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THÈSE POUR OBTENIR LE GRADE DE DOCTEUR DE MONTPELLIER SUPAGRO

En Science Economiques

École doctorale [EDEG – Économie et Gestion]
Portée par

Unité de recherche G-EAU

**Economic optimization of a brownfield redevelopment
program at a regional scale**

**Optimisation économique d'un programme de
redéveloppement de friches à échelle régionale**

**Présentée par Joaquin Ameller Pavez
Le 17 Novembre 2020**

**Sous la direction de Jean-Daniel Rinaudo
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Invité

Invité



**UNIVERSITÉ
DE MONTPELLIER**



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Abstract

Brownfield Redevelopment (BFR) is an issue of growing concern for urban planners all over the world. Brownfields are sites which once supported economic or industrial activities, but are now vacant, abandoned or underutilized. Their number is likely to increase, especially in former industrialized regions of Europe. Brownfields are often a source of nuisance for nearby residents, particularly in the case of contaminated sites (environmental and human health risks). At the same time, brownfields located within metropolitan areas offer genuine opportunities for urban development by reinvigorating distressed neighborhoods and avoiding costs linked to urban sprawl. The cost of removing derelict buildings and chemical pollutants in soil and groundwater may significantly exceed the expected financial benefits on which private investors base their decisions. Many indirect benefits (environmental, social, avoided public expenses), which could justify public investment in such projects, are hard to assess in monetary terms. As shown in the literature review presented in **Chapter 1**, most analyses and decision-support tools addressing BFR are carried at the site level. In view of assisting policy makers to design a portfolio of redevelopment projects that could maximize social welfare, the objective of this research is therefore to develop a model for the economic optimization of a BFR program at a regional scale. The implementation of the model is empirically illustrated in the Valley of Chemical Industry (Vallée de la Chimie in French), which is presented in **Chapter 2**, and includes the identification and characterization of 30 brownfield sites and 9 future land use activities. **Chapter 3** presents the assessments of rehabilitation costs, where uncertainty is addressed using an approach built on the subjective knowledge of experts. Four sources of costs were identified: soil decontamination, management of excavated soil, deconstruction of derelict buildings, and soil reconditioning. **Chapter 4** focuses on valuing in monetary terms the private, social and environmental benefits of BFR. The approach is based on benefit transfer to deal with the multiple benefits of a portfolio of several sites and several redevelopment options. **Chapter 5** presents how the model, based on mathematical programming, uses cost-benefit analysis to compare different redevelopment options for brownfield sites, and to identify the optimal combination of BFR alternatives to maximize the overall net benefit over a 20-year period. The model also accounts for interactions between projects and sites, allowing to identify a better outcome than a site-by-site approach. **Chapter 6** first presents a stochastic approach to test the sensibility of results in regard to the uncertainty of the input data illustrated with the intervals of rehabilitation costs. Then, the chapter presents the implementation and simulation of various scenarios. Overall, this research consistently demonstrates the relevance of economic analyses for BFR decision-making, and how can uncertainty factors be managed to carry economic approaches at the regional scale.

Résumé

Le redéveloppement des friches (RF) est une question qui préoccupe de plus en plus les urbanistes du monde entier. De plus en plus de friches, sites sur lesquels fleurissaient autrefois d'intenses activités économiques ou industrielles, sont désormais abandonnés ou sous-utilisés. Les friches industrielles sont souvent une source de nuisances pour les populations qui résident dans leur voisinage. En même temps, les friches industrielles situées dans les zones métropolitaines offrent de réelles opportunités de densification des villes. Le coût de déconstruction des bâtiments abandonnés, la gestion des déchets qui en sont issus et celle des polluants chimiques présents dans le sol et les eaux souterraines peut largement dépasser les bénéfices financiers escomptés sur lesquels les investisseurs privés fondent leurs décisions. L'existence de nombreux bénéfices économiques, sociaux et environnementaux, non pris en compte par les investisseurs privés, peuvent justifier un investissement public dans de tels projets, mais sont difficiles à évaluer en termes monétaires. Comme le montre la revue de littérature présentée au **chapitre I**, la plupart des analyses et des outils d'aide à la décision portant sur le RF sont réalisés au niveau des sites. L'objectif principal de cette recherche est de développer un modèle d'optimisation économique d'un programme de réaménagement d'un ensemble de friches à l'échelle régionale, et de vérifier sa pertinence comme outil d'aide à la décision auprès d'une grande collectivité. La mise en œuvre du modèle est illustrée de manière empirique dans la Vallée de la Chimie, qui est présentée au **chapitre II**, et comporte l'identification et la caractérisation de 30 friches industrielles et de 9 futures activités d'utilisation des sols. Le **chapitre III** présente l'évaluation des coûts de réhabilitation, où l'incertitude est traitée en utilisant une approche basée sur la connaissance subjective des experts. Quatre sources de coûts ont été identifiées : la décontamination des sols, la gestion des sols excavés, la déconstruction des bâtiments abandonnés, et le reconditionnement des sols. Le **chapitre IV** porte sur l'évaluation en termes monétaires des bénéfices privés, sociaux et environnementaux du RF. L'approche est basée sur le transfert de bénéfice pour estimer les multiples bénéfices d'un portefeuille de plusieurs sites et de plusieurs options de réaménagement. Le modèle, présenté dans le **chapitre V**, utilise l'analyse coût-bénéfices pour comparer différentes options de RF et pour identifier la combinaison optimale afin de maximiser le bénéfice net global sur une période de 20 ans. Le modèle tient également compte des interactions entre les projets et les sites, ce qui permet d'identifier un meilleur résultat qu'une approche site par site. Le **chapitre VI** présente d'abord une approche stochastique pour tester la sensibilité des résultats en ce qui concerne l'incertitude des données d'entrée, illustrée avec les intervalles des coûts de réhabilitation. Ensuite, le chapitre présente la mise en œuvre et la simulation de différents scénarios. Dans l'ensemble, cette recherche démontre de manière cohérente la pertinence des analyses économiques pour la prise de décision en matière de RF, et comment les facteurs d'incertitude peuvent être gérés pour porter les approches économiques à l'échelle régionale.

Résumé détaillé

Contexte et enjeux

Les friches industrielles sont des sites qui soutenaient autrefois des activités économiques ou industrielles, mais qui sont aujourd'hui vacants, abandonnés ou sous-utilisés et qui souffrent fréquemment de pollution ou dégradation des sols et de l'eau. Leur nombre est susceptible d'augmenter alors que les activités industrielles évoluent et sont délocalisées pour suivre le développement technologique et la mondialisation. Or, dans un contexte de pression foncière croissante, la reconversion des friches industrielles est de plus en plus perçue par les pouvoirs publics comme une opportunité, en particulier dans les anciennes régions industrialisées d'Europe, d'Amérique du Nord et dans les économies émergentes. En effet, ces espaces, souvent situés à proximité, voire intégrés au tissu urbain, peuvent être réutilisés pour contribuer à atteindre divers objectifs de développement durable des métropoles : réduction des nuisances et sources de risques sanitaires, amélioration du cadre de vie, densification urbaine et maîtrise de l'étalement urbain, continuité écologique, production d'énergie renouvelable, maîtrise des déplacements, etc. Cette évolution amène les acteurs de la planification urbaine à analyser de manière plus globale le potentiel de redéveloppement coordonné de plusieurs dizaines de sites à l'échelle du territoire des métropoles, développant ainsi des stratégies régionales de redéveloppement. Cette approche se démarque de l'approche actuelle qui consiste le plus souvent à traiter chaque site indépendamment les uns des autres, en se focalisant principalement sur leur valeur marchande.

En outre, le redéveloppement des friches est souvent entravé par des raisons économiques. En particulier, le coût de déconstruction des bâtiments abandonnés, la gestion des déchets qui en sont issus et celle des polluants chimiques présents dans le sol et les eaux souterraines peut largement dépasser les bénéfices financiers escomptés sur lesquels les investisseurs privés fondent leurs décisions. De nombreux bénéfices indirects (environnementaux, sociaux, dépenses publiques évitées), qui pourraient justifier un investissement public dans de tels projets, sont difficiles à évaluer en termes monétaires et restent souvent non pris en compte dans les outils d'aide à la décision. D'importants travaux de recherche abordent ces difficultés, en particulier dans le domaine de l'économie. Cependant, comme le montre la revue de la littérature présentée dans le deuxième chapitre de cette thèse, l'évaluation des coûts et bénéfices du redéveloppement des friches a été presque systématiquement réalisée à l'échelle du site. La plupart des études se concentrent sur l'évaluation économique des avantages associés à un petit ensemble d'options de réaménagement appliquées à un seul site. Toutefois, aucune étude n'a, à notre connaissance, tenté de réaliser une évaluation économique plus globale des options de réaménagement d'un ensemble de friches (potentiellement contaminées ou non) au niveau métropolitain ou régional, en vue d'aider les décideurs politiques à concevoir un portefeuille de projets de réaménagement susceptibles de maximiser

le bien-être social. Cette lacune et le fait que cette problématique réponde à une demande d'acteurs de terrain ont motivé la présente recherche doctorale dont l'objectif est de concevoir, d'évaluer et d'optimiser des stratégies régionales de redéveloppement de friches urbaines. La thèse porte plus particulièrement sur le développement d'un outil d'optimisation économique répondant à ce besoin, développé dans le cadre d'une recherche appliquée à la Vallée de la Chimie localisée dans la partie Sud de la métropole du Grand Lyon.

Objectifs et étapes du travail de thèse

L'objectif principal de cette recherche est de développer un modèle d'optimisation économique d'un programme de réaménagement d'un ensemble de friches à l'échelle d'une grande métropole et de vérifier sa pertinence comme outil d'aide à la décision auprès d'une grande collectivité.

Le développement de cet outil pose plusieurs questions de recherche qui ont structuré le travail de thèse :

- La première question consiste à repositionner la méthode d'optimisation économique par rapport aux approches multicritères les plus fréquemment évoquées et appliquées dans la littérature pluridisciplinaire traitant de la reconversion des friches à grande échelle.
- La deuxième question est relative à l'identification des bénéfices (non nécessairement marchands) que la reconversion de friches urbaines peut générer pour une collectivité et à identifier les politiques publiques auxquelles elle peut contribuer (densification urbaine, transition énergétique, gestion des déchets, etc.).
- La troisième question est liée à la collecte de données relatives aux coûts de reconversion des friches et aux bénéfices nécessaires au modèle, lorsque l'on s'intéresse à un nombre élevé de sites. La collecte d'informations précise pour chaque site n'étant pas envisageable, sur quelles données existantes peut-on s'appuyer, avec quel risque d'erreur ? Comment extrapoler des résultats d'études existantes (notamment pour les bénéfices) vers des sites dont les caractéristiques sont assez peu connues ?
- Une question similaire se pose concernant les bénéfices associés aux différents projets de redéveloppement de l'ensemble des sites : comment les évaluer sans réaliser de coûteuses études de cas mobilisant les méthodes des préférences déclarées ?
- La cinquième question est celle de l'incertitude associée à la solution optimale. Compte tenu de la difficulté d'estimer les coûts de remédiation de sites, les solutions identifiées par l'outil d'optimisation sont-elles robustes ?

Pour répondre à ces questions, le travail réalisé est organisé en huit étapes :

1. Une revue de littérature systématique a d'abord été réalisée pour décrire les outils disponibles traitant de la reconversion des friches.

2. Un travail de terrain a ensuite été réalisé pour identifier et caractériser les friches de la vallée de la chimie et pour proposer un portefeuille d'alternatives de reconversion pour l'ensemble des friches présentes sur le territoire d'étude.
3. Pour pallier au manque de données précises relatives aux coûts de réhabilitation de chaque site (décontamination des sols et de l'eau souterraine, déconstruction des bâtiments et gestion des déchets associés), une méthode a été développée pour estimer ces coûts pour l'ensemble des sites de la zone d'étude.
4. De manière similaire, une méthode a été développée pour identifier et estimer les bénéfices privés, sociaux et environnementaux des alternatives de reconversion envisageables dans les sites du terrain d'étude.
5. Une attention particulière a été portée à l'identification de l'ensemble des interactions existantes entre sites et activités rendant compte de la complexité et de la pertinence d'une analyse à échelle régionale.
6. Une base de données a ensuite été créée pour décrire les caractéristiques des sites, les alternatives de reconversion, les coûts et les bénéfices, dans le but de fournir les informations nécessaires à la modélisation.
7. Un modèle de programmation mathématique a été développé, d'abord sous forme de prototype, puis appliqué à la vallée de la Chimie, permettant d'optimiser le choix de réaménagement d'un ensemble de friches au regard du bilan coût-bénéfice.
8. Le modèle a enfin été utilisé pour tester différents scénarios, pour évaluer sa sensibilité à l'incertitude relative aux données et pour appréhender sa capacité à répondre aux attentes des décideurs publics.

Description générale du modèle d'optimisation économique

Le modèle est conçu pour optimiser le bénéfice net d'un portefeuille de projets de redéveloppement. L'optimisation vise à choisir, pour chaque site, un projet de redéveloppement parmi plusieurs options concurrentes. Elle intègre les coûts de remise en état des sites (décontamination, déconstruction des bâtiments, ré-fonctionnalisation des sols) et les bénéfices directs (sur site) et indirects (hors site), marchands et non marchands, générés par les nouvelles activités. L'optimisation est réalisée en se positionnant du point de vue d'un décideur public dont l'objectif est de maximiser le bien-être de la société, considérant non seulement les bénéfices financiers des projets de redéveloppement, mais aussi les bénéfices environnementaux, sociaux et tous les coûts que leur redéveloppement permet d'éviter pour la collectivité à l'échelle de la métropole.

Pour accompagner empiriquement le développement de cette analyse, le modèle a été appliqué à la Vallée de la Chimie (VdC), une zone composée de 12 communes localisées au sud du Grand Lyon et regroupant une trentaine de friches (plus de 180 hectares disponibles). Pour chaque friche, un

portefeuille de neuf alternatives de reconversion est considéré : usine à terres (fabrication de terres fertiles à partir de matériaux inertes et de déchet organiques), production de biomasse à destination énergétique, phyto-remédiation des sols contaminés, ferme urbaine, unité de production énergétique (chaufferie biomasse), production d'énergie photovoltaïque, et trois types d'installations industrielles privées orientées vers l'industrie chimique. Un ensemble de contraintes limitant les possibilités de redéveloppement des sites sont intégrées au modèle : zonage du Plan de Prévention des Risques Industriels et Technologiques, distance des habitations, présence d'infrastructures (routes, réseaux électriques), taille minimale requise pour développer certains projets, etc. Le travail de caractérisation des sites, des contraintes, des coûts et des bénéfices a été réalisé en étroite collaboration avec la mission de la Vallée de la Chimie de la métropole du Grand Lyon.

Principaux résultats

Les six chapitres de ce manuscrit présentent les principaux résultats de ce travail de thèse.

Chapitre 1. Revue de littérature

La première étape a consisté en une revue de la littérature qui analyse comment les économistes contribuent à l'analyse de la problématique du redéveloppement des friches. La revue a été réalisée en utilisant à la fois une méthodologie d'examen standard (également appelée classique ou pivot) et une approche systématique (basée sur une recherche systématique dans les bases de données avec des mots clés sélectionnés). Au total, environ 600 articles ont été analysés. Cela a permis d'identifier les récentes découvertes dans l'état de l'art de l'économie appliquée au réaménagement des friches industrielles, de saisir les informations utiles concernant les préoccupations d'actualité, réglementaires et méthodologiques, et d'argumenter et de confirmer la pertinence et le caractère innovant de la thèse. La revue a été publiée dans le journal of *Integrated Environmental Assessment and Management*.

Chapitre 2 : Présentation du terrain d'étude

La deuxième étape a consisté à caractériser les friches industrielles dans le cas d'étude (VdC), sur la base d'entretiens avec des urbanistes et des acteurs du territoire, et à développer une base de données SIG (système d'information géographique) intégrant diverses sources de données (cadre réglementaire, documents d'urbanisme, contraintes et objectifs régionaux, limites des friches industrielles, caractéristiques du sol, bâtiments, etc.). Cette étape a permis d'identifier 30 friches industrielles candidates à un réaménagement et de préciser les contraintes limitant les possibilités de réaménagement. Neuf options de réaménagement ont été examinées et caractérisées : usine à terre, production de biomasse, phytoremédiation, compensation écologique, ferme urbaine, unité de production d'énergie (chauffage à la biomasse), production photovoltaïque, et trois autres initiatives privées orientées vers l'industrie chimique. Lors de cette phase du travail, les interactions avec les parties prenantes ont

constitué un aspect essentiel de la recherche. Cette partie de la recherche a conduit à l'élaboration d'un atlas cartographique et d'une base de données des sites identifiés (figure i.).

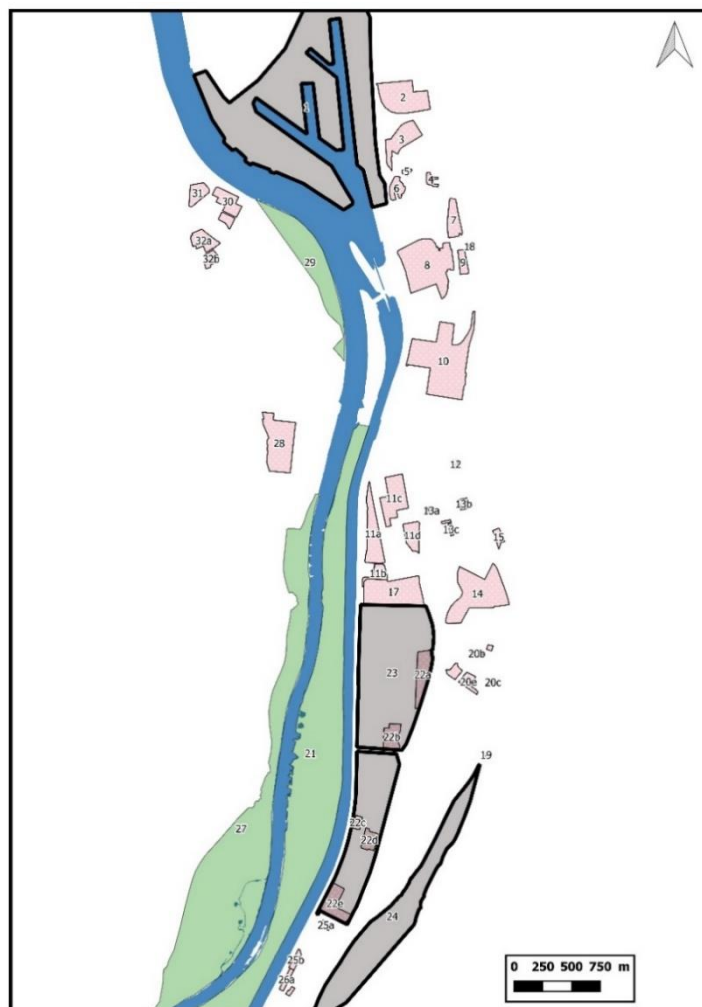


Figure i. Sites identifiés dans VdC. En gris : sites stratégiques qui sont actuellement actifs mais qui sont susceptibles de devenir des friches industrielles à très long terme. En rouge : sites actuellement en friche dans VdC. En vert : les espaces ouverts, qui sont disponibles pour un développement soumis à des restrictions d'aménagement.

Chapitre 3 : Estimation des coûts de réhabilitation

La troisième étape a consisté à évaluer les coûts de réaménagement, en accordant une attention particulière aux sources d'incertitude. Par rapport à l'approche à l'échelle du site, l'approche régionale confronte une amplification de l'incertitude qui provient du coût d'acquisition d'informations détaillées sur la pollution des sols et des eaux ainsi que sur les déchets issus de la déconstruction des bâtiments. Pour surmonter cet obstacle, cette partie de la recherche s'appuie sur la théorie des possibilités, ce qui consiste à fixer des intervalles de coûts sur la base des connaissances (en partie subjectives) des experts. Nous évaluons trois types de coûts : la décontamination des sols, la destruction des bâtiments abandonnés (y compris l'enlèvement et le traitement des déchets associés) et la régénération des sols. En ce qui concerne la décontamination des sols, l'analyse repose principalement sur le dire d'experts,

étayé par toutes les informations existantes. En ce qui concerne les coûts de destruction des bâtiments, une approche systématique utilisant le coût unitaire de référence a été développée et appliquée à 385 bâtiments, dont les principales caractéristiques ont été identifiées (nombre d'étages, matériaux utilisés, etc.). En ce qui concerne la reconversion des sols, nous avons évalué le volume et le coût de l'importation de sols naturels de qualité nécessaire pour assurer la compatibilité avec certaines alternatives de reconversion telles que la production de biomasse ou la compensation écologique.

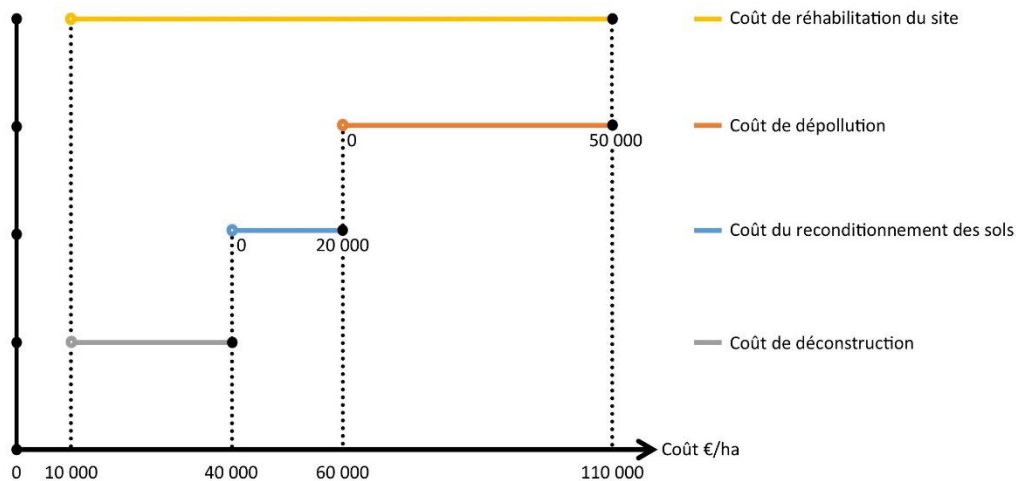


Figure ii. Obtention de coûts de réhabilitation. Chaque source de coûts a conduit à l'estimation d'intervalles représentant l'incertitude liée aux coûts attendus. Cette figure illustre l'addition (ligne jaune) d'intervalles pour obtenir les limites des coûts de réhabilitation attendus pour un site.

