustness and saved profit in the following.

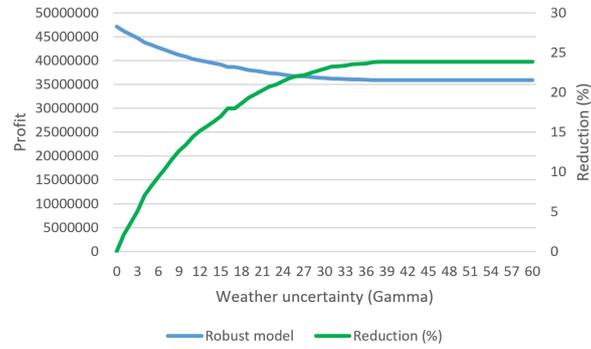


Figure 5.12 – Weather uncertainty



Figure 5.13 – Price uncertainty

Table 5.4 – Trade-off between profit and robustness (weather uncertainty)

row	$\Gamma^{price}$	Profit	Reduction	System robustness
1	1	46185019.2	994765.2	0.0537897310513447
2	2	45492019.2	1687765.2	0.107579462102689
3	3	44770432.95	2409351.45	0.161369193154034
4	4	43851024.08	3328760.325	0.207090464547677
5	5	43276507.28	3903277.125	0.25281173594132
6	6	42745839.82	4433944.581	0.298533007334963
7	7	42236399.06	4943385.339	0.344254278728606
8	8	41705403.56	5474380.839	0.389975550122249
9	9	41214924.2	5964860.199	0.430317848410758
10	10	40841828.56	6337955.839	0.456723716381418
11	11	40370968.38	6808816.024	0.483129584352078
12	12	40025811.22	7153973.184	0.509535452322738
13	13	39757518.78	7422265.622	0.535941320293398
14	14	39466027.07	7713757.335	0.56039119804401
15	15	39168129.47	8011654.935	0.584841075794621
16	16	38690390.3	8489394.101	0.609290953545232
17	17	38690390.3	8489394.101	0.633740831295843
18	18	38385372.29	8794412.111	0.65721271393643
19	19	38045692.68	9134091.721	0.680684596577017
20	20	37845429.16	9334355.246	0.704156479217604
21	30	36325808.48	10853975.92	0.894376528117359
22	35	36041818.23	11137966.17	0.962836186
23	36	36025747.53	11154036.87	0.976528117
24	37	35953237.33	11226547.07	0.990220049
25	38	35927080.08	11252704.32	1

Table 5.5 – Trade-off between profit and robustness

row	$\Gamma^{price}$	Profit	Reduction	Robustness
1	1	45924790.82	1254993.576	0.23121387283237
2	2	44860365.26	2319419.145	0.346820809248555
3	3	43902890.5	3276893.899	0.462427745664745
4	4	43534052.94	3645731.457	0.5491329479768795
5	5	43512634.53	3667149.869	0.61849710982659
6	6	43506396.72	3673387.681	0.687861271676301
7	7	43506396.72	3673387.681	0.751445086705202
8	8	43506396.72	3673387.681	0.809248554913295
9	9	43506396.72	3673387.681	0.867052023121387
10	10	43506396.72	3673387.681	0.92485549132948
11	11	43506396.72	3673387.681	0.971098265895954
12	12	43506396.72	3673387.681	1

### 5.5.6 Sensitivity analysis

In this part, the sensitivity of profit is investigated when the values of the parameters change. First, the following parameters are considered to be analyzed: (a) cost of purchasing biomass; (b) conversion rate; (c) holding costs; (d) maximum demand of products; (e) production costs; (f) price of bio-energy; (g) cost of purchasing biomass. Each parameter is changed in a reasonable range (-20% to +20%), and then ran the model to obtain variation in the total profit. Figure 5.14 shows the results. First conversion rate has a high effect on the profit. This indicates the importance of biomass perishability. Second, the effect of biofuel holding cost is more than the biomass holding costs. The robust model tends to store more biofuel comparing with deterministic model. Price of bioenergy in negative variation has less effect comparing with positive variation. This is one of interesting features of the proposed model. In other words, under negative variation, model switches to sell more biofuel than bioenergy to obtain profit. Third, the proposed model is not sensitive to demand. the proposed model includes powerful tools (converting biofuel to bioenergy, biofuel storage, biomass storage, energy storage, etc.) that lead to smoother production even under highly fluctuating demand.