Chapitre 4 : Estimation des bénéfices

La quatrième étape a consisté à identifier et à évaluer (en termes monétaires) les bénéfices potentiellement associés à chaque option de réaménagement de chacune des friches industrielles étudiées. Cela a été fait sur la base de propositions de projets réels, pour lesquels les valeurs de bénéfices ont été normalisées afin que les estimations puissent être utilisées dans l'analyse coûts-avantages de n'importe lequel des sites identifiés. Comme le portefeuille comprenait plusieurs sites et plusieurs options de réaménagement, seules les méthodes de transfert de bénéfices et de coûts évités ont pu être utilisées. L'analyse tient compte de trois types d'avantages : 1) les bénéfices privés ; 2) les bénéfices sociaux ; et 3) les bénéfices environnementaux. La méthode d'évaluation a consisté à envisager une application réaliste des alternatives de réaménagement dans l'un des sites ; puis, en utilisant des références bibliographiques, des documents urbains et des avis d'experts, à estimer par transfert de valeur la valeur monétaire de chacun des bénéfices identifiés. Enfin, les valeurs ont été normalisées en euros par hectare et par an pour être ensuite appliquées à tous les autres sites. Bien que les résultats de l'évaluation des bénéfices aient été cohérents, et validés par les parties prenantes, l'évaluation d'une pluralité de bénéfices pour chaque alternative de reconversion reste difficile, car elle est basée sur l'extrapolation d'études menées dans des contextes différents à la VdC.

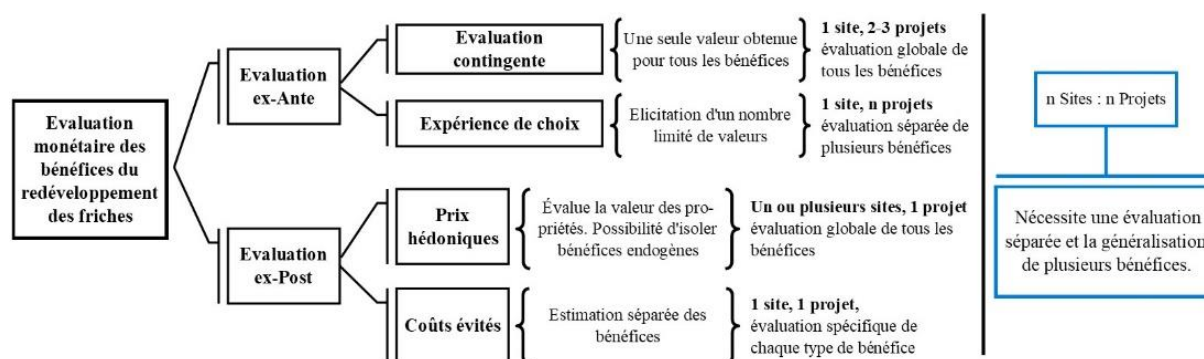


Figure iii. L'estimation des bénéfices du redéveloppement des friches en termes monétaires à l'échelle régionale a nécessité l'adaptation des résultats trouvés dans la littérature et l'acceptation d'hypothèses et de généralisations.

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Chapitre 5 : Développement du modèle

La cinquième étape a consisté à développer le modèle d'optimisation en utilisant la programmation mathématique. Le modèle utilise les données collectées dans les étapes précédentes pour trouver la combinaison de projets de réaménagement pour l'ensemble des sites qui maximise le bénéfice net total (somme des bénéfices moins somme des coûts de réaménagement). L'approche est une analyse coûts-avantages étendue qui maximise le bénéfice net sur une période de 20 ans, tout en tenant compte des interactions entre les projets et les sites (souvent des synergies), ce qui permet d'identifier un meilleur résultat qu'une approche site par site. D'une certaine manière, le modèle recrée la prise de décision des planificateurs urbains dans une perspective strictement économique. En fait, tous les sites ne se réaménageront pas pour devenir l'alternative la plus avantageuse. Non seulement en raison de la compatibilité physique, mais aussi en raison des besoins, des objectifs et des possibilités du territoire. Ainsi, la systématisation de l'analyse permet d'identifier rapidement la compatibilité entre les sites et les activités, de tester la sensibilité de certaines contraintes et le coût d'opportunité des priorités données. Le modèle, un algorithme développé à l'aide du logiciel GAMS, permet d'identifier la combinaison de projets de réaménagement sur les 30 sites qui donne le bénéfice net total le plus élevé à 20 ans. Il rassemble les informations des études de cas à partir de feuilles de calcul (données sur les sites et les alternatives de réaménagement), internalise l'estimation des coûts de réhabilitation et explore par itération toutes les combinaisons viables jusqu'à ce qu'il trouve la configuration de réaménagement qui maximise le bénéfice net total.

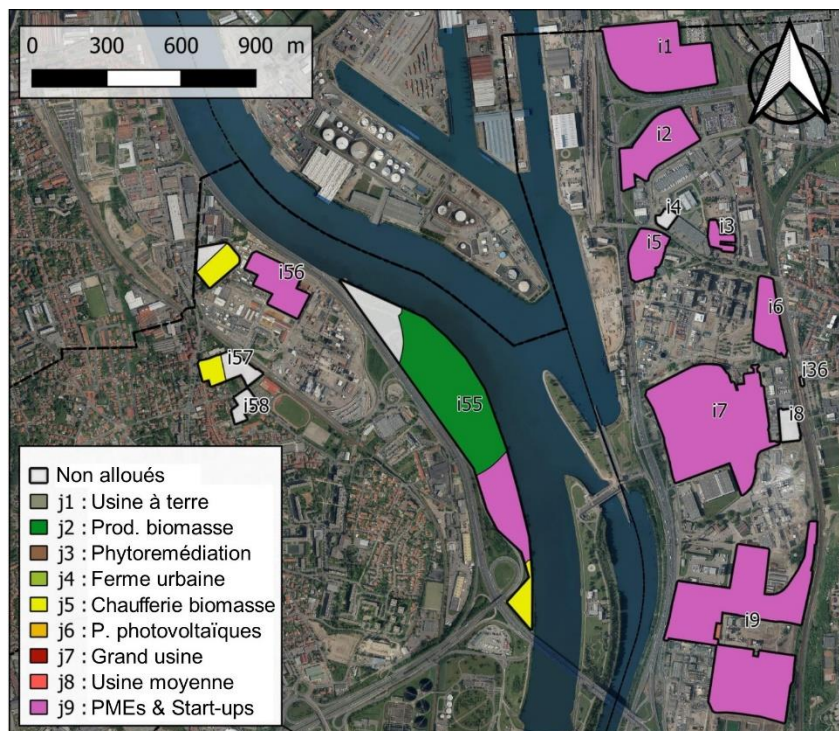


Figure iv. Solution modèle. La figure illustre la représentation graphique de la configuration optimale des sites.

Chapitre 6 : Mise en œuvre du modèle et simulations

L'étape six a consisté à utiliser le modèle pour tester différents scénarios et à évaluer la sensibilité des résultats par rapport à l'incertitude liée à l'estimation des coûts de réhabilitation. Le test des scénarios consiste à faire varier certains paramètres ou à incorporer de nouvelles équations afin de représenter différentes orientations de politique publique. La figure v montre trois résultats parmi les scénarios qui ont été simulés. Le premier représente la solution de référence du modèle tel que décrit au chapitre 5. Le second représente un scénario de production d'électricité plus élevée, dans lequel les changements de paramètres augmentent à la fois l'exigence de production d'électricité minimale et la limite maximale de la demande d'électricité. Le troisième résultat représente la simulation d'un scénario consistant à l'assouplissement des restrictions concernant une activité (j_7) qui n'était pas compatible avec pratiquement aucun des sites. En outre, ce scénario limite le montant maximum d'une autre activité (j_9) ce qui représente de manière plus réaliste le potentiel de réaménagement par rapport au marché actuel. Ces résultats (fig v) montrent que les activités redéveloppées varient significativement en fonction des hypothèses de ces scénarios. En revanche, la valeur du bénéfice totale ne change que peu (de l'ordre de 15%).

SCENARIO DE REFERENCE			SCÉNARIO DE PRODUCTION D'ÉNERGIE			AFFINAGE DES CONTRAINTES		
Bilan des bénéfices	6890	M€	Bilan des bénéfices	7256	M€	Bilan des bénéfices	6166	M€
Création d'emplois	3016		Création d'emplois	3027		Création d'emplois	2624	
Énergie produite	70	MWh	Énergie produite	140	MWh	Énergie produite	70	MWh
Recyclage des sols	0	m ³ year	Recyclage des sols	0	m ³ year	Recyclage des sols	0	m ³ year
Surface totale réaménagée	205	ha	Surface totale réaménagée	248	ha	Surface totale réaménagée	202	ha
Sites réaménagés	30		Sites réaménagés	30		Sites réaménagés	30	

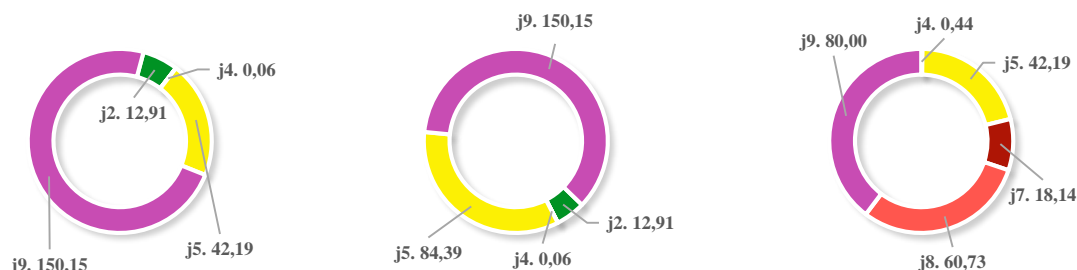


Figure v. Solutions de scénarios. La figure représente le programme de redéveloppement optimal des sites pour trois scénarios contrastés.

Après avoir utilisé le modèle dans un environnement déterministe (coûts de réhabilitation égaux à la valeur médiane des intervalles donnés par les experts), nous sommes passés à la simulation stochastique pour tester la robustesse des solutions. Une approche inspirée de la simulation de Monte Carlo a été mise en œuvre : le modèle d'optimisation est exécuté plusieurs centaines de fois avec un paramètre de coût tiré au hasard à l'aide d'une distribution triangulaire. Une analyse statistique des solutions a ensuite été effectuée pour identifier les solutions qui sont robustes compte tenu de cette incertitude sur les coûts. Dans l'ensemble, les résultats du scénario de base ont été jugés cohérents face à l'incertitude des coûts de réhabilitation, car toutes les allocations sauf une ont été répétées dans toutes les itérations.

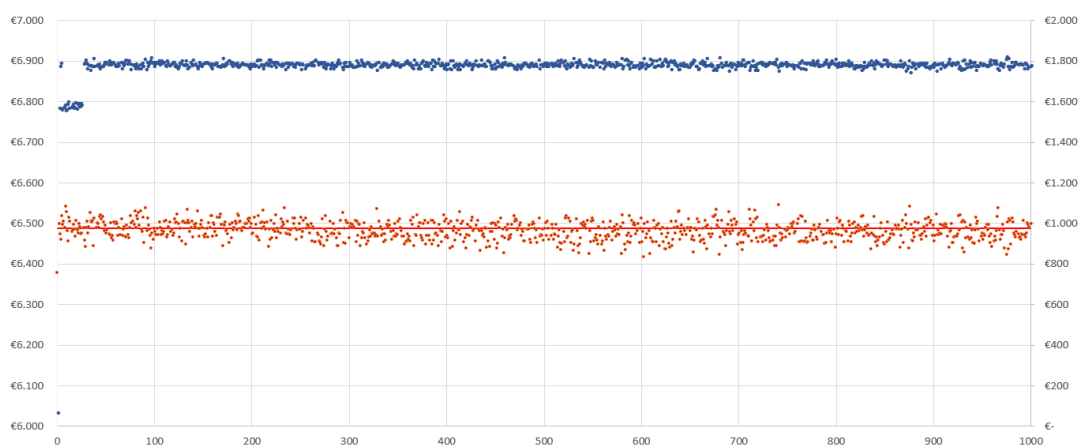


Figure vi. Résultat de 1000 simulations avec tirage aléatoire des paramètres de coût du modèle. La figure affiche en bleu (échelle sur l'axe de gauche), le bénéfice net global. En rouge (échelle sur axe de droite), les points aléatoires des coûts de réhabilitation.

Conclusion et perspectives

En dépit des limites relatives à la fiabilité des données de coûts et de bénéfices, le modèle d'optimisation économique développé dans la thèse est considéré, par les acteurs du redéveloppement de la vallée de la chimie, comme un outil pertinent pour explorer l'impact de diverses stratégies politiques de gestion globale de ces espaces. La simulation de scénarios contrastés est jugée particulièrement utile, à condition de considérer les résultats en valeur relative et non absolue, ce qui permet de comparer différents scénarios et non de prescrire une solution optimale.

La thèse développe et utilise des approches innovantes dans le domaine du redéveloppement des friches. L'idée n'étant pas de remplacer l'approche site spécifique conventionnelle, mais de prouver l'intérêt d'utiliser de façon complémentaire des approches prenant en compte l'interaction et synergies des sites et alternatives de reconversion face aux objectifs du territoire. Les résultats de la thèse invitent à continuer l'amélioration des méthodologies d'estimation des coûts de réhabilitation à l'échelle des territoires, de mieux intégrer les techniques d'évaluation économique des bénéfices dans le domaine, et d'explorer d'autres utilisations de modélisation, par exemple incluant la possibilité de développer des activités temporaires.

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Introduction

As industrial activities continue to change and migrate to keep pace with technological development and globalization (Simons 1998; Leigh and Coffin 2000; Adams et al. 2010; Payá Pérez and Rodríguez Eugenio 2018), more and more sites, which once supported intense economic or industrial activities, are now abandoned or underutilized. Consequently, Brownfield Redevelopment (BFR) is an issue of growing concern for urban planners and managers all over the world, especially in former industrialized regions of Europe, North America and in emerging economies (De Sousa 2004; Panagos et al. 2013; U.S. EPA 2016; EPA 2017). Brownfields are often a source of nuisance for nearby residents (Gayer et al. 2000; Longo and Alberini 2006; Lesage et al. 2007), particularly in the case of contaminated sites (environmental and human health risks) or derelict buildings (risk of accidents, illegal occupation and crime). In the European Union, up to 340,000 contaminated sites were listed in 2014 (Van Liedekerke et al. 2014) which costs nearly 6 million euros per year to manage (Panagos et al. 2013). In France, although no exhaustive inventory of brownfields has yet been completed, estimations based on existing data identify at least 2133 contaminated brownfields in urban areas (Tendero 2018). Rehabilitation costs of French contaminated sites were estimated at 470 million euros in 2010 (Bouagal 2012).

At a first glance, research on brownfields redevelopment may seem heterogeneous and scattered because of the heterogeneity of definitions and juridical frameworks adopted in different countries. In this research, brownfields are referred as “any land or premises which has been used or developed and is not currently fully in use, although it may be partially occupied or utilized. It may also be vacant, derelict or contaminated. Therefore, a brownfield site is not available for immediate use without intervention” (Alker et al. 2000: 64)(See also Syms 1999; Yount 2003). In regard to juridical frameworks, even though European guidelines include common elements such as the need to prevent or limit future pollution; and the application of the precautionary principle and polluter pays principle (usually accompanied with a system of assistance for non-labile owners), in practice the applications differ from one State to another (Ferguson et al. 2005). As for the scale of analyses, the French National methodology for managing contaminated land requires orientating decision-making analysis into site-specific diagnoses for each site, in particular to ensure the proper management of sanitary and environmental risks (Ministère de l’environnement de l’énergie et de la mer 2017).

Soil and water contamination often require rehabilitation that may entail high remediation costs, complex administrative procedures and unexpected delays. The risks of future liability, stigma and uncertainty on remediation costs, all linked to the residual contamination, are elements that need to be well accounted for (Bartke 2011). These difficulties, in addition to frequent discrepancy between public and private interests, often represent important obstacles to BFR (Coffin and Shepherd 1998; Bartsch and Wells 2003; Whitney 2003; Paull 2008; BenDor et al. 2011; Spiess and De Sousa 2016). Thus,

redevelopment is often hampered for economic reasons. In particular, the cost of managing abandoned buildings and chemical pollutants in soil and groundwater can far exceed the expected financial benefits on which private investors base their decisions. Many indirect benefits can help justifying public investment in brownfield redevelopment projects, but these are difficult to assess in monetary terms and often remain unrecognized in decision support tools.

Brownfields, which are frequently located close to settlements, offer genuine opportunities for urban development. Their redevelopment leads to the densification of urban areas, reinvigorates distressed neighborhoods and helps avoiding costs linked to urban sprawl. For instance, by reducing human health risks, reducing available space for illicit activities such as delinquency and crime, and fostering social interaction, BFR improves perceived well-being and quality of life of inhabitants (Accordino and Johnson 2000; De Sousa 2006; Tonin et al. 2012). By reducing urban sprawl, it reduces the costs of public infrastructure (public transport, water, sewerage, communication, etc.), and reduces travelled distances, which comes along with less CO₂ emissions, energy consumption, and urban heat (De Sousa 2002; Meyer 2003; Amekudzi and Fomunung 2004). BFR also prevent environmental risks, and helps preserving ecosystems and landscapes (Ruelle et al. 2013; Mathey et al. 2015). Moreover, the spillover effect of all the precedent benefits combined results into raising the attractiveness of land, increasing property values and encouraging further investment in surrounding areas (Paull 2008). Therefore, national and local governments are trying to promote BFR to encourage commercial, residential, new industrial activities as well as the development of natural amenities supporting the production of ecosystem services (De Sousa 2003; EC 2012; Schädler et al. 2012). European initiatives integrating a holistic management approaches include international efforts such as CABERNET (Concerted Action on Brownfield and Economic Regeneration Network), TIMBRE (Tailored Improvement of Brownfield Regeneration in Europe), HOMBRE (Holistic Management of Brownfield Regeneration), and SURF (Sustainable Remediation Forum).

The awareness of the nuisances of brownfields and the potential of BFR is leading urban planning actors to consider and analyze redevelopment opportunities as a whole. That is to say, approaches of joint analysis of large groups of sites on the scale of the territory of metropolises, in order to develop regional redevelopment strategies. However, as shown in the literature review presented in the second chapter of this thesis, the evaluation of the costs and benefits of brownfield redevelopment has been almost systematically carried out at the site level, mainly using data intensive methods such as hedonic pricing or stated preference surveys. Most studies focus on the economic evaluation of a narrow range of benefits associated with a small set of (if not a single) redevelopment options applied to one specific site. To the best of knowledge as it concerns the elaboration of this research, no studies have attempted to conduct a comprehensive economic evaluation of brownfield redevelopment options at the metropolitan or regional level to assist policy makers in designing a portfolio of redevelopment projects that can maximize social well-being. This is the gap that motivated this doctoral research.

Hence, the main objective of this research is to develop an economic optimization model as part of an extended cost-benefit approach for brownfield redevelopment at a regional scale. To empirically support its elaboration, the model is applied to the Vallée de la Chimie (So called "Valley of chemical industry" in the rest of the manuscript), an area including 12 municipalities located south of Greater Lyon metropolis, containing more than 180 hectares of brownfields. This main objective translates into the following research questions:

What is the optimal allocation of redevelopment for the brownfield sites in the valley of the chemical industry?

How can economic optimization on a regional scale be mobilized to support public decision-making in brownfields management?

What main factors of uncertainty compromise the application of regional economic optimization modelling approaches, and how can these factors of uncertainty be managed in order to implement robust economic assessments?

To address the main objective and the research question, this research is built on the theoretical foundations of cost-benefit analysis and total economic value. The notion of cost-benefit analysis (CBA) dates back to the 19th century and has since been widely used in economic and management sciences to examine if and by how much the benefits of implementing a project (or policy) outweigh its costs, and to compare the performances of alternative choices (Pearce 1983; Hanley 2001). Complementarily, the total economic value (TEV) framework which refers to an anthropocentric definition of value, assumes that individuals can hold multiple values for a good or service (e.g. ecosystem services). It provides a basis for categorization of benefits, which helps avoiding double counting values when multiple valuations are required (National Research Council 2005). The TEV framework distinguishes between use values and non-use values. The former refers to those values associated with current or future (potential) use of a resource (e.g. extractive and recreational uses), while non-use values arise from the continued existence of the resource and are unrelated to its use (e.g. cultural heritage, saving resources for future generations, existence of emblematic species) (Farber et al. 2002). Thus, TEV represents the flows of values, present and future, of an environmental good or service.

The modelling approach developed in this research relies on mathematical programming. A mathematical programming model is an equation-based representation of a problem, which aims at identifying the allocation of scarce resources that allows maximizing a specific objective function. In our case, this concerns finding the optimum allocation of limited resources among competing activities by maximizing benefits or minimizing costs, while respecting a set of constraints imposed by the nature of the problem being studied (Bradley et al. 1977).

As for the methodological framework, this research represents in itself the exploration of a feasible methodology to develop an economic model of BFR optimization at a regional scale. The research embeds a sequence of stages that are essential to achieve the main objective, and each chapter of this document relates to one of those stages. In turn, each chapter is self-sufficient in the sense that it addresses a particular purpose, and is supported by a specific methodology which is described within it. The first chapter provides a review of the literature that analyses how economists have contributed to the analysis of BFR projects and how they helped removing some of the barriers that prevent or limit BFR. The review was conducted using first a standard review methodology (also called a classic or pivotal review) and then a systematic approach (based on a systematic search of databases with selected keywords). In total, about 600 articles were analyzed. This allowed identifying recent findings in the state of the art of economics applied to brownfield redevelopment, to capture useful information regarding current regulatory and methodological concerns, and to verify the novelty of the thesis. These findings were published in the *Journal of Integrated Environmental Assessment and Management* (Ameller et al. 2020).

Chapter 2 presents the study case with the purpose of identifying and characterizing the brownfield sites as well as the potential future use activities in the Valley of Chemical Industry (VoCI). This was based on interviews with urban planners, local stakeholders, and private investors. It includes identifying 29 sites (subsequently characterized in 71 plots), and 9 future land use activities. The outcomes of this stage of the research include identifying the constraints of sites and future land use activities that determine their mutual compatibility; developing a GIS (geographic information system) database integrating various data sources (regulatory framework, urban planning documents, regional constraints and objectives, boundaries of the brownfield sites, soil characteristics, buildings, etc.); producing an atlas of the sites which facilitated discussion during the interviews; and elaborating a spreadsheet database containing all the data that was ultimately used to feed the model. From this point, interaction with stakeholders was a constant and essential aspect of the research.