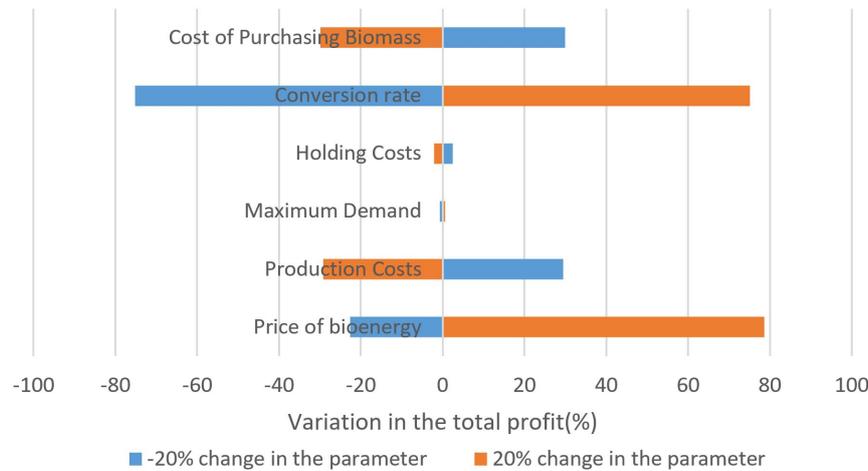


Figure 5.14 – Sensitivity analysis (conservative level=90%)

### 5.5.7 Model evaluation

In this section, the proposed robust model is validated. To do so, I formulate a deterministic linear programming model. I call it "realization model", because it is a simulation of reality. In this model, the value of uncertain parameters are generated randomly. The random values are generated into the corresponding interval according to a uniform distribution. The compact form of the realization model is presented as follow:

$$\text{Maximize } Z - R^1.P_1 - R^2.P_2 \quad (5.41)$$

$$\text{Subject to:} \quad (5.42)$$

$$X_{b,0,t} - P_1 \leq \tilde{\psi}_{b,t}, \forall b, t \quad (5.43)$$

$$\begin{aligned} \sum_t \left( \tilde{p}_t^F . F_t^C + p_t^E (E_t^B + E_t^F) \right) - \sum_b \sum_a \sum_t (c_{b,t}^B . X_{b,a,t} + c_{b,t}^{BF} X_{b,a,t}^F + c_{b,t}^{BE} X_{b,a,t}^E) \\ - \sum_t c_t^{FE} . F_t^E - \sum_b \sum_a \sum_t h_b^B . I_{b,a,t}^B - \sum_t h^F . I_t^F + P_2 \geq Z \end{aligned} \quad (5.44)$$

$$P_1, P_2 \geq 0 \quad (5.45)$$

$$(3) - (13) \quad (5.46)$$

Where  $P_1$  and  $P_2$  are decision variables that determine the constraint violations related to the supply and price uncertainties (imprecise parameters) under each random realizations. In addition,  $R^1$  and  $R^2$  are penalty costs for constraint violation. The computational results of solving realization model for two models under 25 realizations are presented in Table 5.6.

As shown in Table 5.6, the proposed robust model outperforms deterministic model in terms of the average and standard deviation of the realization model objective function values. As mentioned before, the difference between profit of the deterministic model and profit of the robust model (i.e., 47179784 - 32947541= 14232243\$) is called "cost of the robustness (price of robustness)". Here, the expected value of the realization model objective function for deterministic and robust model under 25 random realization is shown in Table 5.6, implies that 15774790\$ (i.e., 32066538- 16291747) is the amount of profit which will be saved in future (based on the presented random realizations of uncertain parameters). I assume that in the future the realized values of uncertain parameters would be as presented 25 realizations in Table 5.6. Consequently, choosing the optimal solution of

the deterministic or robust model at the present time, will lead to the expected profit of 16291747 or 32066538 respectively. Nevertheless, considering the cost of robustness which is paid at the present time to achieve a robust solution, I call the difference between these values (i.e.,  $15774790 - 14232243 = 1542547\$$ ), as "value of robustness".

## 5.6 Conclusion

A multi-period production planning model for a biorefinery is developed and solved. The biorefinery transforms different types of biomasses into either bioenergy or biofuel. The biomass can be stored but its quality is deteriorated over time, which incurs a lower yield. The biofuel can also be stored to be transformed later to bioenergy. The applicability of the developed model was illustrated by a case study. Extensive numerical experiments were performed to understand the behavior of the model and derive managerial insights. The results showed that the higher the biomass perishability rate the lower the profitability of the biorefinery, but there is a threshold value on the biomass perishability rate above which perishability does not have any more impact on the profit. The biofuel storage is an important feature of the proposed model. While bioenergy cannot be stored and biomass storage leads to reducing its quality, the biofuel can be stored and transformed later into bioenergy to match supply with demand. I showed that this results in considerable profit increase and smoother production at the facility even under a high fluctuation in bioenergy selling price and demand.

the proposed modeling framework comes with limitations that offer avenues for future work directions. First, it is interesting to consider the uncertainty on the supply of biomass and evaluate its impact on production strategy and profit. Second, bioenergy price and demand uncertainties could also be incorporated into the model. Finally, applying the proposed model to a real case study would certainly require to make some adjustments in the modeling framework and constraints.