Chapter 3 deals with the assessment of rehabilitation costs. Site-specific approaches, based on intensive soil sampling and analysis, are usually considered the most adequate approach to estimate rehabilitation costs, as these are very sensitive to details in regard to contamination, future use, and sanitary and environmental risks. Escalating to a regional scale implies relying on less data and accepting a certain degree of uncertainty. Mostly, uncertainty stemmed from the cost of acquiring detailed information on soil and water pollution as well as waste from the deconstruction of buildings. To overcome this obstacle, this part of the research is based on the theory of possibilities, which allowed eliciting cost intervals based on the subjective knowledge of experts. Four sources of rehabilitation costs were identified: (1) soil decontamination, (2) management of excavated soils, (3) deconstruction of abandoned buildings (including waste removal), and (4) soil regeneration. With regard to soil decontamination and management of excavated soils, the analysis is mainly based on expert judgement,

supported by all available information. For costs of destruction of buildings, a systematic approach using references for unit costs was developed and applied to the 385 buildings existing on the identified sites. With regard to soil reconditioning, the assessment focuses on the volume and cost of importing natural soil of sufficient quality to ensure compatibility with specific future land use activities such as biomass production or ecological compensation.

Chapter 4 deals with identifying and assessing (in monetary terms) the benefits of brownfield redevelopment. This was done on the basis of real redevelopment project proposals (corresponding to future land-use opportunities), which provided figures for some of the benefits (mostly direct). Those figures were standardized so that the estimates could be used to assess benefit redevelopment for all redevelopment options in all of the identified sites. As the portfolio included several sites and several redevelopment options, benefit transfer and avoided cost methods were used. The analysis considers three types of benefits: 1) private benefits; 2) social benefits¹; and 3) environmental benefits. The approach consisted in considering a realistic application of the redevelopment options in a selected site; then, using bibliographical references, urban documents and expert knowledge, for estimating the monetary value of each of the benefits identified. Finally, the values were standardized to euros per hectare per year. The challenging evaluation of a plurality of benefits for different future use activities results in the consistent benefits assessment validated by the stakeholders.

Chapter 5 presents the formalization of the mathematical programming model. The model uses the data collected in the previous chapters to find the combination of redevelopments on all sites that maximizes net benefits (total benefits minus redevelopment costs). The approach is an extended cost-benefit analysis that maximizes the net benefit over a 20-year period, while taking into account the interactions between projects and sites at regional scale (thus identifying a better outcome than a site-by-site approach). In a way, the model simulates the VoCI urban planners decision-making process from a strictly economic perspective. The model, developed using GAMS software (2019), effectively systematizes the analysis making it possible to quickly identify the compatibility between sites and activities, and to explore viable combinations until it finds the choices that maximize the overall net benefit. All in all, simulation results can only be considered as the best solution under the particular context that has been described within the database.

Chapter 6 presents the operational implementation of the model and the simulations made with the model. First, it discusses a limitation of this research in terms of optimization algorithms and how this problem was addressed. Then, after running the model in a deterministic environment (rehabilitation costs equal to the median value of the intervals given by the experts), the second section describes how the model is used following a stochastic approach to test the robustness of the solutions. Inspired by the

¹ In this study the notion of ‘social benefits’ is used as a category of values stemming from BFR that are in the interest of the community. These social benefits are therefore distinguished from income for private investors and environmental benefits (Paull 2008; R. Paul Bardos et al. 2016).

Monte Carlo simulation approach, the optimization model is run several hundred times with cost parameters randomly selected using triangular distributions. This allowed performing a statistical analysis of the solutions to identify solutions that are robust to the uncertainty embedded in rehabilitation costs estimations. The final section of the chapter illustrates the ability of the model to test different decision-making contexts (i.e. scenarios) by varying certain parameters or incorporating new equations and then observing the changes within the outcomes.

Finally, the last chapter provides an overview of the work presented in this manuscript and presents conclusions on the elaboration of an economic model to optimize BFR at a regional scale. Perspectives for improvements on the model and further applications are also discussed. Overall, the main strengths of this research are the relevance of the model results for urban planners and its potential to support decision making and its potential for replicability on other territories.

Chapter 1. Literature review

The two main objectives of the literature review presented in this chapter are identifying methodological approaches that have been developed to assess (and possibly rank) BFR projects at regional scale, and collecting sources of information on the economic benefits of BFR, which will be used in our modeling approach. The chapter, which was published as a journal paper, more generally examines how economists have contributed to the analysis of BFR. It also discusses the integration of economic analysis within the multidisciplinary mainstream of BFR literature, and provides pathways for future research.

1.1. Literature review methodology

The scope of the literature review presented in this paper is framed by the thematic issue under investigation (brownfield redevelopment) and the disciplinary perspective (economics). Brownfields are defined as “sites that have been affected by the former uses of the site and surrounding land, are derelict or underused, may have real or perceived contamination problems, are mainly in developed urban areas and require intervention to bring them back to beneficial use” (Oliver et al. 2005). Redevelopment refers to the complete intervention process that leads to a new land use. Brownfield redevelopment includes different kinds of cleanup or rehabilitation measures, as well as the implementation of future land-use projects. The process may involve a broad range of studies, including contamination investigations, risk assessments, environmental and suitability tests and choice of remediation technologies. As far as the disciplinary perspective is concerned, we only focus on studies that address at least one economic dimension of BFR at project or policy level.

A systematic review, compared to a standard review, requires a sample of methodically chosen studies (Hunt 1997). The method we used for the systematic review in this study comprises three main analytical steps: 1) Constructing the publications database; 2) Selecting relevant publications; and 3) Screening and analysis of selected papers. Our main source of data was the Web of Science database (WoS). We chose to focus on literature published in scientific journals. The last database searches were conducted in August 2019.

1.1.1. Selection of keywords

In step 1, we began by selecting keywords. A simple search with the keywords “brownfields”, “redevelopment” and “economic” generated a very limited number of results (57). This was unexpected given the number of relevant papers identified within the standard review. Hence, we increased the number of keywords in order to generate a broader sample of results. Four groups of keywords were

used in the search (Figure 1.1). Group (①) comprises five keywords related to the physical object under study, which in literature is referred to using various keywords including “brownfields”, “contaminated land”, “contaminated sites”, “derelict sites” or “vacant sites”. Group (②) comprises six keywords used by authors to describe the redevelopment process (“redevelopment”, “reuse”, “remediation”, “restoration”, “regeneration” and “reconstruction”). Two additional groups of keywords were identified in relation to the disciplinary dimension. Group (③) is composed of keywords depicting sustainability assessment approaches and the corresponding Decision Support Tools. The keywords in group (④) refer to the different concepts and methods used in economic science. Group 4 was subdivided as follows: the valuation of BFR benefits (sub-group 4.1); resource allocation efficiency (sub-group 4.2); institutional set-up, including incentives, economic instruments, regulation, etc. (sub-group 4.3); and negotiation analyses (subgroup 4.4). All selected keywords were drawn from the articles identified in the preliminary standard literature search.

As the relevant literature is scattered across an array of journals and produced by scientific communities with different disciplinary backgrounds, 2 main bodies of literature were distinguished. The first brings together research involving multidisciplinary research groups focusing on the development of decision support tools (DST) designed to guide redevelopers (Pediaditi et al. 2010; Huysegoms and Cappuyns 2017). DST are generally used to assess and hierarchize alternative redevelopment projects on the basis of a wide range of environmental, social, and economic criteria. This multidisciplinary stream of literature is hereafter referred as Sustainability Assessment Literature (SAL).

The second body of literature is drawn from a diverse community of applied economists. Most contributions from the Economic Literature (EL) focus on very specific aspects of BFR, such as the valuation of specific health, environmental, or social impacts, or the design of economic instruments for policy intervention. In addition, a number of economic studies focus on issues of economic methodology, where BFR is simply used as an example to test a methodological innovation. Thus, EL is scattered across very diverse speciality journals that cover domains such as environmental and resource economics, public economics, urban and real estate economics, and environmental management. This review aims to help bridge gaps between SAL and EL scientific communities.

1.1.2. Selection of relevant publications

In step 2, we screened (based on abstract reading) the contents of the two groups of articles identified in the search (EL and SAL). This selection was conducted as follows.

Regarding the Economic Literature, we only retained papers applying a theoretical framework, concepts, methods or tools that were clearly related to one of the domains of economic science (e.g. environmental economics, urban economics, real estate economics, health economics, political economy, public economics, etc.). We discarded papers that were neither investigating a clearly defined economic

question nor producing new knowledge on an economic issue related to BFR. Many were only mentioning the economic dimension of BFR in the introduction or conclusion; many others were only dealing with technology costs. Hence, out of 1316 results, only 137 were retained (10.4%).

Regarding the SAL, we discarded papers that were not including any economic indicator (qualitative or quantitative) in the sustainability assessment methodology. The final selection maintains 148 of the 324 papers identified with the keywords search. Additionally, we added 196 papers originally found with EL keywords, but which after screening and classification corresponded to SAL criteria. SAL presents very diverse tools and methodological approaches to compare and prioritize BFR options, for example, GIS based multi-criteria analysis, sustainability indicators, integrated assessments, and other modelling approaches.

The selection based on the systematic review was complemented by papers identified with the standard review and which had not been found with the keywords search. Hence, we added 112 economic papers to the EL selection and 50 papers to the SAL selection. Altogether, the final database comprises 557 papers, 249 EL papers, 395 SAL papers, and 87 papers dealing both with economic and sustainability aspects (which does not mean that they all integrate the economic contributions reviewed in the paper).

It is worth noting that plenty of relevant papers were identified with the classical (pivotal) review. The systematic review allowed identifying 414 papers which would have been missed otherwise.

Step 3 involved analysis and classification of the 557 selected papers (full references are available in the supplemental material of the published paper). First the main contribution of each paper were summarized in a few words or sentences. Based on that first analysis, a classification of contributions was developed and all papers subsequently recoded using that classification. The results are presented in a database that can be used by readers willing to investigate a specific issue (supplemental material of the published paper).

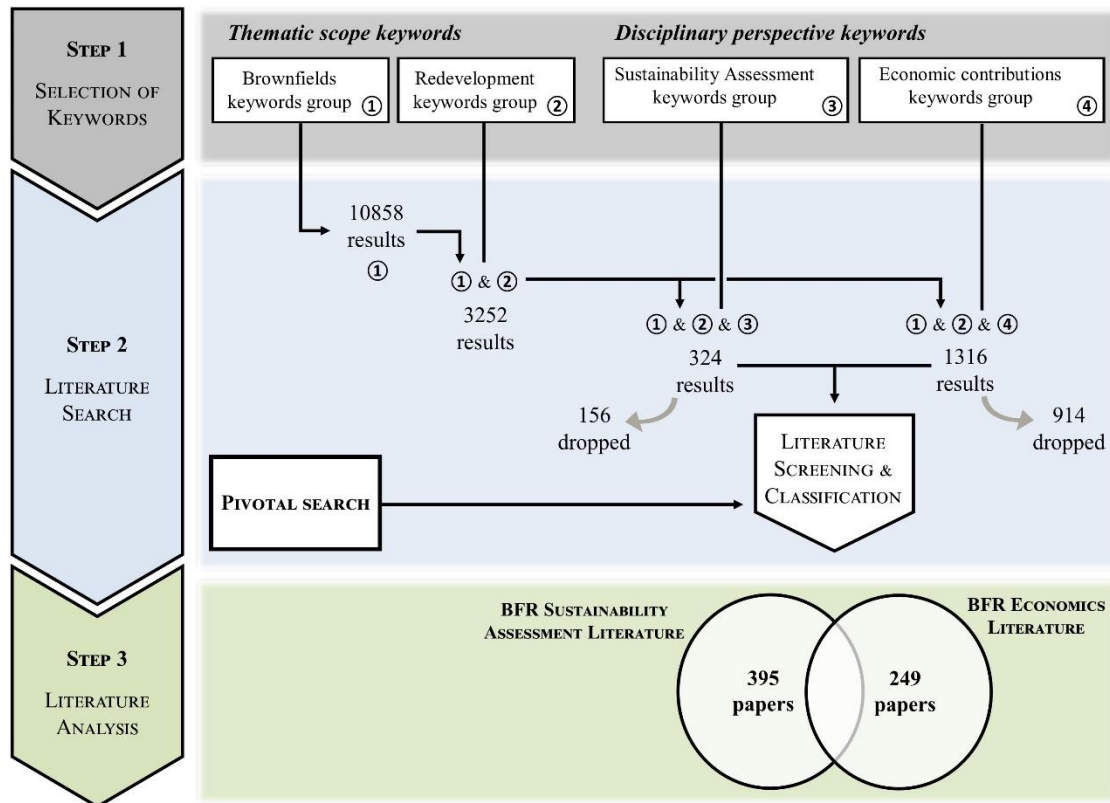


Figure 1.1 - Groups of keywords used to identify the targeted literature and number of papers identified with successive combinations of keywords.

1.2. Sustainability Assessment Literature (SAL)

This literature mainly includes papers on the development of decision support tools, which assess and compare the sustainability of various BFR projects or management options. In these papers, sustainability is defined by environmental, social and economic criteria. It is frequently assessed using multi-criteria analysis (MCA) (Hou and Al-Tabbaa 2014) and involves multidisciplinary research. The economic criterion is not seen as an overarching factor, but is considered alongside environmental and social criteria. This approach has led to the development of many decision support tools, designed to facilitate the identification of possible trade-offs between the three dimensions (Bartke and Schwarze 2015). MCA uses a wide spectrum of qualitative and/or quantitative criteria, which are weighted according to expert knowledge or stakeholders' needs (Rizzo et al. 2015; Bartke et al. 2016). MCA methodologies are flexible and the choice of criteria can be adapted to the particular requirements of case studies. However, there is a drawback: selecting and weighting criteria is challenging because it involves a degree of subjectivity. In other words, representativeness and transparency can be problematic (Wedding and Crawford-Brown 2007; Doick et al. 2009; Bardos et al. 2011).

In most cases, SAL considers BFR decision-making processes at two different scales. At (local) site scale, DST are often designed to select the most appropriate remedial technology (Carlton et al. 2007; Critto and Agostini 2009; Li et al. 2010; Sorvari and Seppälä 2010; Beames et al. 2015). At regional

scale, the goal is to set priorities for the redevelopment of a portfolio of contaminated sites. We illustrate these approaches with the examples provided in Table 1.1.

Scale	Case Study	Supplemental Material
Site level	Rosén, et al. (2015) developed SCORE, a tool based on Multi-Criteria Decision Analysis (MCDA) designed to provide a flexible and transparent sustainability assessment of alternative BFR scenarios for a contaminated site. This DST integrates qualitative and quantitative indicators to account for social and environmental criteria, a cost-benefit analysis to compare the economic performance of scenarios and a Monte-Carlo simulation to address uncertainty issues.	Number of papers: 129 (Select SAL=1; Site-Specific=1)
Regional level	Pizzol et al. (2016) developed TIMBRE, a prioritization tool that identifies which brownfields are better suited for successful redevelopment. The evaluation methodology, tested on a portfolio of 252 sites in the Czech Republic, incorporates economic, social and environmental criteria. The authors identified success factors (e.g. education index, land value, transport links, contamination) and indicators (e.g. percentage of people that have had a higher education, average price, proximity to highways, contamination status) to represent the three dimensions: local redevelopment potential (economic), site attractiveness and marketability (social) and environmental risks. The weight and aggregation of indicators make it possible to rank sites and identify the most promising.	Number of papers: 42 (Select SAL=1; Regional=1)

Table 1.1 - Selected examples of sustainable assessment decision support tools.

1.3. Economics literature (EL)

EL covers three broad groups of papers, which focus on the following issues:

- The valuation of BFR benefits, which includes non-monetary benefits (e.g. environmental, social and health); Number of papers: 96.
- Economic appraisal of BFR projects, which takes into account a wide range of costs and benefits, assessed in monetary terms (e.g. cost-benefit or cost-effectiveness analysis); Number of papers: 52.
- The assessment of policy instruments and institutional arrangements, which may foster stakeholder's engagement and investment in BFR. Number of papers: 109.

1.3.1. Valuation of BFR benefits

Economics has an important contribution to make when it comes to the evaluation of BFR benefits. Herein financial benefits can be distinguished from non-financial benefits: the former mainly consist on the profits and tax revenues generated by BFR projects; and the non-financial benefits involve social welfare generated by improving environmental, health and social factors. The monetary value of these benefits can be estimated, aggregated and compared. The literature primarily considers three types of benefits: economic (private profit, tax revenues), social (employment, quality of life) and environmental (De Sousa 2002; Turvani and Tonin 2008; R Paul Bardos et al. 2016). It often makes a distinction between the benefits derived from the cleanup of contaminated sites and site reuse (new activity). As far as cleanup is concerned, EL attributes an economic value to improvements in soil, air and water quality, by examining how improvements reduce human health risks, enhance ecosystem services, provide new amenities for residents, reduce crime and stigma, as well as boost the value of surrounding property. As far as site reuse is concerned, EL considers direct economic benefits, such as tax revenues, job creation (Jenkins et al. 2006; Paull 2008), as well as indirect financial benefits, for example, containing urban sprawl. Indeed, the redevelopment of BFs may reduce energy consumption, transport costs, CO₂ emissions and the need for new public infrastructure.

Figure 1.2 shows how BFR benefits can be classified according to the EL surveyed in this paper.

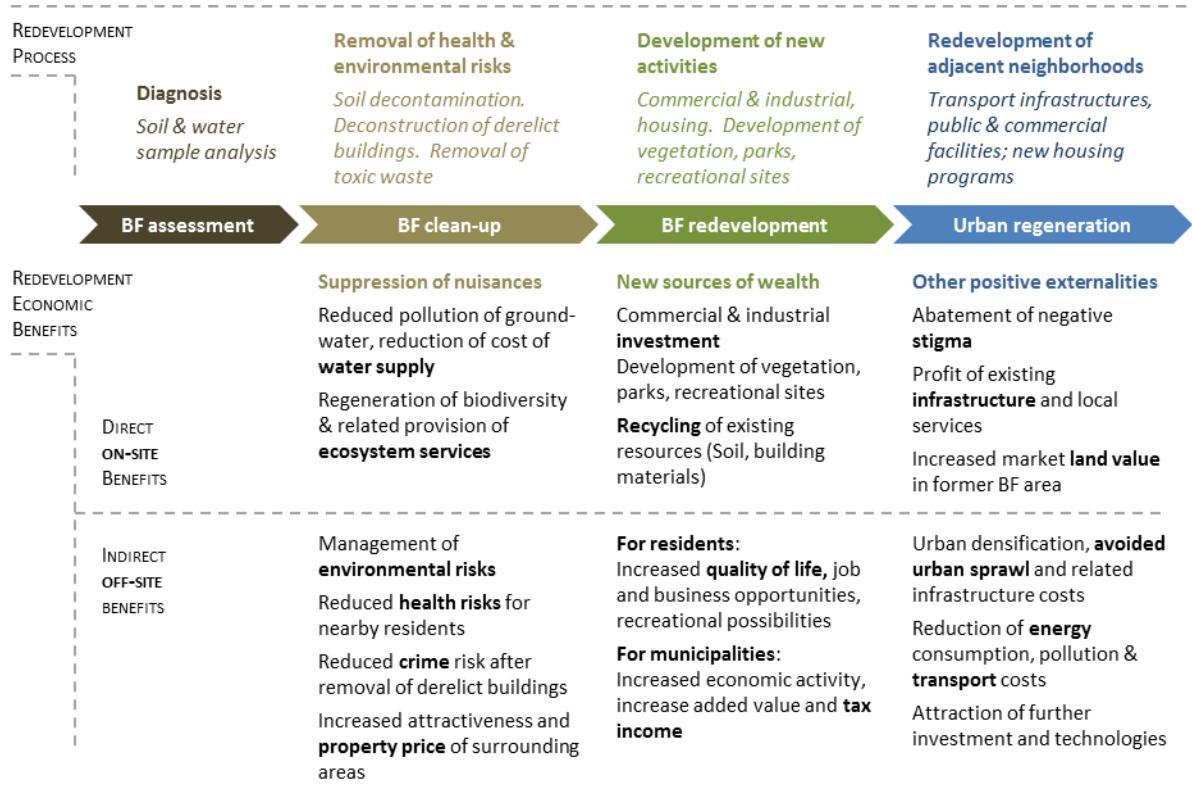


Figure 1.2 - Main benefits of brownfield redevelopment.

Method	Concept	Illustrative case study	Supplemental Material
Revealed preferences			
Hedonic Pricing	The hedonic pricing method assumes that residents are willing to pay more to live in areas with fewer risks or nuisances. Consequently, property markets capitalize on the impacts of BFR and how it affects adjacent land use (Farber 1998). Using real data from property transactions, the method identifies the properties' characteristics, obtains estimates of the implicit price of each characteristic and develops econometric regression models to explain observed property market prices as a function of their intrinsic and locational characteristics (Palmquist 1984).	Neupane and Gustavson (2008) carried out a hedonic pricing valuation method to evaluate the property value effects of the presence of the Tar Ponds and Coke Ovens, former industrial sites in Nova Scotia, Canada. The authors found that the presence of brownfields had a significant negative effect on the value of residential property, estimating a total loss of \$CDN 36 million. Notably, the effect was localized within a few hundred meters of the sites.	Number of papers: 35 (Select EL=1; Hedonic pricing=1)
Avoided costs	This approach consists in identifying and measuring the costs and efforts avoided by redeveloping brownfields in comparison to an alternative scenario. Given that many brownfields are located in dense urban areas, most avoided costs (i.e. benefits) are related to the impacts of urban sprawl (See also Mashayekh et al. 2012).	De Sousa (2002) estimated the BFR benefits of preserving agricultural land, as well as avoiding transport costs and externalities, in comparison to the development of greenfield sites in Toronto, Canada. The author's findings demonstrate that including avoided costs and other BFR benefits in the analysis enhances the economic viability of BFR.	Number of papers: 6 (Select EL=1; Avoided Costs=1)
Stated preferences			
Contingent Valuation	The approach consists in directly asking individuals to express their willingness to pay for an environmental change. As far as BFR is concerned, a Contingent Valuation Method (CVM) survey could be used to elicit public preferences for remediating a specific contaminated site (Tyrväinen and Väänänen 1998; Simons and Winson-Geideman 2005; See for example Simons and Saginor 2010).	Damigos and Kaliampakos (2003) conducted a CVM to assess the preferences of the residents in Athens, Greece, regarding the redevelopment of an abandoned quarry located in the center of the city. Results allowed authors to quantify public preferences for land reclamation and the construction of a park with underground parking.	Number of papers: 7 (Select EL=1; Contingent valuation=1)
Choice Modeling	Choice-modeling experiments (also known as conjoint analysis) entail designing hypothetical scenarios with a number of attributes, including a cost reference. Participants are then asked to choose the scenarios. In addition to valuing their preferences for a certain change, this method can be used to ascertain stakeholders' preferences regarding the possible attributes (See Strazzera et al. 2010).	Alberini et al. (2007a) used conjoint choice questions to estimate the value of statistical life (VSL) regarding the reduction of mortality risks as a result of remediation policies in four cities in Italy. The survey allowed the authors to quantify the preferences for these remediation policies on the basis of income and demographic characteristics. Thus, the authors were able to identify preferences for immediate, future and permanent reductions in mortality risks.	Number of papers: 13 (Select EL=1; Choice modelling=1)

Table 1.2 - Economic methods for valuation of BFR benefits.