Table 5.6 – The performance of the proposed model under realization

Realization	Objective function value of the realization model	
	Deterministic model	Robust model
1	16359522.37	32844635.64
2	16744171.56	31490779.62
3	16805739.6	32097444.87
4	16690123.28	31929489.3
5	15582099.97	31914663.41
6	17112169.85	32103682.85
7	15479441.8	31837842.22
8	15479106.1	31627032.56
9	17154871.35	32098256.66
10	16465201.87	31627032.56
11	15935931.56	32337179.97
12	17174946.43	32245319.25
13	15835354.76	31520602.31
14	16429013.02	31849506.39
15	17101695.9	32036517.71
16	16886644.17	31940341.68
17	16530664.07	32176445.08
18	15079551.67	32499922.97
19	16057523.41	32111031.71
20	15346301.75	32401738.82
21	15820986.65	32251129.98
22	16446671.03	32758243.84
23	16101970.57	32112142.58
24	16994002.18	31801268.84
25	15679991.14	32051215.43
<b>Average</b>	16291747.84	32066538.65
<b>Standard Deviation</b>	634827.0299	340795.3085

**Appendices:****Appendix A. The adjustable row-wise robust optimization**

Bertsimas and Sim (2004) developed a row-wise robust optimization approach "the price of robustness", In this part, I use the following linear programming to briefly describe it.

$$\text{Minimizing } cx \tag{47}$$

$$\text{St: } \sum_j \tilde{a}_{ij} x_j \geq b_i \quad \forall i \tag{48}$$

$$x \in X \tag{49}$$

Where coefficients  $\tilde{a}_{ij}$  are subject to uncertainty. The set of uncertain coefficients of row  $i$  is shown by  $J_i$ . Each coefficient  $\tilde{a}_{ij}$  takes value in the interval  $[a_{ij} - \hat{a}_{ij}, a_{ij} + \hat{a}_{ij}]$  as a random variable. The variation/perturbation amplitude and the nominal value of the uncertain parameter are shown by  $\hat{a}_{ij}$  and  $a_{ij}$ , respectively. Parameter  $\Gamma_i$  is defined for each constraint  $i$  to adjust the conservatism level of the solution. It is uncertainty budget and it is not necessarily integer. It takes value in  $[0, |J_i|]$ , where  $|J_i|$  is the cardinality of set  $J_i$ .  $\Gamma_i$  aims at forcing  $\lfloor \Gamma_i \rfloor$  parameters to acquire their worst values, then goes for next one (i.e.,  $\tilde{a}_{it_i}$  and moves the next one to its worst value from its nominal value by  $(\Gamma_i - \lfloor \Gamma_i \rfloor)\hat{a}_{it_i}$ ). Therefore, the following form, which is nonlinear, is considered as the robust counterpart model:

$$\text{Minimizing } cx \tag{50}$$

$$\text{St: } \sum_j a_{ij} x_j - \max_{\{S_i \cup \{t_i\} | S_i \subseteq J_i, |S_i| = \lfloor \Gamma_i \rfloor, t_i \in J_i \setminus S_i\}} \left\{ \sum_{J \in S_i} \hat{a}_{ij} x_j + (\Gamma_i - \lfloor \Gamma_i \rfloor) \hat{a}_{it_i} x_j \right\} \geq b_i$$

$$\forall i$$

$$X \geq 0$$

$$\tag{51}$$

The coefficients which totally change are shown by  $S_i$ , and the coefficients which change if  $\Gamma_i$  is not an integer are shown by  $t_i$ .