Two major methodological approaches are used in environmental economics to assess the economic benefits of BFR (Turvani and Tonin 2008). Stated preference methods directly elicit individuals' preference and demand for BFR benefits, usually through surveys, using the contingent valuation method or the discrete choice experiment approach. These methods are used to estimate individuals'

willingness to pay for environmental, health and other social improvements associated with BFR. By contrast, revealed preference methods (2) analyze how BFR affects the market value of goods (in particular, the housing market). In other words, they are used to estimate the impact that nuisances linked to BFs may have on the value of goods (or the benefits associated with eradicating the nuisance). The hedonic pricing method has been widely used to assess the impact of BFs on property values. Table 1.2 presents a brief description and provides an illustrative example of the economic valuation methods applied to BFR found in the literature.

1.3.2. Comparing the economic performance of alternative projects or policies

Public economics also has a major contribution to make to BFR. It can be used to assess the efficiency of public resource allocation, through economic appraisal methods, such as Cost-Benefit-Analysis (CBA) or Cost-Effectiveness-Analysis (CEA). CBA and CEA are used to evaluate, compare and rank the outcome of alternative policy interventions or projects. Cost-Benefit Analysis (CBA) identifies and aggregates the financial, social and environmental benefits of a BFR project or policy, which are then compared to its implementation costs (Hanley 2001). If the difference between benefits and costs is positive, the project is economically desirable. The higher the net benefit, the more viable the project. Hence, CBA requires a systematic assessment of all costs and benefits relating to BFR projects (using the methods described in sub-section 1.3.1). In the context of BFR projects, conducting a thorough cost-benefit analysis can be challenging because it can be difficult to account for and quantify all the costs and benefits, and its distribution among the stakeholders (Rinaudo and Loubier 2005).

A recent example of CBA applied to BFR was conducted in Sweden by Volchko et al. (2017). They assessed the redevelopment of four different alternatives of copper recovery projects in Köpmannebro, a contaminated site formerly used to produce impregnated telegraph poles. All options involved the same conventional “excavation and disposal” remediation method. They differed in terms of the pre-treatment approaches and the other metal recovery procedures. The study considered internal project benefits, for example, improved health, provision of ecosystem services and remediation costs, as well as the negative impact of the remedial action, including impaired health and reduced ecosystem services. Other positive and negative externalities were also considered. Thus, findings allowed the authors to identify the best remedial option for two different scenarios. For more examples, see (Lavee et al. 2012; Rinaudo and Aulong 2014; Söderqvist et al. 2015; Huysegoms et al. 2018).

The Cost-Effectiveness Analysis aims to identify the BFR alternative that minimizes cost, while meeting specific objectives as effectively as possible (Döberl et al. 2013). Costs are considered in monetary terms and effectiveness is assessed in quantitative non-monetary terms. In this regard, CEA allows allocating resources by selecting the policy that achieves a specific global objective at lower cost. A good illustration of this approach is given by Schädler et al. (2011). They developed an integrated assessment

method to evaluate redevelopment options (including remediation concerns) for different plots of land at a 113-hectare 'mega-site' in the city of Potsdam, Germany. Their approach included an assessment of (i) subsurface remediation and site preparation costs, (ii) market-orientated economic appraisal and (iii) the expected contribution of future land use to sustainable development objectives. The methodology made it possible to combine the first and second elements and express them in monetary terms: remediation costs, land-market value estimation and market value reduction. Authors then compared this combined monetary criteria with a third element (an aggregation of sustainable development indicators). Although this example goes beyond a classic performance-over-investment CEA, the findings allowed the authors to identify the most cost-effective combination of revitalization options for the site in terms of economic and sustainability criteria. Other examples are presented by (Day et al. 1997; Gomez-Navarro and Garcia-Melon 2011).

1.3.3. Studying the economic relations between the institutional frameworks and stakeholders' behavior

The third group of economic papers identified in the survey look at how institutional set-ups and stakeholders' interests drive actual BFR decision-making. Unlike public economic approaches, where it is assumed that decisions are driven by the general interest, this body of literature reveals that decisions are shaped by a number of stakeholders with different interests: landowners, developers, financial institutions, end-users, community groups and different levels of government (e.g. municipalities, regional and national agencies). Thus, this literature examines different actors' economic behavior and how they interact through negotiation processes in relation to BFR. It explores the role of institutions, defined in a broad sense, in terms of the economic behavior that drives BFR projects. This literature investigates how different policy instruments can help remove the obstacles to brownfield redevelopment. These include liability in terms of inherited pollution risks, regulatory burdens and associated transaction costs, uncertain evolution of clean-up standards and funding mechanisms (BenDor et al. 2011). In this regard, Adams and his colleagues (2001) show that BFR is hindered by certain factors that affect the land market (transaction costs, limited supply and demand, imperfect information and externalities). In response, public authorities offer incentives and adopt regulatory policies to foster BFR. For instance, policymakers may provide financial incentives (subsidies) to encourage private investors. For this purpose, direct policy instruments can be used, including: (i) Subsidies (e.g. to facilitate contamination assessments or decontamination expenses); (ii) Minimization of liability burdens and uncertainties linked to future cleanup requirements and community complaints; (iii) Alleviation of transaction costs by simplifying administrative procedures and requirements. On the other hand, indirect policies can also be used to make brownfields more attractive economically: (iv) Taxing greenfield developments; (v) Developing public infrastructure and facilities to improve the real

estate market in the area (e.g. public transport, recreation, education, culture). Table 1.3 presents some examples of studies on policy effectiveness.

Institutional framework component	Case Study
<ul style="list-style-type: none"> •Subsidies •Taxes 	<p>Adams, Disberry et al. (2000) interviewed a number of landowners and experienced organizations in order to assess the efficacy of fiscal measures in four cities in the UK. The authors conclude that taxes and subsidies do provide incentives for developers to invest, but there are certain nuances when it comes to their acceptance: carefully designed taxes may be appropriate in markets where there is a strong demand, but development can spill onto greenfield sites, despite the existence of brownfield alternatives. Fiscal penalties might result inappropriate whereas financial support incentives seem to be consistently plausible measures.</p>
<ul style="list-style-type: none"> •Liability relief •Direct financial incentives •Regulatory relief 	<p>Alberini, Longo et al. (2005) gathered information in a survey from a sample of developers and real estate professionals at an international conference in Cannes, France. Following a conjoint choice experiment, results suggested that developers are positively responsive to liability reliefs, financial support and regulatory flexibility. In addition, the authors observed that developers highly appreciate transport facilities and do not discriminate against prior contamination once a given site has been remediated.</p>
<ul style="list-style-type: none"> •Reimbursement of study costs •Requirement of public hearings •Protection against further liabilities for cleanup costs •Protection against third party liabilities •Subsidies for construction costs. 	<p>Wernstedt et al. (2006) conducted a nationwide mail survey of private developers in the USA to identify the most effective public incentives for fostering private investment in BFR. Using a conjoint analysis (i.e. choice model experiment), the authors found that protection from third party liability is highly effective. They also revealed that protection from cleanup liability and relief from public hearing requirements were important. Furthermore, the developers' experience is likely to play a role in their acceptance of the different policies.</p>
<ul style="list-style-type: none"> •Liability relief •Public disclosure 	<p>Blackman et al. (2010) analyzed real data from Oregon's database in order to assess the effectiveness of voluntary cleanup programs (VCP). Hence, 33% of 1534 sites participated in VCPs, whereas 8% took independent pathways and 59% participated in neither. Authors carried a multinomial probit regression, which revealed that liability relief incentives, a feature of Oregon's voluntary programs, were an effective incentive to clean highly contaminated sites. They observed that regulatory pressure, such as the public disclosure of lists of contaminated sites, also encouraged participation.</p>
<ul style="list-style-type: none"> •Economic incentives •Liability relief 	<p>Eckerd and Heidelberg (2015) conducted a time-series logistic regression with data from 6932 brownfield sites across the USA's states. The authors conclude that tax credit mechanisms seem to encourage private investment. However, they argue that some direct incentives may simply make profitable projects more attractive, while less favored sites remain sidelined. In addition, of all the liability relief instruments, only insurance facilities seem to significantly encourage private involvement.</p>

Supplemental Material: Taxes (31 papers); Subsidies (32); Liabilities (40); Stakeholders attitudes or perceptions (55).

Table 1.3 - Illustrative examples of studies to assess effectiveness of policymaking.

Overall, lessons learned from this literature are context-specific, conditioned by the specific legal and institutional framework of each case study. Therefore, it is difficult to apply the conclusions to other contexts. We also found that a large number of studies were based on ex-post analysis. These frequently involved econometric analyses of time series, in an attempt to provide statistical evidence and reveal the impact on BFR decisions of various policy instruments or institutional set-ups. We found very few ex-ante studies, which assess the effect of different policy instrument scenarios, using micro-economic models or experimental approaches. Some leads for future research include the use of game theory models to represent courses of action (Samsura et al. 2010; Glumac et al. 2011; Blokhuis et al. 2012;

Glumac et al. 2015) or accounting for the divergent interests of stakeholders to analyze decision-making (Yousefi et al. 2007; Walker et al. 2010; Yousefi et al. 2010).

1.3.4. Links between the two literatures (SAL & EL)

Interestingly, the two bodies of literature overlap, which suggests that the two scientific communities already interact. For instance, 196 papers identified with the search for economic keywords (Search EL) were ultimately attributed to SAL. Similarly, 52 papers identified with SA keywords were actually considered as part of the EL. The analysis of the publication outlets led to a similar conclusion: as shown in Table 1.4, a significant number of selected papers were published in just five journals (119, which represents 21.36%), and several journals publish both papers on EL and SAL.

Main publication outlets	SAL	EL
Science of The Total Environment	33	10
Journal of Environmental Management	27	17
Sustainability	13	10
Journal of Cleaner Production	15	8
Environmental Science and Pollution Research	14	1
Journal of Urban Planning and Development	9	8
Environmental Management	9	5
Integrated Environmental Assessment and Management	12	2
Journal of Hazardous Materials	10	1
Land Use Policy	2	10
Landscape and Urban Planning	7	3
Economic Development Quarterly	0	7
Environment International	7	0
Journal of Environmental Planning and Management	0	7
Urban Forestry & Urban Greening	6	4
Secondary publication outlets		
Chemosphere, Environmental Science & Policy, Human and Ecological Risk Assessment, International Journal of Environmental Research and Public Health, Journal of Soils and Sediments, Ecological Economics, Journal of Urban Planning and Development-ASCE, Water Air and Soil Pollution, Environment and Planning A, Environmental Engineering and Management Journal, Environmental Modelling & Software, Environmental Science & Technology, International Journal of Life Cycle Assessment, Journal of Real Estate Research, Journal of The Institution of Water and Environmental Management, Journal of Urban Economics, Soil & Sediment Contamination, Waste Management	56	38
Other publication outlets		
Abstracts of Papers of the American Chemical Society, Building Research and Information, Ecological Engineering, Ecosystem Services, Environmental Health Perspectives, Environmental Practice, Environmental Research, International Journal of Environment and Pollution, Journal of Environmental Economics and Management, Journal of Environmental Radioactivity, Land Economics, Moravian Geographical Reports, Nuclear Energy-Journal of the British Nuclear Energy Society, Proceedings of the Institution of Civil Engineers-Municipal Engineer, Risk Analysis, Urban Studies	34	23
Other journals	141	95

Table 1.4 - Analysis of results and journal outlets.

Table 1.5 presents the economic approaches and methodologies most commonly used in the SAL. We find that 22% of SAL studies include economic criteria (quantitative or qualitative). Monetary values are frequently limited to the costs of remediation (engineering-economic approach), while economic methods and monetary valuations of benefits are poorly integrated (6%). Similarly, methods involving the economic appraisal of projects and policies, such as CBA and CEA (3% and 6% respectively), as well as institutional orientated approaches (9%) and economic behavior modelling approaches are relatively seldom used. Therefore, there is substantial scope for improving the integration of economic approaches in DST for sustainability assessments, particularly with regard to the economic assessment of BFR benefits.

SAL (n=395)	Yes	No	Yes	No		Yes	No	Yes	No
Integration of economic approaches	87	308	22%	78%					
Includes monetary valuations	23	372	6%	94%	Includes institutional economics approaches	34	361	9%	91%
- Property values	9	386	2%	98%	- Taxes	5	390	1%	99%
- Avoided costs	1	394	0%	100%	- Subsidies	5	390	1%	99%
- Human health	5	390	1%	99%	- Liabilities	11	384	3%	97%
- Environmental impacts	5	390	1%	99%	- Stakeholders attitudes/perceptions	18	377	5%	95%
- Other benefits	16	379	4%	96%	- Other	13	382	3%	97%
Includes valuation methods	1	394	0%	100%	Decision support tools	83	312	21%	79%
- Hedonic pricing	1	394	0%	100%	- Includes Cost-Benefit Analysis	13	382	3%	97%
- Avoided costs	0	395	0%	100%	- Includes Cost-Efficiency Analysis	22	373	6%	94%
- Contingent valuation	0	395	0%	100%	- MCA (Includes more than costs values)	19	376	5%	95%
- Choice modelling	0	395	0%	100%	- MCA (Costs or qualitative economic criteria)	45	350	11%	89%

Table 1.5 - Papers in the SAL database that include economic analyses and methods.

1.4. Discussion

1.4.1. Different research postures in SAL and EL

The two bodies of literature surveyed in this paper deal with the economic dimensions of BFR in very different ways. The SAL mainly reports on the development of multidisciplinary operational methodologies, designed to support decisions that concern redevelopment at local or regional scales. The advantage of the methods proposed by SAL is their holistic approach, which encompasses the technical, environmental, health, social and economic dimensions of BFR. The corollary is that each dimension is assessed using ad hoc methods and tools that may not fully exploit existing knowledge and methodologies geared to specific fields; for example, the economic impacts of BFR may be assessed based on expert judgement using semi-quantitative indicators, instead of using economic valuation methods. In contrast, EL is generally far more interpretative than prescriptive (with the exception of CBA and CEA studies). For instance, it highlights the processes that determine the nature and magnitude of the impact of BFR, rather than evaluating alternative BFR options. EL has a more fragmented

approach to BFR. Most papers focus on relatively narrow issues (e.g. impact of BFR on property values), but adopt thorough and progressive approaches and go beyond the state of the art in the discipline. Overall, SAL and EL have very different research postures in terms of the trade-off between operational scope and advances in the disciplinary field.

Figure 1.3 presents the sub-groups of the literature (EL and SAL) in terms of their scale of application (local to global) and operational level (from conceptual level to decision support). This figure shows that Decision Support Tools are commonly applied at the site-specific scale to select remediation techniques. They are less frequently applied at regional scale to prioritize site development and remediation. In terms of development, CBA and CEA are operational economic tools that have been widely tested and applied in the economic literature. However, they are rarely or only partially applied in BFR. Indeed, simple CBA is sometimes performed to select remediation technologies on the basis of remediation costs, without taking the full valuation of benefits into account. Moreover, it is difficult to apply CBA to back up DST at a regional scale because only a few studies provide a monetary valuation of BFR benefits. When more literature on the monetary valuation of BFR benefits is available, it will be possible to conduct a full CBA on a broader scale. Lastly, studies that focus on policy instruments and stakeholders tend to be more applied when it comes to subjects beyond local site specificities.

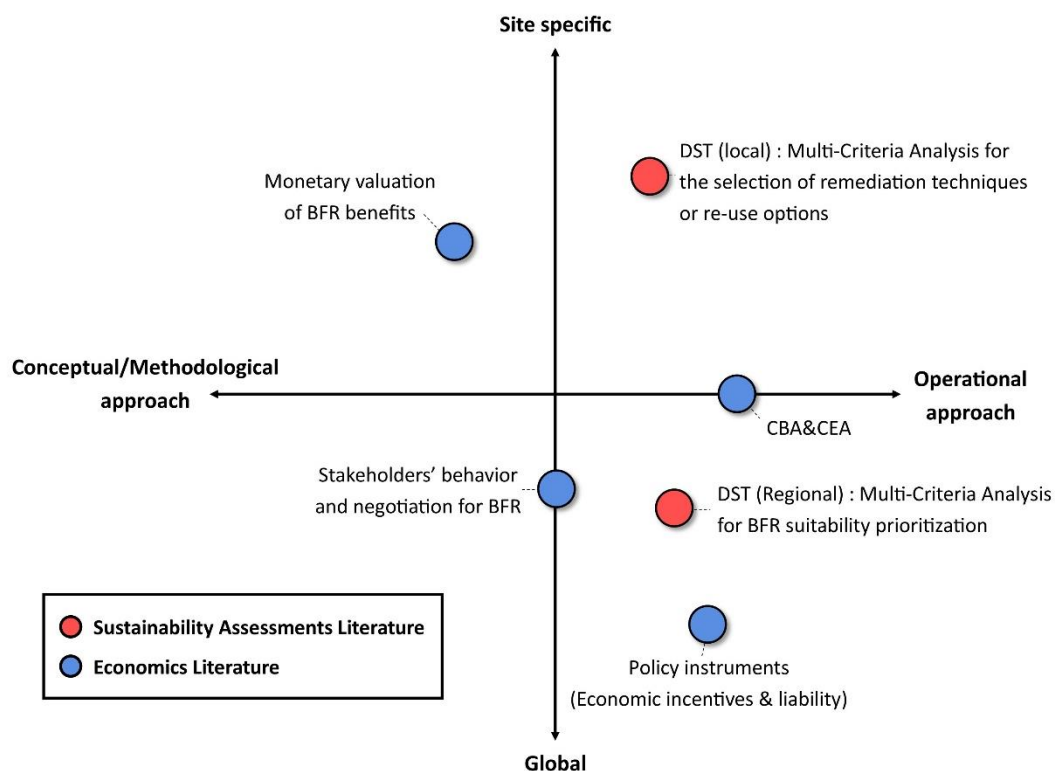


Figure 1.3 – Analysis of economics literature and sustainability assessments literature. BFR = brownfield redevelopment; CBA = cost-benefit analysis; CEA = cost-effectiveness analysis; DST = decision support tools.

1.4.2. Gaps and directions for future research in EL

Our review of EL revealed several gaps in current literature, which include:

- The monetary valuation of BFR impacts. Most papers use hedonic pricing methods, which assess the impact of BFR alternatives on property value. This approach provides results that are easy to communicate to stakeholders, but it fails to indicate how the different social, environmental, health and other impacts contribute to changing property values. Very few studies actually examine the monetary values of each of these benefits separately. Also, most BFR benefit studies focus on specific sites and we did not find attempts to assess the benefits that could be generated by a portfolio of projects at metropolitan or regional level. This is an area where additional research is needed.
- The economic valuation of ecosystem services associated with the redevelopment of brownfields into green spaces or soft reuse (e.g. CO₂ storage, storm water management, soil biodiversity, etc.). We did not find a single study on the evaluation of the indirect costs associated with the loss of ecosystem services following the commercial, residential or industrial redevelopment of abandoned sites reclaimed by nature. Studies of this kind are needed to calculate the true benefits of turning brownfields into green spaces, which are independent from the inherent rise in property values for nearby residential areas.
- Most case studies reported in the EL focus on redevelopment options (residential, commercial, industrial, parks, etc.) that derive an economic value from human presence. Many BF sites are actually located within large industrial complexes, where redevelopment projects involving people are not feasible because of industrial constraints (noise, pollution and risk of explosion). Alternative uses are the only possible options on these sites, for example, photovoltaic production, biomass production or ecological compensation. The economic value of BFR for these uses should be investigated.
- BFR's impact on mitigating urban sprawl. Many papers claim that BFR reduces urban sprawl, limiting the loss of agricultural land and natural resources, as well as the cost of developing infrastructure. However, the claims are generally qualitative. Further economic research on the subject is necessary.
- The absence of studies on benefit transfer within the field of BFR. Given that numerous studies use the hedonic pricing method, we consider that there is sufficient scientific material to conduct a meta-analysis capable of producing a benefit transfer function. This would make it possible to predict the impact of a given BFR project on property values, taking into account a range of determining factors. This type of benefit transfer function could easily be used by researchers working on the development and application of sustainable assessment methods and tools. It would be a way of enhancing the link between the EL and SAL.

- Lastly, the absence of a holistic approach. Developing holistic approaches, by moving from single or limited economic evaluations (e.g. cost remediation, property value) to an economic assessment of the diverse direct and indirect benefits of BFR. This may require the use of a combination of economic tools.

1.4.3. Gaps and directions for future research in SAL

The SAL approach would also benefit from the above proposals for future R&D. SAL is primarily based on decision support tools and Multi-Criteria Analysis, which are complementary. Two main developments can be envisaged for SA literature.

Appraisals of BFR projects call for a multidisciplinary approach. Indeed, Multi-Criteria Assessments (MCA) are the most widely used approach to help decision-making. However, complementing MCA with economic assessments (Cost-Efficiency and Cost-Benefit Analysis) would facilitate decision-making for BFR projects that have a high social value. Here, we agree with the findings presented by Bartke and Schwarze (2015): there is no perfect tool to suit all cases. Economic analyses (CBA & CEA) provide insights into the economic aspects of BFR projects. Therefore, we argue that they are complementary to sustainability assessments.