Consider  $x_i^*$  is the optimal solution, the protection function of constraint  $i$ , i.e.,

$$\max_{\{S_i \cup \{t_i\} | S_i \subseteq J_i, |S_i| = \lfloor \Gamma_i \rfloor, t_i \in J_i \setminus S_i\}} \left\{ \sum_{J \in S_i} \hat{a}_{ij} x_j + (\Gamma_i - \lfloor \Gamma_i \rfloor) \hat{a}_{it_i} x_j \right\}$$

is equivalent to the following linear form:

$$\text{Minimizing } \sum_{j \in J_i} \hat{a}_{ij} |x_j^*| v_{ij} \quad (52)$$

$$\text{subject to: } \sum_{j \in J_i} v_{ij} \leq \Gamma_i \quad \forall i \quad (53)$$

$$0 \leq v_{ij} \leq 1 \quad \forall i, j \in J_i \quad (54)$$

Now, the dual variables  $Q_i$  and  $\gamma_{ij}$  are defined to obtain the dual problem of the above problem (52). Problem (3) is bounded and feasible for all  $\Gamma_i$ , thus, its dual pair has the same objective value and also is bounded and feasible according to the strong duality property.

$$\text{Minimizing } \Gamma_i Q_i + \sum_{j \in J_i} \gamma_{ij} \quad (55)$$

$$\text{subject to: } Q_i + \gamma_{ij} \geq \hat{a}_{ij} |x_j^*| \quad \forall i, j \in J_i \quad (56)$$

$$\gamma_{ij} \geq 0 \quad \forall i, j \in J_i \quad (57)$$

$$Q_i \geq 0 \quad \forall i \quad (58)$$

The problem (55) is substituted into problem (51) to obtained the robust counterpart model as follows:

$$\text{Minimizing } cx \quad (59)$$

$$\text{St: } \sum_j a_{ij} x_j - \Gamma_i Q_i + \sum_{j \in J_i} \gamma_{ij} \geq b_i \quad \forall i \quad (60)$$

$$\gamma_{ij}, Q_i, x_j \geq 0 \quad \forall i, j \in J_i \quad (61)$$

## Appendix B. The adjustable column-wise robust optimization

Soyster(1973) proposed a linear optimization model to hedge against uncertainty that generates solutions feasible for all possible values of uncertain data belonging to a convex set. This is a high conservative model in practice, because all uncertain parameters take their worse-case values. Therefore, Ben-Tal and Nemirovski (1998) and El-Ghauai et al (1998) proposed a less conservative robust counterpart using a polyhedral uncertainty set that was nonlinear model.

Then, Bertsimas and Sim (2004) proposed a less conservative model but linear which can adjust the protection level of uncertain parameters. The uncertainty budget of robustness can be set by additional parameter  $\Gamma_i$  for aggregative uncertain parameters in each constraint (row).  $\Gamma_i$  take values in the interval of  $[0, |\Gamma_i|]$ . This method which is called "price of robustness" can made trade-off between robustness and optimal cost. After that, Bertsimas and Thiele (2006) proposed a periodic robust counterpart model that protection level is considered for planning horizon. They applied the previous approach to an inventory problem and considered the uncertainty budget on the cumulative periods.

There is a subtle deficiency in these studies to hedge against uncertainty in a special circumstance. We want to tackle uncertainty when there is only one uncertain parameter in RHS of each constraint through a column-wise robustness rather than a row-wise one. Ghelichi et al (2018) proposed a adjustable column-wise robust optimization model to address this problem. Here, I adopt this approach to tackle weather uncertainty.

Now, the following uncertain linear optimization model is considered:

$$\text{maximize } c'x \tag{62}$$

$$\text{St: } \sum_j A_{i,j} \cdot x_j \leq \tilde{b}_i \quad \forall i \tag{63}$$

$$l \leq x_j \leq U \quad \forall j \tag{64}$$

Where uncertain parameter  $\tilde{b}_i$  takes value in the symmetric interval  $[b_i - \hat{b}_i, b_i + \hat{b}_i]$  that  $\hat{b}_i$  is the constant perturbation and  $b_i$  is the nominal value. The aim, here, is maximizing objective function while protecting against changes in the value of  $b_i$ .

The first step is that both sides of constraint (17) are summed up in the index  $i$  as follows:

$$\sum_i \sum_j a_{i,j} \cdot x_j \leq \sum_i \tilde{b}_i \quad \forall i \quad (65)$$

Then, base on the description of interval  $[b_i - \hat{b}_i, b_i + \hat{b}_i]$ , constraint (19) is developed in the following constraints (20) and (21). Note that  $\eta_i = (\frac{\tilde{b}_i - b_i}{\hat{b}_i})$  is a random variable that its values are in the interval  $[-1,1]$  (Ben-Tal and Nemirovski, 2000).

$$\sum_i \sum_j a_{i,j} \cdot x_j \leq \sum_i b_i - \sum_i \hat{b}_i \cdot \eta_i \quad \forall i \quad (66)$$

$$-1 \leq \eta_i \leq 1 \quad \forall i \quad (67)$$

Now, the solution space must be tightened to deal with uncertainty contamination. We have more protection in uncertain model if  $\sum_i \hat{b}_i \cdot \eta_i$  takes greater values in constraint (20). Consequently,  $\xi_i = |\eta_i|$  that its values are in interval  $[0,1]$  is defined to consider the positive part of  $\eta_i$ . The column-wise robust model is formulated as follows:

$$\text{maximize } c'x \quad (68)$$

$$\text{St: } \sum_i \sum_j a_{i,j} \cdot x_j \leq \sum_i b_i - \max \left\{ \sum_i \hat{b}_i \cdot \xi_i \right\} \quad (69)$$

$$l \leq X_j \leq U \quad \forall j \quad (70)$$

If  $\xi = 1, \forall i$ , the formulation (23) results in Soyster's approach. If  $\xi = 0, \forall i$ , the formulation (23) results in its nominal problem ( $\sum_i b_i$ ). Therefore,  $\Gamma$  is defined to control the conservation level of robustness. In other words,  $\Gamma$  is an adjustable integer parameter, and protection function of constraint (25) is stated as follow:

$$F(\xi_i, \Gamma) = \max_{\{S_i | S_i \subseteq I, |S_i| = \Gamma\}} \left\{ \sum_i \hat{b}_i \cdot \xi_i \right\} \quad (71)$$

In (71), I demonstrates the set of uncertain parameters  $b_i, i \in I$ , and  $S_i$  is a subset of  $I$ . The following leaner optimization problem is equivalent to equation (71) (see Bertsimas and Sim (2004)).

$$F(\xi_i, \Gamma) = \text{maximize } \sum_i \hat{b}_i \cdot \xi_i \quad (72)$$

$$\text{subject to: } \sum_i \xi_i \leq \Gamma \quad (73)$$

$$0 \leq \xi_i \leq 1 \quad \forall i \quad (74)$$

The following model is equivalent to model (68) to (70):

$$\text{maximize } c'x \quad (75)$$

$$\text{subject to: } \sum_i \sum_j a_{i,j} \cdot x_j \leq \sum_i b_i - (\Gamma \cdot O) - \sum_i P_i \quad (76)$$

$$O + P_i \geq \hat{b}_i \quad \forall i \quad (77)$$

$$\sum_j a_{i,j} \cdot x_j \leq b_i \quad \forall i \quad (78)$$

$$\sum_j a_{i,j} \cdot x_j \geq b_i - \hat{b}_i \quad \forall i \quad (79)$$

$$\sum_j a_{i,j} \times x_j \leq b_i - P_i - (O \times Y_i) \quad \forall i \quad (80)$$

$$P_i \leq M \times Y_i \quad \forall i \quad (81)$$

$$\sum_i Y_i \geq \Gamma \quad (82)$$

$$l \leq x_j \leq U \quad \forall j \quad (83)$$

$$P_i \geq 0 \quad \forall i \quad (84)$$

$$Y_i \in \{0, 1\} \quad \forall i \quad (85)$$

$$O \geq 0 \quad (86)$$

The constraints (76) and (77) are obtained by considering the dual form of problem (72) to (74) as follows:

$$\text{minimize } (\Gamma \times O) + \sum_i p_i \quad (87)$$

$$\text{subject to: } O + P_i \geq \hat{b}_i \quad \forall i \quad (88)$$

$$P_i \geq 0 \quad \forall i \quad (89)$$

$$O \geq 0 \quad (90)$$

$O$  and  $p_i$  are first and second dual variables, respectively. Constraints (78) to (82) are additional constraints to make constraint (63) compatible with constraint (69), the cumulative form of uncertain elements in column  $i \in I$ .

Constraints (78) and (79) insure that the uncertain parameter for all  $i \in I$  remains between its nominal value and worst-case value to consider the tighter solution space.

Constraints (80) and (81) have more complicated logic. First of all to control  $\Gamma = |S_i|$ , a binary variable ( $Y_i$ ) is defined. In other words, constraint (82) demonstrates that how many of  $b_i$  elements can take their worst value.

Constraint (80) demonstrates that each  $i \in I$  takes its worst value whenever its respective  $Y_i$  takes value 1. It determines elements of column  $b_i$  ( $i \in S_i$ ). Consider a particular ( $i \in I$ ),  $Y_i$  takes value 1, so constraint (80) can be formulated as follows:

$$\sum_j a_{i,j} \times x_j \leq b_i - P_i - O \quad \forall i \quad (91)$$

Considering constraint (77), ( $\sum_j a_{i,j} \times x_j \leq b_i - P_i - O \leq b_i - \hat{b}_i$ ), so formulation (92) is obtained.