In-depth BFR sustainability assessments are often conducted on a site-specific scale, whereas studies at a regional scale tend to prioritize different sites for BFR. However, in some cities, developers are faced with more complex situations with dozens of sites that need to be managed. Each site can be redeveloped according to several scenarios (future end-uses). In this context, we argue that there is scope for developing DST that are designed to identify solutions for a portfolio of sites (on a regional scale). This involves the development of optimization models capable of identifying which BFR projects (rehabilitation and future end-use) maximize social welfare. This finding justifies the PhD research presented in this manuscript.

1.5. Conclusion

In the coming decade, the decline in heavy industry in developed countries is likely to generate more brownfields. At the same time, society is increasingly demanding when it comes to environmental matters and no longer accepts the nuisances generated by these sites. While the problem is growing, available funds continue to be scarce. Policymakers are forced to maximize efficiency and promote private stakeholder involvement in BFR. This situation requires decision support tools that would allow an in-depth economic analysis of BFR (Nathanail et al. 2018).

In that context, it is essential to promote a greater integration of concepts and methods developed in isolation by different scientific groups. The SAL community is already familiar with interdisciplinary

approaches. Therefore, it may be better placed to develop an integrated approach than is the case for economists. However, it is important to raise awareness about the diverse approaches developed by the many sub-disciplines of economics, what can they offer to stakeholders involved in BFR projects or policies, the issues can they address, at what scale, the methods they use and the data they require, etc. Additional efforts are required to break down the barriers between research fields. Public agencies have a responsibility when it comes to setting the research agenda at national, European and international level. Indeed, scientific societies that organize large conferences and individual researchers operating in the BFR field also have a responsibility.

Chapter 2. Presentation of the study case: the valley of the chemical industry (VoCI)

This doctoral research is framed within an applied economics perspective. In that sense, the empirical application of the analysis on a case study has essential relevance. Each step of our research required detailed field knowledge and involved intensive communication with field actors. The purpose of this chapter is therefore twofold: First, it aims at providing a description of the case study to enable the correct understanding of the modeling process; and second, it presents a realistic overview of the methodology and data requirements for replicability perspectives. The characterization of the case study was an iterative process that started at the beginning of the research (November 2016) and continued until the first phases of the model development (May 2019). The situation of some sites has changed over time, and some future land use activities have already been implemented. However, this chapter presents the characterization of the case study from an ex-ante analysis, that is, describing the situation at in the beginning of the research.

2.1. The Valley of Chemical Industry, an opportunity for industrial renovation

Applying a regional BFR decision support tool required choosing a case study with a significant amount of derelict industrial sites and for which the regional authorities were developing a strategic agenda. Early contacts with the administration of the metropolis of Lyon, which met both criteria, facilitated the search of a territory. Initially, two case studies were considered: the “Carré de la Soie” (CdS, Silk Industry Square), and the “Vallée de la Chimie” (Valley of Chemical Industry). The primary difference being that the former was at a final redevelopment stage, with most brownfields already redeveloped, whilst the latter was still at an early stage, for which most sites were still brownfields. While keeping both case studies was out of scope of a PhD research, the choice involved a clear tradeoff: CdS would allow ex-post analyses for the economic valuation of costs and benefits; and the Valley of Chemical Industry (VoCI) allowed testing the economic optimization model for regional BFR within an uncertain ex-ante environment. Finally, VoCI was selected because it enabled testing, from an ex-ante perspective, the relevance and feasibility of the regional approach, which is the overarching goal of this research. In addition, it is worth mentioning that brownfield redevelopment in large industrial areas similar to VoCI is a current issue in many regions of France, as it is in several countries within Europe and around the world.

Since its first settlements in 1853, the VoCI has been a strategic territory not only for the Lyon Metropolis but also for the French industry, through its diversified activities and its technical and economic links with other industrial regions. VoCI is the cradle of French chemistry (synthetic

chemistry, specialty chemicals, petrochemicals, refineries), and the house of global size firms such as Total, Arkema, Solvay, Bluestar Silicones, Engie and IFP Energies Nouvelles. It is not only an industrial zone nor just a cluster in the usual sense of the term, neither it is a neo-industrial city. Its history is highly linked to the continuous evolution and diversification of Lyon industry. However, this historical evolution also implied changes in land occupation, and has naturally lead to the abandonment or underutilization of certain spaces.

VoCI is a complex territory that also includes residential and natural zones. Green corridors along the VoCI are considered valuable assets within the environmental agenda of the metropolis. Mainly, because these areas, so called 'lônes et balmes', play an interesting ecological role by establishing a physical continuity between several major urban ecosystems such as the Rhone river bank ecosystems of Miribel-Jonage, the Tete d'Or Park, the Blandan park, and the Saône River banks.

The connection of the residents and the industrial zone is also rather intricate. Historically, residents considered that the nuisances of the industrial zone were balanced with the provision of employment and tax incomes. Nowadays, employment generated in VoCI is not necessarily granted to local residents and it represents a small share of local jobs. On the other hand, residential zones are usually isolated from the industrial areas by some physical barriers such as railway lines, highways, vegetation or difference in altitude. Hence, many inhabitants feel unconcerned by the proximity of brownfields since the disadvantages can be confounded with the overall perceptions generated by the whole industrial zone.

Located in the south of the city of Lyon, VoCI includes 12 of the 59 municipalities of the Greater metropolitan area of Lyon. Namely: Saint Fons, Pierre Bénite, Feyzin, Irigny, Solaize, Vernaison, Serezin du Rhône, Millery, Ternay, Grigny, Chasse du Rhône and Givors (See Figure 2.1). In total, these municipalities host 100,000 inhabitants in an area of approximately 9,400 hectares. The strictly industrial zone of VoCI has a surface area of 3200 hectares and stretches for 15 kilometers along the Rhône River. With over 12,000 jobs in 2015, VoCI is also the third largest employment hub in the Lyon metropolitan area.

In recent years, the economic vocation of VoCI has been strengthened thanks to an ambitious approach supported both by public and private stakeholders. The aim is to support the industrial regeneration as a leading pole combining research and industry, fostering the development of green-tech companies and the generation of renewable energies. The challenge is to preserve its economic power yet limiting the nuisances caused by industrial activities, encourage innovative approaches, and support sustainable development solutions.

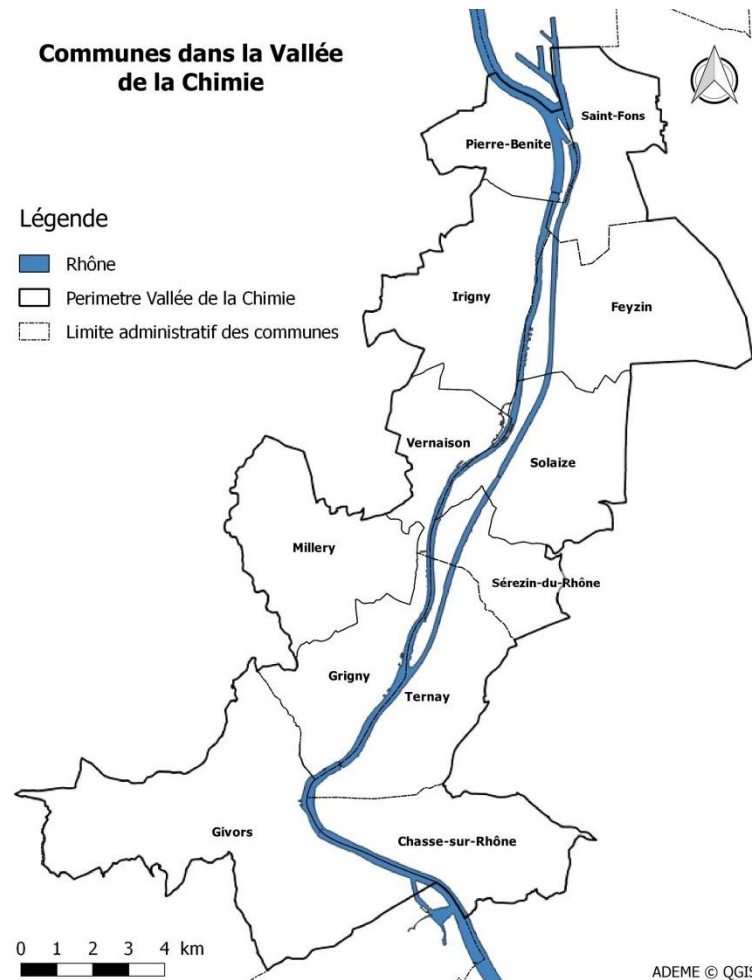


Figure 2.1 - The municipalities of the VoCI along the Rhône river.

2.1.1. Managing a brownfield sites portfolio: Mission “Vallée de la Chimie”

The VoCI mission is a task force mandated by the public authorities of Greater Lyon metropolis. The task force is piloting the development of the 2030 territory’s renovation master plan. The task force involves a partnership with 10 major industrial companies, the metropolis, the Auvergne-Rhône-Alpes region, and consulting companies. The task force plays herein a major role by leading stakeholders dialogue, logistics, providing advice, and funding exploratory studies. The project was initiated in 2010 and concretized in 2013 with the establishment of the VoCI regional task force mission. Since then, the call for redevelopment projects called “Appel des 30!” (A30!) has been the major tool to foster brownfield redevelopment in VoCI. Within the A30!, the task force identifies sites that are readily available for redevelopment, highlights the advantages of the sites, and orientates the call of projects according to site-activity compatibility. So far, three A30! have been launched in 2014, 2016 and 2018. The call usually receives around 30 project redevelopment propositions, bringing together manufacturers, municipalities, public stakeholders, technical and financial partners in offering public and private land as well as innovative redevelopment solutions. Laureates are selected according to their

viability and the needs of the territory. Then, they are granted with technical support and legal advice, with the possibility of receiving financial help.

2.2. Methodology: Characterizing the VoCI

The characterization of the VoCI is essential for identifying the constraints and setting the parameters of the model. The overarching objective of this stage of the research is therefore to create the database for the mathematical programming model. The procedure includes the following steps: 1) Establishing contact with the experts on BFR in VoCI; 2) First round of information collection through interviews; 3) Collecting secondary source information; 4) Identifying missing information 5) Second round of interviews; 6) Generating primary source information to complete the data required for the model; 7) Validation of collected information and database. These steps can be organized in three phases as in Figure 2.2.

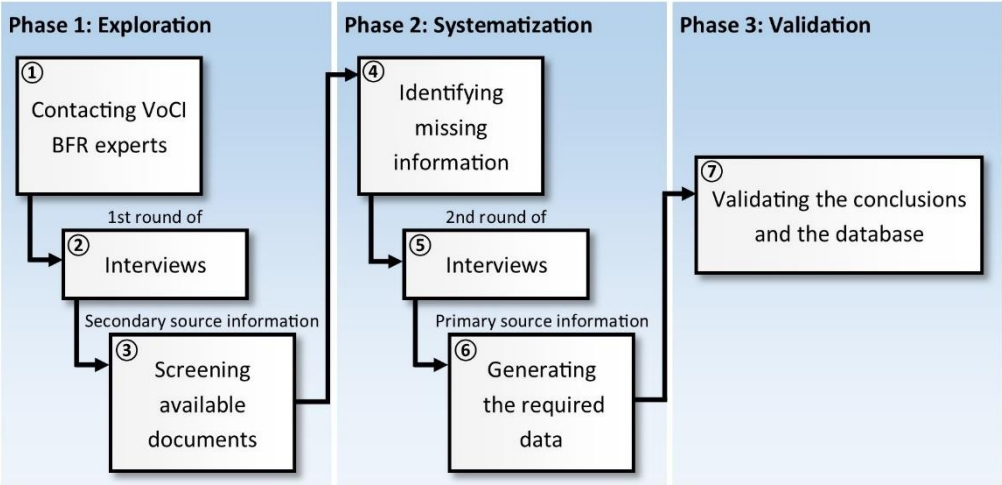


Figure 2.2 - Methodology of the case study characterization.

The experts consulted in this research include employees from the metropolitan administration, consultants of independent firms, and representatives of investment groups. Their areas of expertise cover the requirements of the case study characterization: Land and Real Estate Management, Territorial foresight, Energy, Technological Risks, Construction and deconstruction, Ecology and Biodiversity, Trees and Landscapes, Future Land Use Activities, and Urban Planning.

The first round of interviews consisted in 23 non-structured interviews. The experts were given the main topics of the meeting in advance, and during the interview an open dialogue was established covering multiple elements of the study case characterization (regulations, stakeholders, sites, land use activities, constraints). Choosing unstructured interviews was the most approachable solution since there was no indication on what information the experts had available or whether they were familiar with the modelling concept and its requirements. In this way, the interviewees had time to describe in an extended

way all the knowledge they could share, and then a round of questions was addressed according to the topics of the meeting. Usually, the interviewees provided documents with information, and in some cases they recommended contacting other experts to ask for specific data. A brief report was prepared after each meeting to synthesize the exchange of information, these reports were then sent to -and validated by- the interviewees. Interviews lasted 1 hour in average within a range from 45 min to 4 hours. Respondents allowed being tape-recorded, with some exceptions. Screening available information consisted in reviewing up to 400 files including reports, working documents, spreadsheets, brochures, technical datasheets, maps and urban planning guidelines. An excel database for internal use was created containing around 200 files with useful information.

The next step consisted in identifying what information was still required in order to develop the model. This was only possible after developing pilot versions of the model, which in turn drew on the information already collected. This step allowed preparing a list of missing data (mostly parameters). The second round of interviews consisted in 12 semi-structured interviews. The approach was similar as in the first round of interviews, but after the open dialogue the interviewees were questioned on missing data according to their expertise. Interviews lasted between 45 to 90 minutes, and also included tape recordings and follow-up reports. Thereafter, the required information that was still missing was generated through cross-checking available information and estimated using raw GIS data (such as surface area, location, etc.) and simple calculation methods set with experts.

Finally, the final database of sites, activities, objectives and restrictions and all the relevant parameters was submitted to and validated by the director of the VoCI task force.

This research has therefore benefited from the collaboration of several external experts whose previous work has been essential to characterize the case study. The availability of information was therefore an important asset for the development of the study.

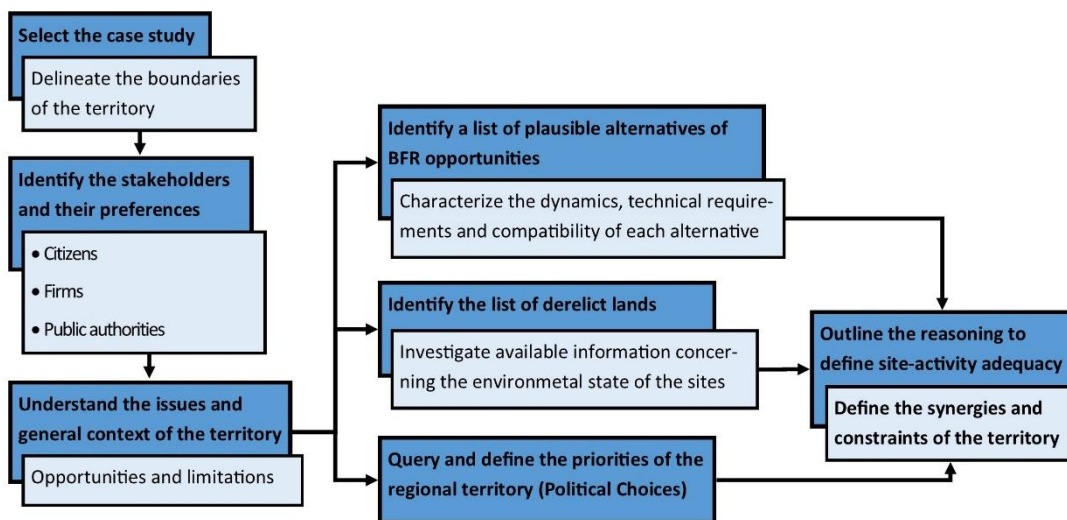


Figure 2.3 - Flowchart of tasks for the characterization of the case study.

Concerning the guidelines for the interviews, the majority of meetings were conducted with multiple objectives which are described graphically in Figure 2.3.

2.3. Results

2.3.1. Brownfields inventory

Sites were identified after a sequence of field visits and thanks to several interviews with some experts of the VoCI task force. Besides some abandoned sites, most of brownfields in VoCI are under-used plots that represent a fraction of larger properties of the firms established in the Valley. Hence, the identification of these under-used plots relies on the voluntary declaration of the owners to the urban planning task force. In that sense, it is likely that some sites are still to be identified. From 32 identified sites, 29 have development potential in a time horizon of 20 years, these are presented and enumerated following the chronological order of identification in Figure 2.4. Herein, dialogues with stakeholders allowed identifying 3 sites that are not brownfields but large open spaces that have not hosted activity because of some restrictive conditions (Sites 21, 27, and 29); 3 strategic sites that widely influence the industrial orientation of the territory, which are not currently brownfields, but for which there are discussions on the possibility that in the very long term these will be moved to locations more distant from urban areas (in which case these sites would become brownfields; Sites 1, 23, and 24); and 26 brownfield sites as it has been previously defined. One of these brownfield sites (16), is composed of several plots of land that come from the establishment of the risk management plan (PPRT in French) regulation. All in all, there are 596 ha of available space in VoCI (178 ha brownfields and 418 ha open spaces).

In regard to the incorporation of the sites to the modelling approach, the strategic sites Port Edouard Herriot (1), Total refinery (23), and SNCF Sibelin rail station (24) were not included in the CBA analysis since they are still and will surely remain in activity. However, acknowledging the presence and influence of these 3 sites remains relevant to understand the case study.

Moreover, the brownfields inventory was initially identified with experts using a large-scale map. However, during the characterization of the sites, aerial image views and cadaster limits enabled perceiving that these initially identified sites were sometimes large derelict areas composed of different plots (i.e. more than one site). Therefore, in some cases, it was decided to divide site into several sites in order to describe contrasted environmental states and compatibility with the constraints of the model. Hence, the final sites database separated the 29 initial sites into 71 smaller sites.

- *Characterizing brownfields*

The next step was to prepare a brownfields database appropriate for the modeling process. The main aim was to characterize the context of each site with regard to their compatibility with future land use activities. Preparing this data included interviews with the experts of Lyon metropolitan administration, screening urban planning documents, and using available GIS databases. Then, both a unified GIS database (delineating the polygons of the identified sites) and spreadsheet database were created. This also enabled to create an atlas of the sites to facilitate the dialogue with the stakeholders. The information compiled for each site is as follows:

- *Size*. Expressed in hectares (has), the size is estimated according to the polygons in the GIS database. It is a fundamental data for the compatibility analysis (critical sizes), and for the estimation of rehabilitation benefits and costs.
- *Municipality*. The name of the municipality hosting the site is a complementary data to facilitate its location.
- *Property rights*. The information on the owner(s) of a site allows considering the readily availability of the site and whether separation into several plots is possible.
- *Industrial Risk Management Zone (PPRT) classification*. The PPRT states and defines the types of land-use which is authorized according to the different PPRT zone, in particular with regard to the human presence on the site (see next subsection).
- *Flood Risk Management Zone (PPRI) classification*. The flood risk prevention plan defines various type of areas according to their flood sensitivity and associated possibility of construction.
- *Existence of pipelines*. Indicates the existence of -or approximate distance to- industrial pipelines transporting industrial by-products (hydrocarbons, gas and chemicals; heat network; mainly coming from the refinery). These are considered an asset for future land use activities oriented to the petrochemical industry, and can represent a constraint for building new infrastructures. The presence of these pipelines is mainly located in the municipalities of Saint-Fons and Feyzin.
- *Existence of power lines*. The presence of electrical stations and power lines restricts the construction of new infrastructures. On the other hand, it can represent an asset for future land use activities oriented to electrical energy production.
- *Height constraints*. The presence of overhead electric power lines may condition the maximum elevation of new infrastructures. The elevation constraint was established during interviews with experts in the field.
- *Accessibility*. Road access and proximity to public transport conditions the compatibility with certain future use activities, especially with regard to heavy transport or mobility of employees.

- *Proximity to residential areas.* It is an urban planning criterion to restrain the development of future land use activities that may represent nuisances or risks for inhabitants (dust, noise, odors). In addition, this is also important for the economic evaluation of the benefits (and nuisances) of the projects as they may impact real estate property values.
- *Proximity to the river.* May represent an asset to future use land activities to facilitate transport (active navigation on the Rhône river).
- *Potential for interaction with other sites.* The possibility of jointly redeveloping several adjacent or nearby sites was determined by proximity and positioning (discussed and validated with stakeholders). Thus, the proximity of certain sites could make it possible to join them during the compatibility analysis, thus removing the constraint of the minimum size for its economic viability.
- *Soil quality.* Provides information on the existence or not of a soil study, and in this case, providing information on soil fertility or soil stability of the site.
- *References in BASIAS, BASOL and ICPE databases (national industrial databases).* This section of the database records the identification codes of the points and polygons in these 3 national GIS databases that could be relevant to the site. These codes allow the identification of files containing more information such as the past activities on the site or the potential presence of contamination.