$$\sum_j a_{i,j} \times x_j \leq b_i - \hat{b}_i \quad \forall i \quad (92)$$

In addition, given constraint (79), it can be deduced that:

$$\sum_j a_{i,j} \times x_j = b_i - \hat{b}_i \quad \forall i \quad (93)$$

It is obvious that  $\tilde{b}_i$  takes its upper bound (its worst value), when its corresponding  $Y_i$  takes value 1. Now, it is needed to explain the behavior of the dual variable ( $o$  and  $p_i$ ) to illustrate the application of constraints(80) and (81). Given constraint (82) and  $F(\xi_i, \Gamma)$ ,  $\Gamma$  number of uncertain elements in column  $b_i$  take their worst-case values, which have greatest perturbation values ( $\hat{b}_i$ ). Given the constraint (77), the value of variable  $O$  is evidently constant for all  $i \in I$ , but the value of  $p_i$  for each  $i \in I$  would differ based on its corresponding  $\hat{b}_i$ . By this way,  $O$  tends to take the least  $\hat{b}_i$  value, since  $O$  and  $p_i$  are positive variables, and  $p_i$  takes the excessive value of  $\hat{b}_i$  ( $\hat{b}_i - O$ ). For  $i \in (I - S_i)$ ,  $p_i$  takes value zero, because its corresponding  $Y_i$  is equal to zero. For  $i \in S_i$ ,  $p_i$  can take value zero

or  $\hat{b}_i - O$ .

Now, we can clarify the function of constraints (80) and (81). Constraint (81) demonstrates that for each  $i \in I$  that  $p_i > 0$ , its corresponding  $Y_i$  must get 1, and this element takes its worst value by constraint (80).

In constraint (80), we have non-linear term. We define the artificial variable  $R_i$  to linearize this constraint using the following formulation;

$$R_i = O \times Y_i \quad \forall i \quad (94)$$

$$R_i \leq M \times Y_i \quad \forall i \quad (95)$$

$$R_i \geq M \times (Y_i - 1) \quad \forall i \quad (96)$$

$$(97)$$

### Appendix C. Biomass data

A summary of different kinds of biomass used in the base case, and the features such as moisture content and energy content, as well as annual availability and purchase cost, are presented in Table 7. The energy content of the biofuel is assumed 42.53 GJ obtained from one tonne of each kind of biomass (Mahjoub et al. [2020]; Kathirvelu et al. [2017]).

Note that biomass has a perishable nature (Tavanandi et al. [2018]; Castillo-Villar et al. [2017]; Valdovinos-García et al. [2020]). Biomass could not be stored in the warehouse for a long time. The chemical reactions continuously occur and lead to losses of the valuable materials in the biomass over storage time (Fuller [1985]; Larson et al. [2015]; Kenney et al. [2013]). The perishability of biomass has an important role in the performance of the production process Rentizelas et al. [2009]).

Note that biomass perishability is considered (in this study) as the reduction in the values of: i) energy content (higher heating value HHV) ( $\frac{\text{GJ}}{\text{t}}$ ) (Channiwala and Parikh [2002]), and ii) oil yield ( $\frac{\text{m}^3}{\text{t}}$ ) (Fuller [1985]). This reduction in the values is based on biomass aging.

**Appendix D. Conversion technology data** A summary of conversion technology data used in this study is presented in Table 8.

The yields in Table 8 can vary with the change of the biomass quality. It is worth noting that the yield of the bioenergy can also be obtained by (98) (Akhtari et al. 2018, Kenney et al. 2013, Nur et al. 2021). It indicates that the yield in Megawatt-hour per tonne (MWh/t) is a function of the energy content in Gigajoule per tonne (GJ//t), the coefficient of technology efficiency and a constant of 3.6 to convert GJ to MWh (1MWh =

3.6 GJ). Note that the values of "energy content" in Table 7 are used as inputs for (98), and then, the results are shown in Table 8 as inputs for the model.

$$\text{Bioenergy product Yield} \left( \frac{MWh}{t} \right) = \frac{\text{Energy content} \left( \frac{GJ}{t} \right) \times \text{Efficiency of technology}}{3.6 \left( \frac{GJ}{MWh} \right)} \quad (98)$$

### Appendix E. Demand, price, and holding costs data

The maximum annual demand, holding costs, and selling price of each  $m^3$  of biofuel and each MWh of bioenergy are shown in Table 9 ([www.niopdc.ir](http://www.niopdc.ir); Bairamzadeh et al. [2015]).

Table 7 – Characteristics of biomass

Biomass	Annual available biomass (t)	Moisture content (%)	Energy content (GJ/t)	Purchase cost(\$/ton)
Corn stover <sup>a</sup>	195457	24.1	18.80	20
Wheat straw <sup>a</sup>	1167797	23.53	18.65	21
Switchgrass <sup>b</sup>	11522646	26.5	17.80	26
Forest residues <sup>c</sup>	821700	29	14.65	24
Sawmill waste <sup>c</sup>	26091	30.5	13.71	19

<sup>a</sup>Bairamzadeh et al. [2015]

<sup>b</sup>Ghaderi et al. [2018]

<sup>c</sup>Cambero et al. [2015]

Table 8 – The assigned technology, the processing cost, and the conversion rate for each kind of fresh biomass.

Technology	Yield (unit of product output/ unit of the feedstock input); Processing cost (\$/unit of the feedstock input)					
	Corn stover <sup>a</sup>	Wheat straw <sup>a</sup>	Switchgrass <sup>b</sup>	Forest residues <sup>c,d</sup>	Sawmill wastes <sup>c,d</sup>	Biofuel (as input) <sup>e,f</sup>
1. Biofuel technology: Biochemical conversion process (Fermentation, 600000 t/month)	0.272 ( $m^3/t$ ); 21(\$/t)	0.270 ( $m^3/t$ ); 21(\$/t)	0.313 ( $m^3/t$ ); 21(\$/t)	-	-	-
2. Bioenergy technology: Thermochemical conversion process (Combustion, 5MW) Efficiency 23.5%	-	-	-	0.956 (MWh/t); 16.5(\$/t)	0.895 (MWh/t); 16.5(\$/t)	2.776 (MWh/ $m^3$ ); 15(\$/ $m^3$ )

<sup>a</sup>Bairamzadeh et al. [2015]

<sup>b</sup>Ghaderi et al. [2018]

<sup>c</sup>Cambero et al. [2015]

<sup>d</sup>Akhtari et al. [2018]

<sup>e</sup>Wickwire [2007]

<sup>f</sup>Mahjoub et al. [2020]

Table 9 – Selling prices, maximum annual market demand, and holding costs.

Products	Maximum annual demand	Selling price (\$)	Holding cost (\$)
Biofuel (bioethanol $m^3$ )	118657641	204	5.283
Bioenergy (electricity MWh)	7194050	81	-
Biomass (t)	-	-	0.0375



# CONCLUSION

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This thesis focused on the different challenges which a biorefinery is facing. We consider a biorefinery as a plant converting biomass to bioenergy and biofuel. Since biomass absorbs CO<sub>2</sub> during growth, when it is converted to biofuel or bioenergy, it generate net zero emissions. Therefor, it can be considered as a clean alternative (instead of fossil fuel) to supply the energy demand. Biomass has some features that impact the bioenergy production system. These features lead to more challenges for the manager of biorefinery who would commercially generate bioenergy and biofuel form biomass. The manager needs an optimal production planning which considers the challenges. This thesis helps the manger achieve his goal. This thesis includes five chapters.

An introduction was proposed, and the important issues and terms that are used in the thesis were defined in Chapter one. In Chapter two, a general literature review was proposed which focuses on the studies proposing the mathematical models and optimization methods for bioenergy production systems (bioenergy supply chains). The studies have been seen from different perspectives. For example, production planning for bioenergy supply chains, considering sustainable development in the bioenergy network, designing the supply chain network (finding the optimal locations), and considering uncertainty.

The basic mathematical model was proposed in Chapter three. The first challenge related to the bioenergy production system (biomass availability) was introduced in Chapter three. Biomass is not available during a year although the biorefinery would continuously generate bioenergy. One way to address this problem is to store biomass, but storing biomass for a long time impacts the quality of biomass, since biomass is perishable material. This feature affects bioenergy production planning. This thesis incorporated the age of biomass into the mathematical model to address the challenge and control biomass perishability.

The experiments related to biomass perishability were extended in Chapter four, plus energy storage was introduced as a new contribution. Energy storage is a challenge in the bioenergy production planning. Biorefineries generate bioenergy, although they could store the generated energy. It is not economic, so they must sell it immediately. This thesis proposed a new method for storing bioenergy. Energy is stored in the form of biofuel

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which can be converted into bioenergy later (inside of biorefinery). There is no study in the literature (to the best of my knowledge) considering this method to store energy that includes a mathematical model in the context of converting biomass to bioenergy. Note that the studies introducing storing energy in the form of fuel do not have any mathematical model.