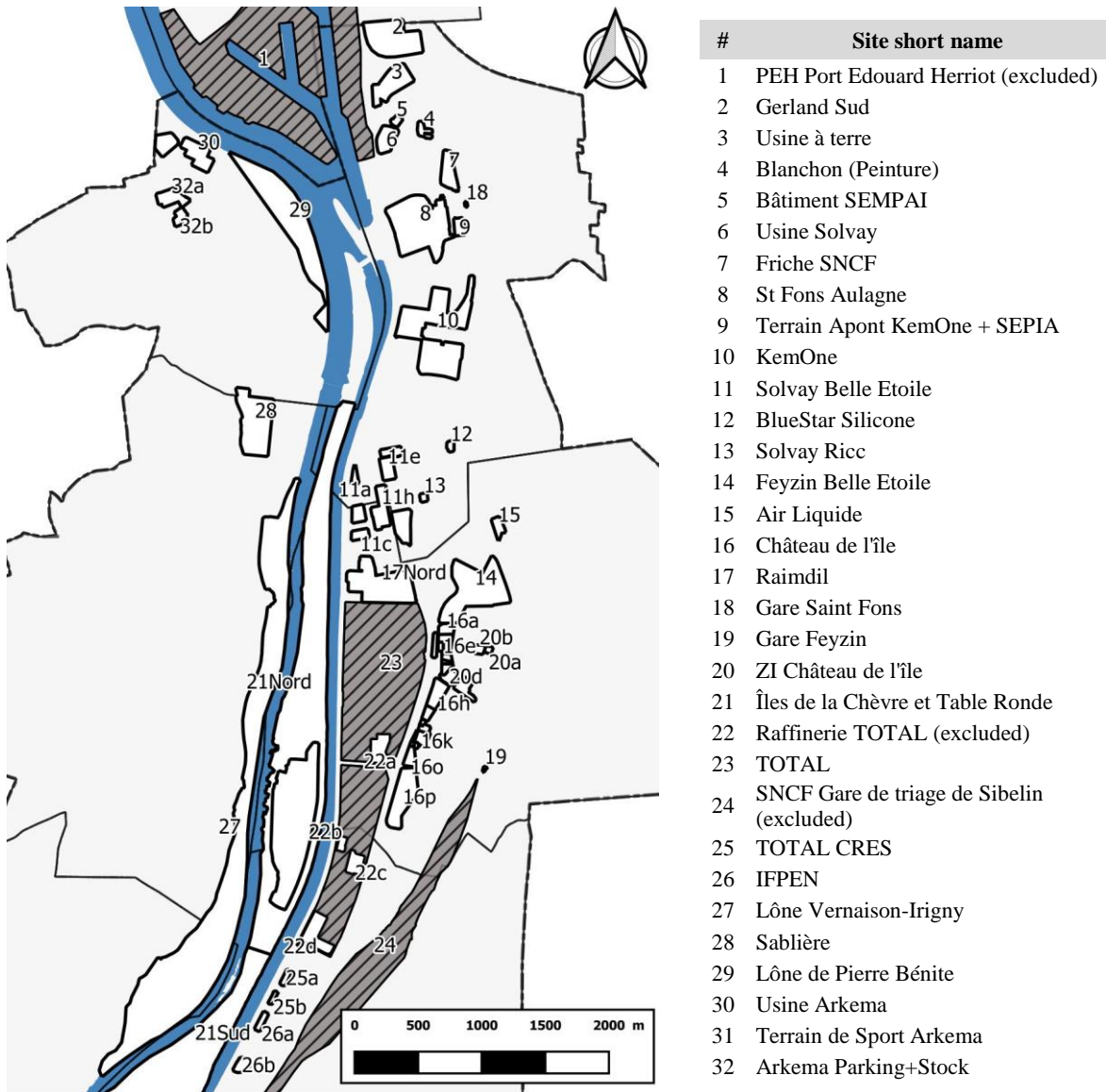


Figure 2.4 - Map of identified brownfield sites in VoCI.

2.3.2. The technological risk prevention plan: A major constraint

Several Seveso-classified facilities that could lead to technological risks are located in VoCI. In accordance with national and European regulations, the regional authorities have established a Technological Risk Management Plan (PPRT in French = Plan de Prévention des Risques Technologiques), which allows actions to be taken on existing and future urban zones in VoCI in order to protect the population. The PPRT establishes, on the basis of hazard studies, zones or perimeters around establishments that pose risks to human life in the event of an accident. It regulates the existing and future urban planning: zones with land measures for the existing land use (e.g. expropriation), zones of prescription on the existing (e.g. reinforcing safety measures), and zones of control of future land use. As it deals with future land use, the latter is of most importance for the modelling objectives this research. Herein, six areas can be distinguished (see Figure 2.5).

Dark red zone: predominant interdiction of construction.

Light red zone: predominant interdiction of construction with exceptions.

Dark blue zone: predominant avoidance of densification of the area.

Light blue zone: predominant permission to build with few exceptions.

Green zone: predominant permission to build with recommendations.

Grey zone: specific perimeter belonging to owners of an establishment generating the risks in case of accident. Current owners have permission to build with exceptions.

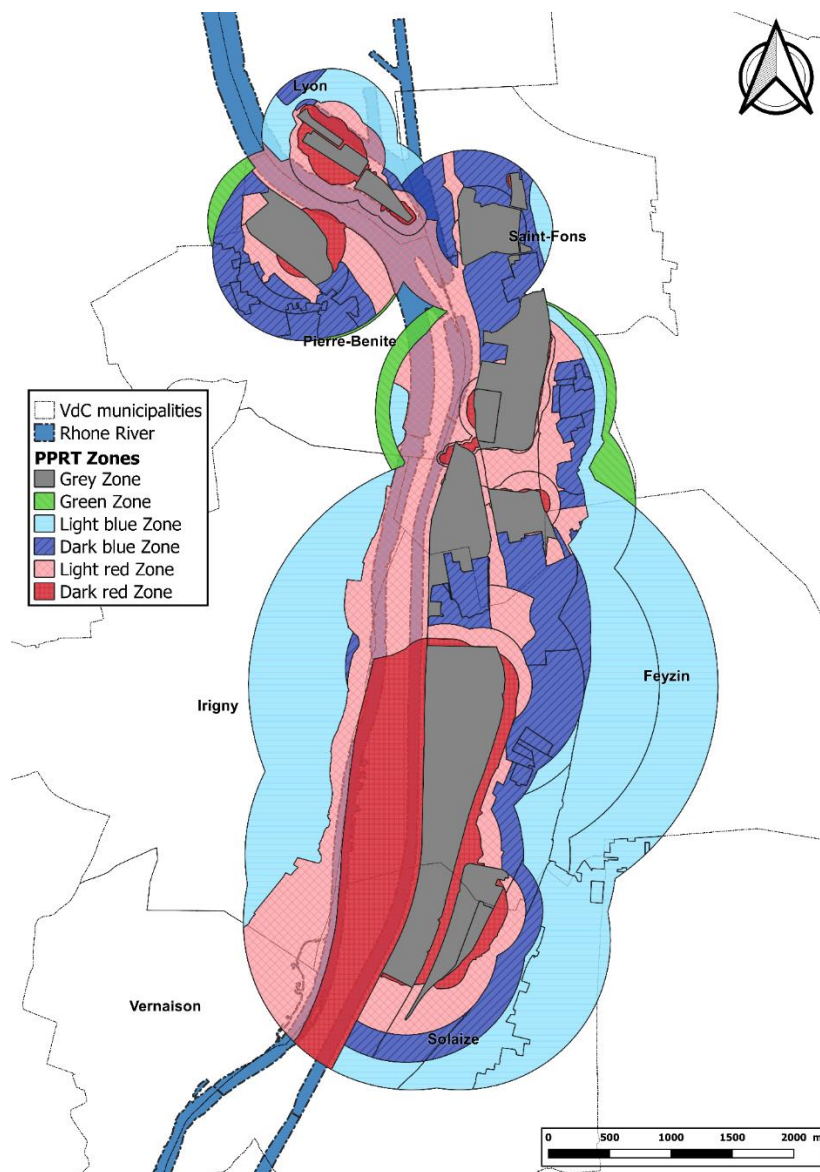


Figure 2.5 - Technological Risk Prevention Plan (PPRT) zoning regulation in VoCI.

2.3.3. Future use land activities

Possible future land use activities were mainly identified based on proposals submitted by private and public actors in response to the A30! calls for project of 2014 and 2016. Three main types of redevelopment were identified: ‘Productive Landscape’ (Green orientated developments), Energy Production, and Private Industries (generally linked to the petrochemical industrial cluster). Sites were considered unsuitable for commercial and residential developments for lack of attractiveness and regulatory reasons (risk management plan). Public investment is a priori not envisaged to fund projects beyond preliminary support studies and logistics. Although A30! specifically calls for private initiatives, the metropolitan council also reserves some spaces for public infrastructure development. The analysis of A30! candidates and the knowledge of the VoCI taskforce experts allowed selecting a ‘reduced’ list of 11 types of future land use activities. Figure 2.6 presents this list of reconversion alternatives.

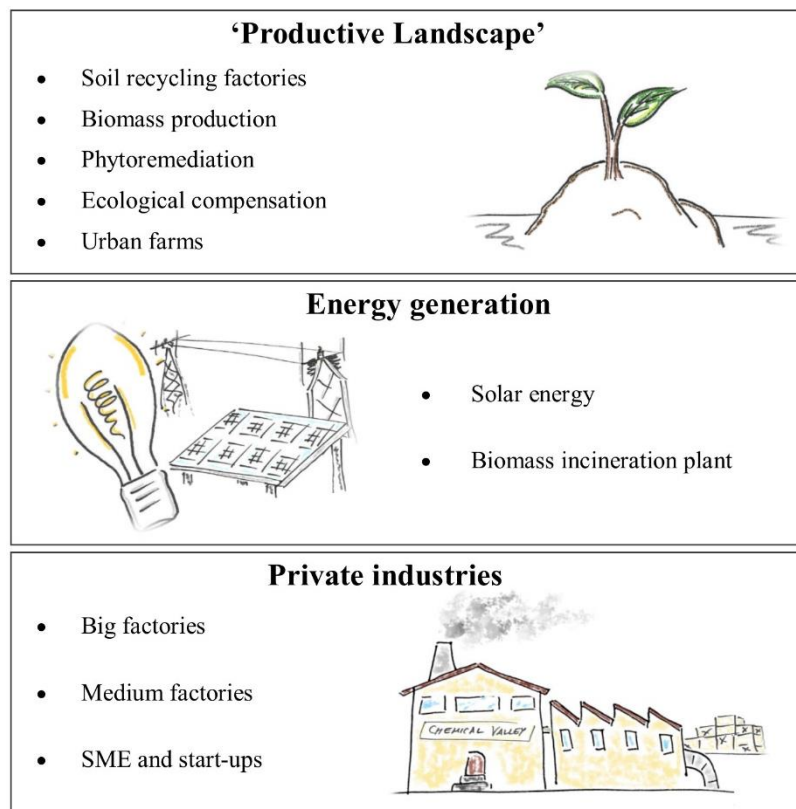


Figure 2.6 - List of future use alternatives considered in the study.

The characterization of future land use activities was based on an analysis of A30! project proposals, supplemented with interviews with the urban planners of VoCI mission task force and leading regional actors interested in investing in the selected activities. This allowed developing and filling a template homogenizing the information available for each future land use activity, especially regarding the elements that allow the identification of benefits and the technical requirements that determine compatibility with the sites. All this information was organized in a spreadsheet database to be used in the modelling process.

- *Soil recycling factories*

The soil recycling factory is a private initiative seeking to produce artificial functional soils by recycling inert soil (silt, mud, gravel) generated by urban development works (excavations, constructions) and organic waste (compost). Currently, the demand for fertile soil of the metropolis is met by importing natural fertile soil. This practice often implies stripping fertile layers from the meadows of the metropolis. In an effort to reduce its ecological foot-print, the public administration wishes to substitute imported fertile soil with artificial recycled soils which could be produced within the limits of the metropolitan area, hence contributing to reducing the amount of soil wastes stemming from urban development projects. The market potential of recycled soil is still unclear. Experts estimated that in the upcoming years, construction works commissioned by the public administration will roughly produce between 40,000 and 50,000 m³ of soil wastes annually, and require between 50,000 and 100,000 m³ of fertile soil annually. In addition, although no estimate was obtained, another large amount of potential demand may come from the private sector. The pre-feasibility study submitted by a private operator to the A30! assumed the development of a soil recycling station covering an area of 4.5 ha, which can produce up to 40,000 m³ of artificial functional soil per year, reducing costs of inert waste soil management, avoiding the import and consumption of natural fertile soil, and reducing transport distances and CO₂ emissions. The economic viability of the activity requires a minimum size of 4 hectares.

In the case of the soil recycling station, life-quality impacts to nearby residents would in any case be negative due to dust generation, compost odours, and truck traffic. In this regard, urban planning requires implementation of these activities in sites which are reasonably far from residential areas (distance greater than 500 meters), with limited visibility (differences in altimetry), and located in an industrial environment that could absorb these positive or negative impacts of the projects.

- *Biomass production*

The initiative of biomass growing consists in generating an economic return on sites where construction is prohibited (e.g. land subject to Risk Management Zones restrictions along the highway) while simultaneously contributing to a greener landscape and ecological services at the scale of the territory. The installation of urban forests would therefore produce biomass to supply local energy production units which are currently based on domestic waste incineration; it would also open the possibility of simultaneously developing public walks and ecological corridors. The tree species considered in the preliminary analyses are poplar, robinia, eucalyptus and red oaks. However, given that the soil must meet certain conditions of fertility, experts signalled that short-rotation coppices are overall better suited to the soil conditions of the VoCI territory. Planting and cutting cycles need to be taken into account for an economic analysis, but these depend on species and management methods, the minimum size of sites to ensure economic viability varies from 2 to 10 ha.

- *Phytoremediation*

Phytoremediation is a viable alternative for the treatment of polluted sites in the VoCI. Phytoremediation consists in the use of plants to extract, degrade or stabilize the pollutants contained in the site. Thus, this helps managing the pollutants while developing a flora which can also contribute to a greener landscape of the territory. Depending on the environmental context of the site, the different types of phytoremediation that can be used are: phyto-volatilization (plants absorbing and releasing pollutants into the atmosphere), phyto-extraction (absorption and accumulation of pollutants in the different parts of the plant), phyto-stimulation (plant stimulating the degradation of pollutants in the soils) and phyto-stabilization (plants reducing the mobility of pollutants in the soils). Accordingly, different plant species are possible (poplars, willows, mushrooms, sunflowers among others). Although in some contexts plants can afterwards be used to generate an economic return, phytoremediation is not in itself an economic activity for the site, but it does imply the physical occupation of the site (and often within a timeframe similar to the 20-year scope of the analysis of this study). This is why phytoremediation has been included within the alternatives of future land use activities. However, it does not necessarily imply that the site will not require further rehabilitation efforts in the future.

- *Ecological compensation*

In France, there are three legal grounds for creating ecological compensation zones, to compensate for the destruction of wetlands, destruction of woodlands, and destruction of areas hosting certain protected species. However, the compensation does not necessarily have to be 1:1, it can go up to 1:10, and the objective is not only to compensate for surface area but also for habitat quality. Thus, the open spaces and wetlands located along the Rhone River constitute an interesting reserve of sites potentially usable for ecological compensation. Ecological compensation necessarily implies that an ecological environment has been damaged elsewhere. Although all this can lead to an environmental gain, there are no arguments to deduce other than a neutral balance without knowing the specific context of each case. This means that after compensation, the ecological situation is not necessarily improved, hence generating no environmental benefits. The use of VoCI for ecological compensation projects could however be less costly than in other places due to the high ecological potential of some sites along the Rhône river and their relatively low market value (as compared to agricultural land which could also host such compensation projects). As this land use significantly depends on the space that is endangered elsewhere, Ecological compensation was considered not suitable for its ex-ante characterisation, and was therefore not included in the list of future land use activities within the modelling process.

- *Urban farms*

The aim of urban farms is developing, within cities, a very intensive mode of agricultural production to help coping with world population growth and food demand, by exploiting non-valued land surfaces. It basically consists in growing vegetables in a vertical industrial mode, based on a time- and space-

intensive cultivation strategy. An urban farm in VoCI could easily adapt to space restrictive sites, and could orientate its production according to the demand of firms within the valley for industrial purposes. The buildings are designed to house and control agricultural production using hydroponics and mainly under artificial climate. By organizing each plant in a horizontal and vertical path, controlling humidity, temperature and ventilation, urban farms can largely increase productivity as compared to traditional agriculture (up to 180 times), and obtain regular and high-quality productions despite weather uncertainties. Urban farms could also help minimising the environmental impact of agricultural production by developing local transport circuits, reducing CO₂ emissions and water consumption, and avoiding waste releases in the environment.

- *Solar energy*

At the metropolitan scale, the VoCI is strategically positioned for the production of renewable energies and could actively contribute to reach sustainable development objectives (10 to 15% of renewable energies by 2020). Having already two hydroelectric plants on the Rhone River, solar energy is an interesting alternative for the use of abandoned areas, and fits well with the constraints of the territory (e.g. in relation to limited human presence imposed by the technological risk management plan). Although the variants of implementation of photovoltaic panels on roofs or in combination with other activities are also relevant, within the scope of this study, the future land use activity of solar energy production corresponds in the current research work to the integral concession and use of the site.

- *Biomass incineration plant*

In France, waste incineration to produce energy, in heat or electricity, is the 2nd source of renewable energy. Each year, the Greater Lyon metropolis collects more than 500 kilotons of household wastes. Among them, 63% are eliminated using two incinerators. However, the tendency of per capita generation of wastes is decreasing (-4.5% between 2010 and 2018) which may require using alternative biomass for running those incinerators in the long term. Knowing that the two incinerators are currently at 2/3 of their life span, they could be replaced in a near future with new integrated infrastructure combining different equipment such as waste recycling units, incinerators, methanization units, and biomass burning units. The energy market prospective analyses and urban planning efforts of Greater Lyon metropolitan council foresee that between 20 and 70 MWh should be produced within the VoCI territory.

- *Big factories, medium factories, SMEs and start-ups*

The last three categories of redevelopment projects relate to three domains which are politically encouraged in the VoCI: the chemical industrial production, cleantech initiatives and innovative initiatives. The stakes of these industrial activities are mainly those of the private investors, but can also be a great source of tax and employment generation. Overall, these are distinguished between big,

medium and small factories (and start-ups) to enable an appropriate characterization of the technical requirements, compatibility issues, and subsequent evaluation of benefits.

2.3.4. Metropolitan objectives for future redevelopment

The redevelopment of a portfolio of brownfield sites can contribute to the achievement of the objectives of various public policies. Figure 2.7 depicts six general objectives that are emphasized by the VoCI task force.

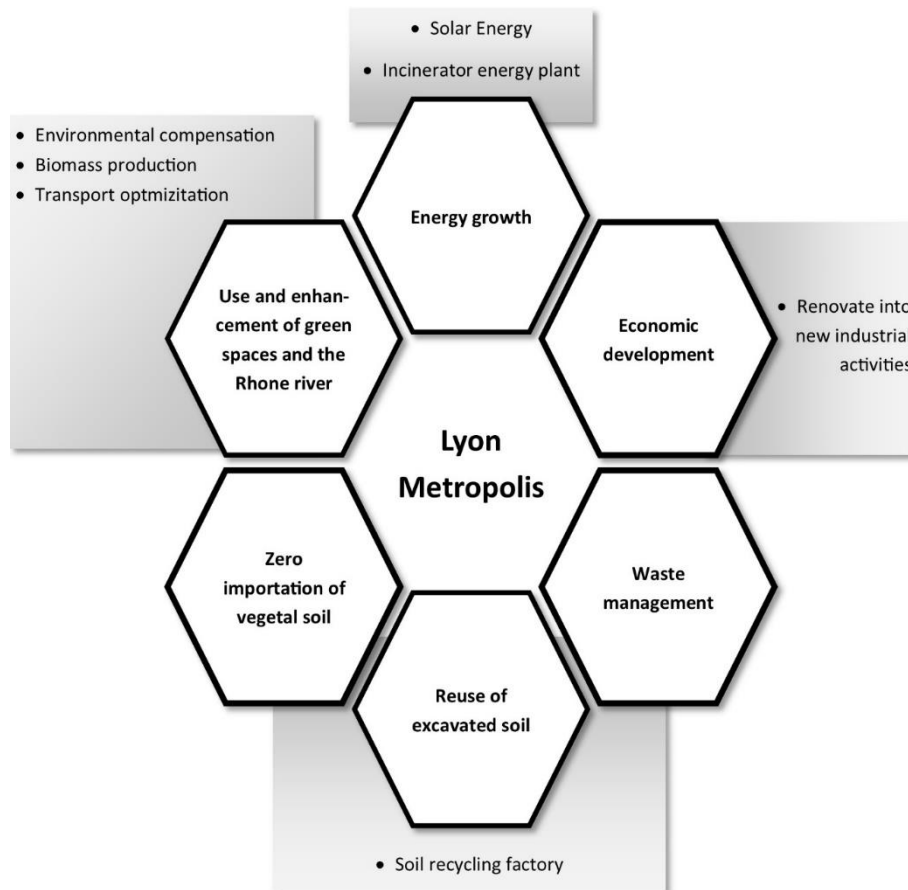


Figure 2.7 - Transversal metropolitan priorities within the framework of urban renewal to which BFR can contribute.

- *The valley remains an area oriented towards economic activity.*

In view of the importance of this industrial zone as a driving force of the economic dynamism of Lyon metropolis, by decision of elected representatives, the planning of the redevelopment of VoCI must remain oriented towards economic growth and creation of employment. Thus, BFR projects are supposed to strengthen the critical mass, the competitiveness and the innovation capacity of the chemical, energy or environmental sectors.

- *Energy growth.*

The constantly growing demand for energy and the upcoming cessation of two energy plants drive the overall objective increasing the production of renewable energy in VdC. Herein, a major opportunity of circular economy is being strongly considered. The idea consists in placing a new clean-energy incinerator & biomass burning plant in the valley in connection with a project for the management of the urban heating network. The project could capture the fatal heat produced by the industrial cluster and an incineration plant and use the resulting hot water to supply the urban heating network. Then reuse water from urban heating network the other way around, to satisfy the need of cooling machinery of the industrial cluster. These energy resources (fatal heat) are currently wasted.

- *Zero importation of vegetal soil.*

As an engagement with sustainable development, the Metropolitan Council has set itself the political objective of stopping the import natural topsoil for carrying the urban projects commissioned by the Council and related administrations. Subsequently, the Metropolitan Council needs, in as much as possible, to develop the production of artificial soil by recycling excavated inert soils, organic wastes and sewage sludge. Brownfields of the VoCI offer opportunities for developing such soil recycling factories.

- *Reclamation of excavated land resulting from urban development work.*

In the coming years, the city is preparing the construction of a new highway around the west and south-west of Lyon to complement the existing transport network. Part of the route will be built as a tunnel, which will produce large quantities of inert soil. As far as VoCI is concerned, this project represents an improvement in transport perspectives, but also a huge amount of excavated soil. This is also the case for several public driven construction projects, which reinforces the attractiveness of soil-recycling factories.

- *Waste management.*

The management of urban waste is seen as an important opportunity for reducing costs in connection with soil recycling and energy production via incineration.

- *Use and enhancement of the river and the adjacent green spaces.*

Finally, the Metropolitan Council also intends to better value the Rhône river, which simultaneously offers opportunities for clean transportation of heavy materials and provides environmental opportunities with a better management of natural spaces along the river banks. Thus, some projects such as biomass production could benefit from the river as a means of transport to incinerators. On the other hand, future land use activities that are inserted in natural areas along the river could benefit from the values of existing ecosystems while providing continuity to the biodiversity corridors. Additionally,

from a continuity perspective, ecological compensation projects could provide environmental gains as a sort of synergy, but then again, this is difficult to ascertain without having any precise detail about the affected areas.

2.4. Conclusion

The characterization of the study case has been a time-consuming part of this research. Urban planners acknowledged that the amount of input data required was quite significant but necessary to give credibility to the model. In this regard, the focus of the interviews and information exchange was initially concentrated on the general problematic of BFR in the VoCI, addressing several topics, and very gradually opening the way to the systematization of the characterization of the sites, activities, and their interactions for the purpose of modelling. In a perspective of replicability, starting from the conceptual and illustrative applications of the model may help to quickly identify which data is essential for the modelling process, and which is only for contextualization matters. It would also be possible to reduce the amount of information needed by targeting the sites for which decision making is more sensitive and exclude from the analysis the sites with very little or no compatibility due to their characteristics.

In that sense, the list of brownfield sites could have included an additional group of underused areas that are located outside the industrial zone of the VoCI (within residential and agricultural areas), but since their redevelopment constraints and orientations were completely different, these sites were excluded from the analysis.

These large data requirements sometimes forced to simplify the analysis, as it happened with the issue of ecological compensation which was excluded from the list of redevelopment options. On the other hand, the simplification of the analysis may allow to reach developed stages of the modelling process with greater speed, point from which the inclusion of additional aspects of the analysis could be reconsidered.

Overall, the characterization of the study case allowed to create the databases of sites and future land use activities, containing all the required parameters for the modelling process. The databases are developed in spreadsheets using Excel. The database of future land use activities contains 9 activities (rows) and 19 parameters (columns), and the database of sites includes 71 sites (rows) and 40 parameters (columns). The databases were also essential to conduct the estimation of benefits and rehabilitation costs of brownfields redevelopment in VoCI. The next chapter describes the way rehabilitation costs are identified and evaluated.

Chapter 3. Assessment of rehabilitation costs under uncertainty

Brownfield rehabilitation generally requires soil and groundwater decontaminating and removing derelict or abandoned buildings in order to manage health and environmental risks according to the future land use. The intensity of remediation activities and their costs depend not only on contamination levels but also on future use which determine decontamination objectives. The estimation of these costs is a complex task given the high spatial heterogeneity of contamination (type and intensity) and the related difficulty to assess volumes of soils that need to be treated and the type of treatment needed. Precise estimation requires detailed site characterization, based on adequate soil and water sampling and detailed appraisal of the structure of buildings to be demolished (in particular to refute/confirm the presence of asbestos). While this information can typically be collected for specific sites where concrete projects are being prepared, it remains too costly to be collected at regional level. More simple approaches thus need to be developed to conduct a global cost-benefit analysis of a large set of sites, as developed in this research. This chapter presents a methodology to evaluate those costs based on information available in national databases and expert judgment.

A key issue addressed in this chapter is the uncertainty attached to cost estimates. At a regional scale, estimating of rehabilitation costs for all possible combinations of use and sites entangles a higher degree of uncertainty. Decision-making in brownfield rehabilitation at regional scale deals with epistemic uncertainty, which stems from lack of information (Baudrit and Dubois 2006; Dubois and Guyonnet 2011). Market forces often absorb a certain degree of uncertainties when contractors set a foregoing price for their services. It seems therefore appropriate to use experts' judgment as a fundamental entry to establish the methodology. The theory of subjective probability stands that individuals are constantly making decisions under uncertainty based on subjective evaluation using available information (De Finetti 1979; Chick 2006). This means that decision-makers weight, in a more or less conscious way, the probability of outcomes based on their degree of belief given their knowledge. Applied to the context of the current research, we found that experts were much more at ease directly estimating intervals of the final costs based on available information and their own experience, than approximating intermediate information on the many variables that determine cost, such as the proportion of polluted area within each site.

The research led identifying four sources of costs to ensure site-use adequacy: costs of decontamination and/or costs of managing excavated soils, costs of demolition, and the costs of soil reconditioning. This chapter is organized as follows: Section 2 introduces the theoretical framework of the possibilistic approach as baseline for the elicitation of subjective knowledge. Section 3 details the methodology applied to the estimation of each source of rehabilitation costs. Section 4 illustrates how results are

calculated and compiled for modelling purposes. Finally, section 5 discusses the limitations and conclusions of the exercise.

3.1. Theoretical framework: Dealing with uncertainty using the possibilistic approach.

In life, individuals are constantly faced to make decisions under uncertainty. The notion of subjective probabilities implies that choices are made by “weighting” the possibility of an outcome based on best available information. Thus, subjective evaluations or degrees of belief determine the behavior of individuals under uncertainty (De Finetti 1979). The case of bets is a typical example; individuals try to forecast the outcome of a sport event based on their knowledge about the game and bid in order to maximize their profit. The issue is that such reasoning accounts for uncertainties that are not necessarily random in nature or objectively quantifiable (Baudrit and Dubois 2006).

Information regarding parameters of our BFR optimization model is sometimes incomplete due to time and financial constraints (i.e. epistemic uncertainty); this is frequently the case when estimating brownfield rehabilitation costs. Epistemic uncertainty issues can be even more heavily expected within regional approaches. Hence, as the value of rehabilitation costs results from multiple issues and associated stakeholders’ perception dealing with decision-making under uncertainty, it can be argued that experts’ knowledge is a relevant reference in the domain (Montpetit and Lachapelle 2015). The possibilistic approach (belief functions) provides a reasonable approach to model useful information as well as its underlying uncertainty (Attoh-Okine and Gibbons 2001).

Box 1 : Perceptive tasks

Gajdos et al. (2012: 5) illustrate subjective knowledge effectively using a perceptual task, where subjects have to compare the number of dots contained in two circles (See Figure 3.1). In this exercise, circles are displayed for a short fraction of time, and subjects have to decide which circle contains more dots with not enough time for counting. As long as subjects have to make the decisions, it is reasonable to assume that they base their decision on noisy signals of the sensory system. The authors use signal detection theory to model levels of confidence experimenting with perceptive tasks and logic quizzes, they test different modelling approaches and find that the rule of matching probabilities fits well with their theoretical predictions.

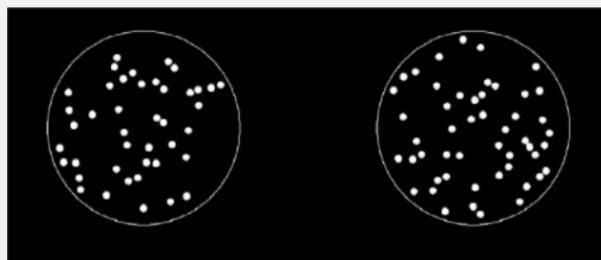


Figure 3.1 - Example of a task based on perception. From Gajdos et al. (2012: 5).

3.1.1. The possibility theory

A brief literature review allowed distinguishing two main theoretical frameworks addressing subjective probabilities: Bayes theory and Possibility theory. However, the Bayesian theory assumes that uncertainty should always be measured by a single probability measure, and values should always be measured by utility functions (Walley 1991). On the other hand, the possibilistic approach can be qualitative or allow imprecision with the use of intervals (Walley 1991; Dubois et al. 2000). In brownfields domain, being able to measure the magnitude of uncertainty allows including awareness for risk-informed management, and is especially valuable for the modelling purposes of this study. This fundamental difference drives the research to adopt the possibility theory.

The possibilistic approach allows assessing the experts' judgement (i.e. degree of belief) concerning different elements of the costs of brownfields remediation, accounting for the best available information. Probability distributions are not suited to represent the subjective knowledge, as it introduces information with a notion of precision that in fact is not available. Instead, it consists in eliciting upper and lower bounds which are interpreted as the degrees of belief in an event. Let A be a set for which the bounds are the minimal and maximal values stated by the expert in regard to the possibility of the parameter x . The representation of this knowledge uses the characteristic function of the set A , such that the possibility (π) of x : $\pi(x) = 1, \forall x \in A$ and 0 otherwise. Unlike probabilities, possibilities are not expressed in percentages but in fractiles of 1. The possibility distribution π encodes the family of all probability distribution functions of x with support in A (Walley 1991; Baudrit and Dubois 2006).

A possibility distribution describes the plausibility of values of some uncertain variable X . Possibility theory provides two evaluations of the likelihood of an event: the possibility (π) and the necessity (N). The possibility of an event evaluates its degree of unsurprisingness while its necessity evaluates its degree of acceptance (Dubois et al. 2000; Baudrit and Dubois 2006). These notions are also known as plausibility (possibility) and belief (necessity) within the Dempster-Shafer theory (Shafer 1976). Sometimes, experts are able to express a more plausible value or a subset of more plausible values, this is called the core of the possibility distribution and is related to high possibility and low necessity. This means that the subjective knowledge allows expecting values near to the core, but this is tied to a higher uncertainty. In that sense, the wider the interval, the more certainty but less useful. On the other hand, a narrow range can be more informative but more uncertain.

Possibilistic approaches commonly use triangular possibility distributions to represent subjective knowledge. In Figure 3.2, there are two vertical axes: on the left ascending from 0 to 1, the possibility (π) axis denotes plausibility. On the right-hand side, descending from 0 to 1, necessity (N) axis denotes acceptance (i.e. belief). The horizontal axis measures the range for the event x . Clearly, the values of the support (c and d) at the base of the triangle are related to the maximum degree of certainty ($N(x)=1$), but are consequently less plausible ($\pi(x)=0$). Alternatively, the value at the core (a), represent the more

plausible value ($\pi(x)=1$), but at the same time the lesser degree of acceptance ($N(x)=0$). Note that core can also have the form of $[a,b]$ as shown in the right-hand side of Figure 3.2. There are other formal frameworks to represent the modelling of subjective knowledge, especially using cumulative distribution functions (see Box 2).

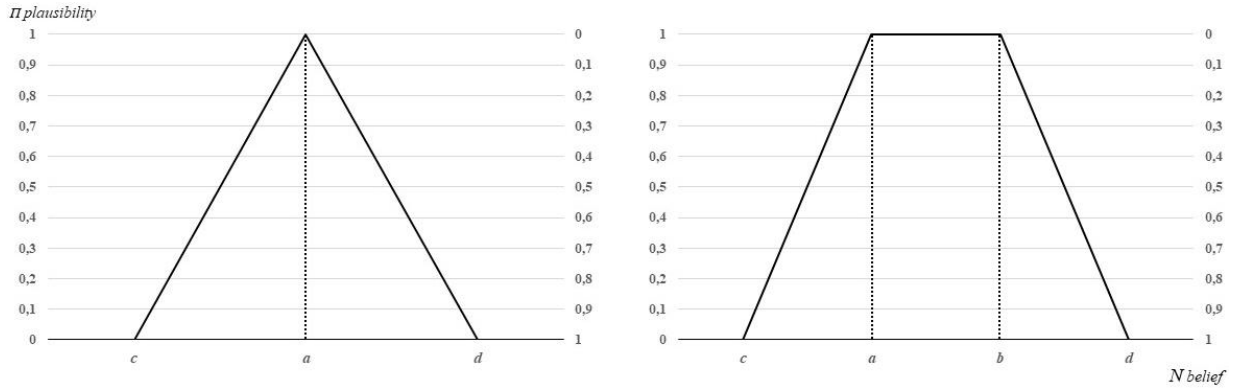


Figure 3.2 - Triangular possibility distribution and possibility distribution with core $[a,b]$.

3.1.2. An elicitation procedure

The elicitation process should allow the expert to model the possibility function as best as possible. For example, let c and d be the values of the support (i.e. min – max interval), z be the median, and a be the core of the function. If $z=a$, then the possibility function takes a form as already seen on left side of Figure 3.2. However, the core of plausibility can also be higher than the median, $z < a$ (Left side Figure 3.3), or vice versa, $z > a$ (Center Figure 3.3). Moreover, one could even adapt the exponential factor of the function in order to represent the tendency of possibilities smoothly (Right side Figure 3.3).

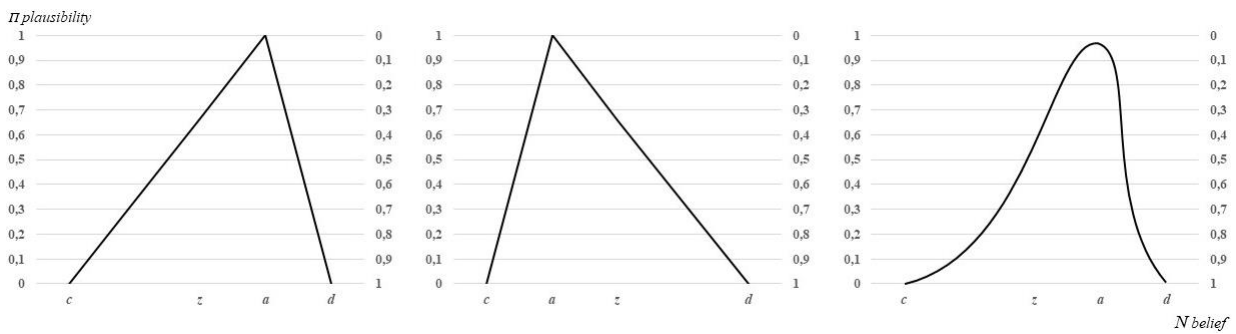


Figure 3.3 - Modelling elicited possibility functions.

Box 2 Representations of imprecise probabilities

Baudrit and Dubois (2006) review different approaches for representing uncertainty within imprecise probability. Modelling imprecise probabilities of the possibilistic approach may result rather complex. It consists in reasoning with a family of probabilities, which is a set of probability functions. One approach for its representation is the use of cumulative distribution functions to depict the upper and lower subjective probabilities of an event (noted \bar{P} and \underline{P} respectively). The interval between these non-intersecting cumulative distributions is called a probability box (See Figure 3.4). Thus, the gap between \bar{P} and \underline{P} contains the set of probability functions of the event and reflects the incomplete nature of the knowledge. When eliciting a triangular possibility distribution, a particular probability box can be drawn by letting the upper cumulative probability function (\bar{P}) rise along with plausibility, then draw lower cumulative probability function (\underline{P}) as belief increases (Figure 3.5).

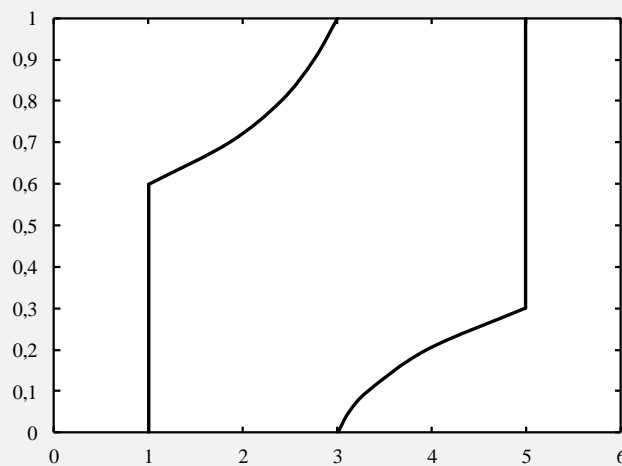


Figure 3.4 - Probability box built for x being a value possible between 1 and 5 with mean 3.

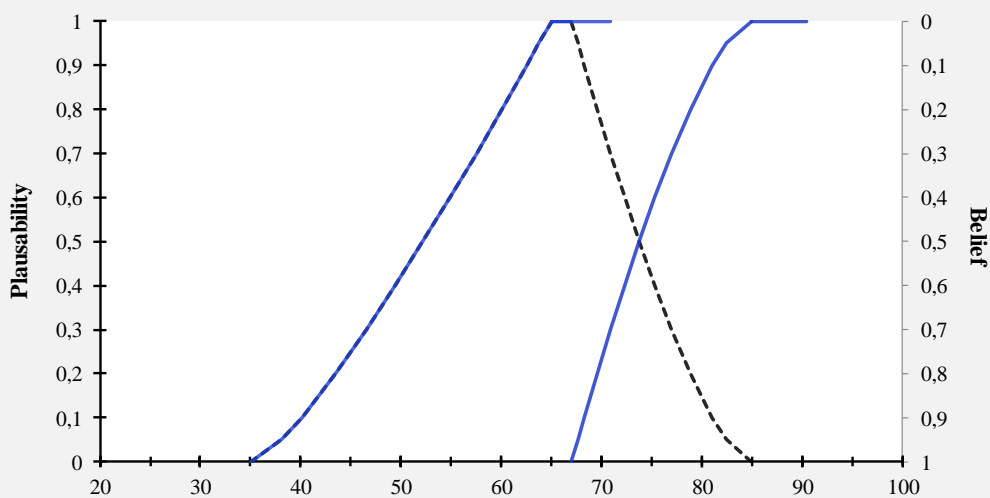


Figure 3.5 - Drawing a probability box with the upper and lower cumulative subjective probability functions from a possibility distribution.

Ranasinghe and Russell (1993) develop a detailed questionnaire to elicit the fifth, 25th, 50th, 75th and 95th fractiles of the subjective knowledge. The questionnaire first asks for the bounds, establishing the minimal and maximal values for x so the probability of exceeding these bounds is as small as to equal zero for practical purposes. Then, the authors proceed to ask for the rest of percentiles, including follow-up questions to clarify the experts thinking about the value of the distribution, and using odds to double-check the consistency of the elicited percentile. Allowing a rather precise modelling of the possibility function (See Figure 3.6), this technique seems an appropriate baseline for elicitation. However, the level of detail clearly depends on the availability of subjective knowledge, and it would naturally tend to a simpler version if the expert were asked to estimate multiple events. As for another thing, the authors argue that beginning by the extremes of the distribution allows minimizing bias of anchoring the center (median) as the plausible value.

Nevertheless, whenever an expert in the field, who works for example on real cases of brownfield rehabilitation contracts, is able to provide intervals (min-max bounds) in terms of depollution costs, but he has no particular information nor judgement concerning the weight of these limits, it can be justified that the preference lies in the center of the range. In the theory of possibility, this preference is explained with the notion of "absence of surprise", in the sense that one will be less "surprised" with values near the center of the range than with values nearing the boundaries. This therefore allows obtaining a triangular possibility distribution which defines a family of probability distributions, limited by the high (Plausibility) and low (Belief) distributions of the Dempster-Shafer theory (1976).

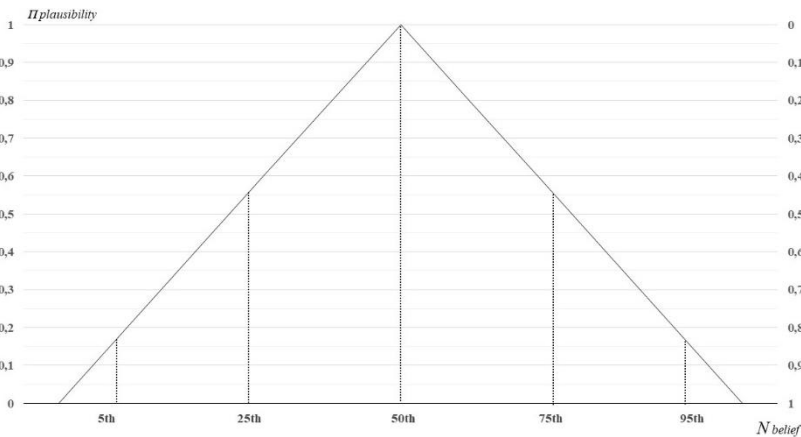


Figure 3.6 - Expert provides bounds and 5th, 25th, 50th, 75th and 95th fractiles.

3.2. Methodology: Expert elicitation of rehabilitation costs

Brownfield rehabilitation entails the set of actions that enables adequate management of risks associated with the site and its future redevelopment. Consequently, this includes accounting for the technical requirements of future land-use. The current research considers eight different future land use activities based on regional planning criteria (see “A30!” in subsection 2.1.1). As aforementioned, site-specific data required for the estimation of rehabilitation costs of the sites of VoCI was only partially available.

In consequence, this research relies on the elicitation of experts' knowledge for the characterization and estimation of brownfields rehabilitation.

All consulted experts were familiar with VoCI case study and come from private or public institutions. First, experts were interviewed to discuss the context of the case study, the goal of the research, and the expertise of the interlocutors. Open questions were oriented to gather any available information on VoCI sites and to understand the expert's view on brownfield rehabilitation costs assessment. Further to these interviews, discussion and a proposition to proceed estimating rehabilitation costs were drafted and validated by the experts. These steps were iterated when modifications were needed. Table 3.1 summarizes the list of experts consulted.

The contact with the experts allowed identifying 4 different sources of rehabilitation costs:

- Decontamination costs, it is relevant whenever the site contains pollutants that endangers human health or environmental safety.
- Soil excavation costs, needed because of soil leveling or underground structure building. This may be required for some future land-uses. VoCI sites contain various types of filling material: some of which are either natural material (alluviums, sand and gravel) originating from the digging required for the creation of the channel of the Rhône River in the 60s, or either man made ground resulting from past industrial activities (having various levels of contamination).
- Demolition costs, relevant when there is at least one building that is no longer suitable for hosting a new activity or if the future land-use requires a site without buildings.
- Costs of soil reconditioning. This is relevant whenever future land-use requires certain soil characteristics (e.g. fertility). Herein we distinguish the generic industrial use from the alternatives that need soil fertility.

Expert	Domain	Institution
1	Land and real estate expertise. In-depth knowledge of the case study.	Public. Grand Lyon
2	Public management expertise. In-depth knowledge of the case study.	Public. Grand Lyon
3	Construction, development and promotion expertise.	Private. EM2C
4	Construction, development and promotion expertise.	Private. VINCI
5	Soil and landscape expertise.	Private. SolPaysage
6	Environment, geochemistry and soil expertise.	Public. BRGM
7	Ecological compensation expertise.	Public. Grand Lyon
8	Provider of phytoremediation essences	Private. Pépinière Soupe

Table 3.1 - List of experts consulted for elicitation.

The decision-tree in Figure 3.7 summarizes how these costs are accounted for within the methodology of estimation. Details on each source of cost are provided in the following subsections.