Two new contributions were considered in Chapter 5, modeling weather conditions and considering uncertainties. Weather conditions can impact the availability of biomass. Collecting biomass needs appropriate weather conditions. For instance, collecting biomass is not possible on rainy days. This thesis defined three factors: i) rainfall, ii) temperature, iii) daylight to model the weather conditions. The uncertain parameter is defined based on the three factors that represents weather uncertainty. In addition, correlation between the price of biofuel and the price of other sources (e.g., crude oil), as well as fluctuating market prices can affect the price of biofuel. This thesis considered the price of biofuel as an uncertain parameter. In order to address the uncertainty, a hybrid model, a row and column-wise robust optimization model was proposed.

The results showed that the higher the biomass perishability rate the lower the profitability of the biorefinery, but there is a threshold value on the biomass perishability rate above which perishability does not have any more impact on the profit. The biofuel storage is an important feature of the proposed model. While bioenergy cannot be stored and biomass storage leads to reducing its quality, the biofuel can be stored and transformed later into bioenergy to match supply with demand. This results in considerable profit increase and smoother production at the facility even under a high fluctuation in demand. In addition, the model determined to store less biomass under uncertain conditions while it is reverse in the case of ignoring perishability. Energy storage has more positive effects under uncertain conditions on production planning. Weather uncertainty has more effects on the production planning compared with price uncertainty. Although extra costs must be paid at the beginning of the planning horizon to make the model robust against uncertainty, the biorefinery saves more profit in the future for us which called the value of robustness.

The framework of this thesis comes with limitations that offer avenues for future work directions. First, it is interesting to consider sustainability into the model. For example, defining new objective to reduced amount of emissions based on Paris agreement. Even carbon trading base on different carbon pricing policies can help achieve this mission. Second, the model would be more realistic by taking into account the time value of money and bring it into financial calculations from an economic perspective. Third, applying

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the international logistics into the model to take advantages of international trade, and considering exports/imports of products in a large scale design. Fourth, machine learning approaches can be applied to estimate more accurately the demand of products. Fifth, considering supply disruptions in the optimization model, because of pandemic or war that directly effect the bioenergy sector. Disaster management can be applied to appropriate response. Finally, applying the proposed model to a real case study would certainly require to make some adjustments in the modeling framework and constraints.



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**Titre :** Modèles de planification tactique pour la production combinée de biocarburants et de bioénergies

**Mot clés :** Planification de la production de bioénergie, Incertitude, Optimisation robuste, Biomasse, Périssabilité, Stockage

**Résumé :** Cette thèse propose un modèle de planification de production pour une bioraffinerie générant du biocarburant et de la bioénergie sous incertitude. Plusieurs défis sont abordés dans la thèse. Premier défi, le stockage de la biomasse sur une longue durée entraîne une baisse de qualité, car la biomasse est une matière périssable. Deuxième défi, les conditions climatiques imprévisibles ont un impact sur la disponibilité de la biomasse. Nous définissons trois facteurs : i) les précipitations, ii) la température et iii) l'ensoleillement pour modéliser les conditions climatiques. L'incertitude météorologique est définie en fonction de ces facteurs. Le troisième défi, la fluctua-

tion des prix du marché conduit à l'incertitude des prix. Le quatrième défi est le stockage de l'énergie. Un modèle hybride, un modèle d'optimisation robuste en ligne et en colonne, est proposé, et plusieurs expériences numériques sont conçues. Les résultats montrent, premièrement, que la périssabilité de la biomasse entraîne une réduction significative du profit. Nous nous attendons à stocker plus de biomasse sur l'horizon de planification dans des conditions d'incertitude, bien que les résultats soient surprenants. Deuxièmement, l'incertitude climatique a plus d'effets que l'incertitude des prix. Troisièmement, le stockage d'énergie augmente le profit jusqu'à 12,6%.

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**Title:** Tactical planning models for combined biofuel and bioenergy production

**Keywords:** Bioenergy production planning, Uncertainty, Robust optimization, Biomass, Perishability, Storage

**Abstract:** This thesis proposes a production planning model for one biorefinery generating biofuel and bioenergy under uncertainty. Several challenges are considered in the thesis. The first challenge, storing biomass for a long time leads to quality reduction, because biomass is a perishability material. The second challenge, unpredictable climatic conditions impact the availability of biomass. We define three factors: i) rainfall, ii) temperature, and iii) sunshine to model the climatic conditions. Weather uncertainty is defined based on these factors. The third challenge, fluctu-

ating market price leads to price uncertainty. The fourth challenge is energy storage. A hybrid model, a row and column-wise robust optimization model, is proposed, and several numerical experiments are designed. The results show, first, biomass perishability leads to a significant reduction in profit. We expect to store more amount of biomass over the planning horizon under uncertainty, although the results are surprising. Second, weather uncertainty has more effects compared with price uncertainty. Third, energy storage increases the profit by up to 12.6%.