Methodology for estimating rehabilitation costs

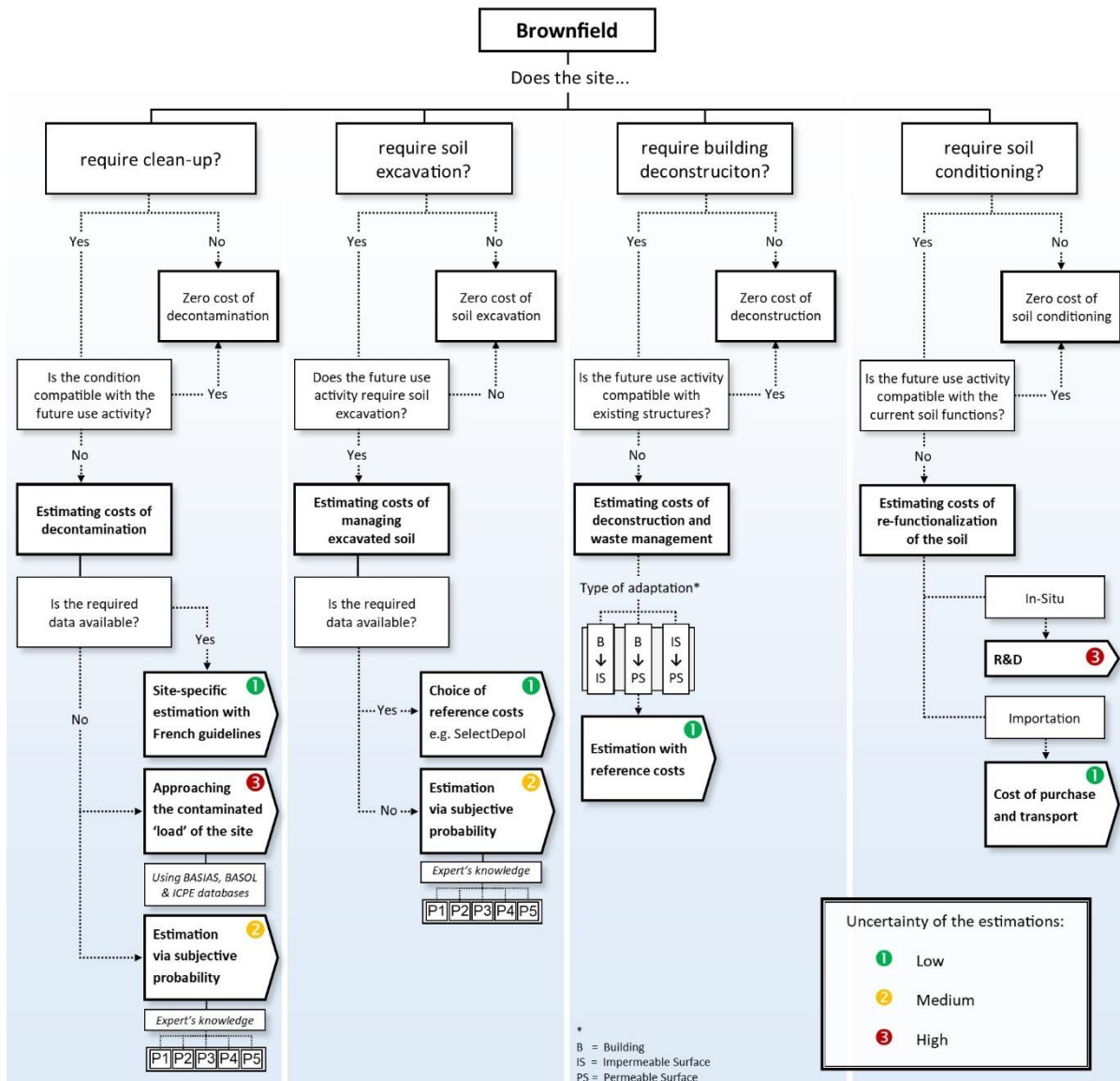


Figure 3.7 - Methodology for the estimation of rehabilitation costs.

3.2.1. Decontamination and soil excavation costs

Brownfield contamination is a result of anthropogenic activities that lead to contamination, its mobilization and its deposition. In past decades, the human health and environmental consequences of contamination had raised a growing attention from government, industry and society. The presence of complex pollutant mixtures requires thorough risks assessment that should typically account for the toxicity, mobility and persistence of contaminants. In addition, such assessment combines the risks from surface and subsurface. The risks of subsurface involving groundwater vulnerability, the analyses need to take into account for migration potential, this depending on solubility, vapor pressure, density,

stability, persistence, and adsorption potential (Kaufman et al. 2005). As toxicity is a critical factor, mobility and persistence are also important as contaminants can migrate to points of human exposure such as surface water or drinking water points, which can be more than kilometers away from the release point (Kaufman et al. 2005). Hence, contamination is considered a threat when it can migrate to the receptors (human or ecological).

Selection of remediation option involves choosing remedial technologies that can achieve remediation objectives agreed with the authorities (for set land use), maximizing sustainability aspects and maximizing the current owner's net benefits. The choice of remediation technique is therefore dependent on the future land-use and vice versa (Tam and Byer 2002).

Box 3. An overview of soil remediation technologies:

1. **Soil washing:** Soil washing uses liquids (usually water, occasionally combined with solvents) and mechanical processes to scrub soils.
2. **Soil vapor extraction:** also known as soil venting or vacuum extraction, is a cost-effective technology for remediating unsaturated soils contaminated with volatile and semi-volatile organic compounds.
3. **Landfarming:** This aboveground technique reduces the concentration of petroleum constituents present in soils through processes associated with bioremediation. It usually involves the spreading of excavated contaminated soils on the ground surface and stimulating aerobic microbial activity within the soils.
4. **Soil flushing:** In situ soil flushing 'floods' contaminated soils with a solution that moves the contaminants to an area where they can be removed.
5. **Solidification/stabilization:** also referred to as waste fixation, reduces the mobility of hazardous substances and contaminants in the environment through both physical and chemical means.
6. **Thermal desorption:** It involves heating soils to temperatures of 100–600 °C so that those contaminants with boiling points in this range will vaporize and separate from the soil. The vaporized contaminants are then collected and treated by other means.
7. **Biopiles:** This treatment involves the piling of petroleum-contaminated soils into piles or heaps and then stimulating aerobic microbial activity by aeration and the addition of minerals, nutrients, and moisture.
8. **Phytoremediation:** Uses plants to clean up contaminated soils and groundwater. This process takes advantage of the ability of plants to take up, accumulate, and/or degrade constituents that are present in soil and water environments.
9. **Bioslurry systems:** It is an ex-situ biological treatment that requires excavation of soil. It combines the excavated soil with water, bacteria and other additives for rapid biodegradation.
10. **Bioventing:** This process injects air into the contaminated media to maximize in situ biodegradation and minimize or eliminate the off-gassing of volatilized contaminants to the atmosphere.
11. **Encapsulation:** Involves physical isolation and containment of the contaminated material. The impacted soils are isolated by low permeability caps, slurry walls, grout curtains, or cutoff walls.
12. **Aeration:** This technology evaporates the volatile components of petroleum from the soil into the air. The contaminated soil is spread thinly and tilled or turned to increase the rate of evaporation.

From Khan et al. (2004), see also Colombano et al. (2012).

During the interviews, an additional issue was noted: site remediation costs not only depended on pollution due to past activities of the site but also on the quality of backfill material (i.e. soils that were brought from other places to level plots) which may represent another source of uncertainty. Some sites received the soil wastes produced during the construction of the channel of the Rhône River in the 60s. However, there is little evidence to confirm if other industrial wastes were also unloaded or not. In some sites, the quality of the soil is so poor that its redevelopment would require excavating and transporting the soil for managing it offsite, and importing good functional soils in replacement. This is why it was

required that the cost of management of excavated soils was elicited separately from decontamination costs. If the excavated soil is simply landfilled elsewhere, this is commonly called dig and dump. This practice is the most common way to manage excavated soils, however, it is not considered as a sustainable remediation technology as it does not enable cleaning of the soils as such as excavated soil is transferred, but not necessarily treated. Whenever the need of excavating the soil overtakes the need of depollution, the former may become the total cost of decontamination and soil excavating. This is not the case the other way around, because some sites may require partial excavation of the soil, and still need decontamination of other surfaces.

The case study being located on an industrial zone, rehabilitation costs are estimated taking as boundary a single “generic industrial” use which encompasses human health and environmental requirements of the different future land-use alternatives studied. This can be justified as long as none of the future land-uses requires the same safety and sanitary standards as housing, schools, or parks. The study therefore proceeds with estimating the decontamination and soil excavation costs of sites for being in adequacy with an industrial use.

Uncertainties were dealt with the inclusion of intervals that afford a certain degree of confidence. Herein the methodology for estimating decontamination and managing excavated costs relies on the possibilistic approach described in the previous section. Box 4 describes a first approach (which was not selected at the end) that intended the use of available information to approach the contaminated ‘load’ of the site, and the second and final approach that classifies sites into a scale that directly sets the intervals of costs for decontamination and management of excavated soils.

Box 4. Approaching the contaminated ‘load’ of the site.

As detailed site-level data was either confidential, unavailable, or out of reach in terms of timing, the second-best alternative was using available data within BASIAS, BASOL and ICPE. These so-called ‘industry databases’ collect information concerning historic activities, potential sources of contamination, and sites that require safety conditions to prevent environmental accidents. The approach consisted in using these databases to gather the available information, establish a scale of ponderation to weigh an approximate ‘load’ of contamination for each site, and then use referential data to estimate the costs of decontamination (e.g. SelecDepol). As long as industry databases do help giving an idea of the environmental state of the sites, the gaps between required and available data were too important. Thus, it seemed that continuing with this approach would had led to uncertain and debatable results. This first pathway was therefore abandoned, which opened space for adopting the possibilistic approach.

Figure 3.8 illustrates the contrast between the data required to carry an estimation using conventional approaches, and the data that was actually available at a regional scale.

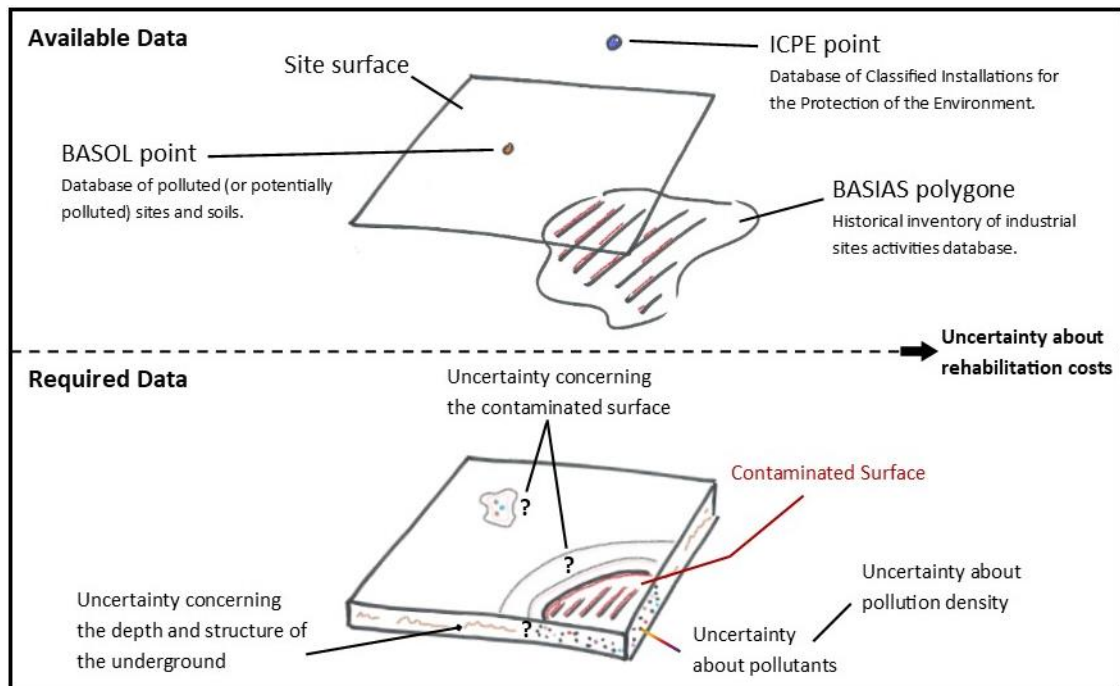


Figure 3.8 - Barriers for the estimation of decontamination costs: available vs required data.

- *Elicitation of costs intervals*

When the approach evolved to expert knowledge elicitation, we found that experts were much more at ease directly estimating intervals for the cost of decontamination than eliciting the levels of contamination. This can be explained due to: 1) the sensitive/confidential nature of the information; 2) reasoning with costs estimations results more intuitive than assessing the multiple issues of decontamination; and 3) the costs of decontamination partially rely on experts responsible for negotiating decontamination contracts.

The procedure consisted in classifying sites within an ad-hoc scale of the environmental state of the sites where each scale is bounded to an interval of cost. This approach relies on the availability of environmental data and the general empirical knowledge of the experts. Each site was characterized with respect to two contamination sources: (1) the presence of pollution originating from past industrial activities; and (2) existence of polluted imported backfill material to be potentially excavated and treated. At the same time, these scales (from 1 to 5) were linked to an approximate range of expected costs. In this way, the expert assesses the environmental conditions qualitatively and use his subjective perception to place the site within an interval of cost. Table 3.2 displays these sensitivity scales. Figure 3.9 displays how this classification was used to work with the possibilistic approach.

Scale	Pollution	Landfills	Decontamination costs
Very low	1	1	0 - 50 000 €/ha
Low	2	2	50 001 - 100 000 €/ha
Medium	3	3	100 001 - 400 000 €/ha
High	4	4	400 001 - 1 000 000 €/ha
Very high	5	5	+ 1 000 000 €/ha

Table 3.2 - Intervals of decontamination and soil excavation costs.

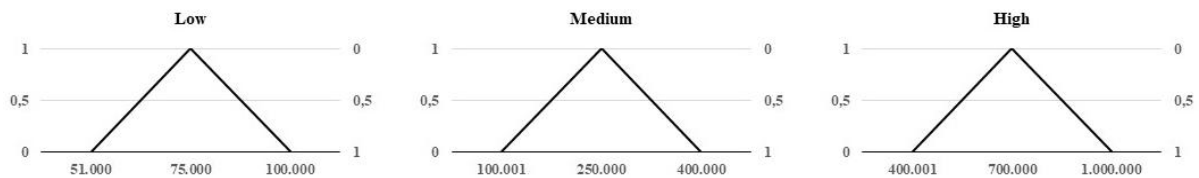


Figure 3.9 – Illustration of the elicited intervals of cost in correspondence with the possibilistic approach.

3.2.2. Deconstruction costs

Building demolition activities are becoming more and more important within the construction industry, which in turn is a significant sector in the economic system globally (Pun et al. 2006). In brownfields redevelopment domain, demolition becomes relevant whenever there are buildings in the site that cannot be further used. This section aims describing the elements that determine the costs of demolition and how this is estimated within the scope of the current research. First, there are three basic kinds of demolition to distinguish:

- Mechanical demolition, which involves directly pulling down the building. Some practices include using excavators, bulldozers, wrecking balls, or explosives. This kind of building destruction is realized in a relatively quick time, but leads to a high amount of unclassified waste, which is more likely to end up in landfills (Pun et al. 2006).
- Deconstruction, involves systematically dismantling buildings while classifying resulting wastes. In consequence, materials can be more easily recycled. It engages a costlier operation in terms of labor. As counterpart, contractors can benefit from the reuse of materials as secondary products (Macozoma 2001).
- Hybrid techniques are a combination of mechanical demolition and deconstruction. Contractors weight high and low demolition costs, timing, and the economic benefits from recycling building materials (Pun et al. 2006).

In order to cope with the environmental sustainability goals, the tendency in France over the past decades is to prioritize deconstruction, which had led to a development on the recycled materials market. On that sense, recent studies show that the benefits of recycling deconstruction wastes can largely offset its costs, and that the negative externalities costs of landfilling practices are not well represented in its costs

(Wang et al. 2018). In the context of VoCI, the liabilities on managing wastes, particularly some hazardous materials, make mechanical demolition not a viable option.

According to Pun et al. (2006) the function of cost of deconstruction ($C_{Deconstruction}$) is determined as in equation 1. Where C_{Admin} represents administrative costs, C_{Labour} refers to the workforce employed, C_{Plant} means the costs related to machinery and transportation costs, $C_{Disposal}$ represents to disposal costs of wastes that are not suitable for recycling, and B_{Reuse} refers to any gain related to recycling materials as secondary products.

$$C_{Deconstruction} = C_{Admin} + C_{Labour} + C_{Plant} + C_{Disposal} - B_{Reuse} \quad (1)$$

For sake of simplicity, the first three elements are hereafter grouped into the cost of service of deconstruction (CService), and the two latter into the costs of waste management (CWM). Accordingly, the approach consists on eliciting price rates for the service of deconstruction and estimating the costs of waste management for the buildings of the brownfield sites. This exercise of assessing the deconstruction costs accounts for buildings and concrete slabs. On the other hand, it bypasses basements and very specific items such as railroads, tower containers, pipelines or chimneys. The major reason being that including such elements would increase the difficulty of the exercise considerably, and it can also be argued that: (1) Basements are rather costly and are usually build for underground car park. Given that VoCI is a rather old and extensive industrial zone where car parks are essentially on the surface, experts signalled that there were probably not many basements structures within the sites. (2) Specific items such as machinery, but also railroads, pipelines and chimneys, are matter of the processes of past activities, therefore these are responsibility of previous users to remove them and, in theory, these should not represent an additional burden for the redevelopment of the site.

All the same, experts also stressed that both components of deconstruction cost (service and waste management) are significantly determined by the presence of asbestos². The issue of asbestos is not only the high cost of confinement (waste management), but also that it is difficult to predict its presence, it can be hidden so it is not accounted for within the preliminary tests, and it may require complex techniques of extraction to ensure the safety of the personal which also results costly (service).

Existing data include cost rates and preliminary studies about deconstruction of some buildings in the zone. Additionally, a reduced number of buildings were effectively deconstructed during this stage of the research (2016-2019). However, the existence and availability of data only concerned very few buildings.

² This is particularly troubling for the aged buildings of VoCI. Asbestos is a material that was widely used over 20th century due to its excellent properties for thermal insulation, but French legislation banned its use for construction purposes since 1997 (Décret N°96-1133) because it has been proved that it entails negative consequences for human health (Selikoff et al. 1964).

In light of what has been said, the methodology used for the assessment of deconstruction costs included three phases:

- 1) Use a simplified approach to identify, classify, and characterize the buildings in VoCI sites.
 - 2) Use referential data and the possibilistic approach to elicit the costs for each component of the deconstruction service.
 - 3) Use existing referential data to estimate the costs of waste management.
- *Characterizing the buildings in VoCI brownfield sites*

Step 1. *Identifying the buildings in VoCI*, buildings were identified using the atlas of sites that was created using the site database as described in the previous chapter. In particular, the identification process relied on the list of buildings of the land register, and observation through aerial view images of the site (Figure 3.10). In total, 384 buildings were identified.



Figure 3.10 - Identification and characterization of buildings in VoCI.

Step 2. *Determining the volume of the building.* The characterization of the buildings included approximating the number of floors through aerial view images observation. The volume of the buildings was then estimated by multiplying the surface by the number of floors of the building (obtaining m² x floor space).

Step 3. Defining a typology of buildings, the idea was to set a classification for which there is referential data available. In particular, the approach consists on using the volume of the building and a grid of material composition by type of building to infer the volume by type of material, which in turn result useful for the estimation of the costs of deconstruction service and waste management with price rates by type of material. Table 3.3 displays two examples of building classification in literature for which there is useful referential data available.

Reference	Building typology	Covered building types
Ortlepp et al. (2016)	Institutional buildings	Non-domestic buildings
	Office and administration buildings	
	Agricultural commercial buildings	
	Factory and workshop buildings	
	Trade and storage buildings	
	Hotels and restaurants	
Rouvreau et al. (2012)	Other non-domestic buildings	All
	Individual housing	
	Collective housing	
	Tertiary and office buildings	
	Industrial buildings	
	Commercial buildings	
	Military buildings	
	Sports buildings	

Table 3.3 - Examples of building classification.

Given that VoCI is an industrial zone, experts mentioned that it was reasonable to limit the classification of the buildings into three types: office and administration buildings, storage buildings (hangar), and industrial buildings (factory and workshops). Noting that industrial buildings usually include some office areas (around 15%). The entire list of identified buildings was preliminary classified through observation, and then corrected and validated by the experts.

Step 4. Establishing a reference of material composition by building type. The indicators were set using referential data provided by Ortlepp et al., (2016). Table 3.4 displays the material composition references.

t/m ² fs (%)	Office buildings		Storage buildings		Industrial buildings	
Plaster, screed, mortar	0,305	12%	0,433	17%	0,35	15%
Concrete	1,285	49%	0,71	28%	0,601	25%
Masonry	0,347	13%	0,629	25%	0,533	22%
Building boards	0,02	1%	0,001	0,04%	0,003	0,1%
Wood, engineered woods	0,053	2%	0,087	3%	0,034	1%
Insulation materials	0,045	2%	0,014	1%	0,011	0,5%
Roof coverings	0,004	0,2%	0,002	0,08%	0,001	0,04%
Floorings, sealing sheetings	0,002	0,1%	0,074	3%	0,124	5%
Other materials	0,398	15%	0,429	17%	0,45	19%
Metals	0,141	5%	0,121	5%	0,293	12%
Total	2,6		2,5		2,4	

Table 3.4 - Material composition indicator by building typology. Expressed in tons per m² of floor space and percentages. From Ortlepp et al., (2016).

- *Eliciting the costs of the deconstruction service*

Consulting experts on deconstruction cost on building-per-building basis was not feasible. Our approach thus consisted in developing a simplified method to estimate the cost of deconstruction service using experts' knowledge elicitation to establish reference values. In some cases, experts were confident to gauge a single reference value, and in others they established intervals of cost. Experts requested to keep references confidential due market competition reasons. The consulted deconstruction service experts deemed more appropriate to classify buildings with predominance of concrete or predominance of metal. A correspondence was made using the building material composition indices (Concrete: Offices, Industrial & Concrete slabs; Metal: Storage).

Step 5. Simplified estimation of deconstruction service costs. The estimation included a correspondence between the volume of the buildings, their composition of materials, and the elicited reference values of the deconstruction services costs. Four stages of deconstruction were taken into account for the simplified approach:

- Stage 1: Organization of the work site including the installation of bungalows for the total duration (meeting rooms, workshops, sanitary facilities).
- Stage 2: Stage of dismantling and selective sorting of the materials that can be recycled.
- Stage 3: Building removal phase. It is necessary to estimate the total time required to carry out the deconstruction. The overall time of deconstruction is optimised minimizing the time of the excavator machine.
- Stage 4: Evacuation and resale of deconstruction wastes. Experts signalled that the resale price rates of metal structures were particularly uncertain.

The elicited reference values that enable the calculations in this step include: cost per day per bungalow; cost of dismantling per m²fs (floor space) by typology of building; pace for the excavator machine by building typology; costs per day for site manager, workers and excavator machine (including driver, tool and diesel); pace and cost of crushing concrete into rubble; pace, capacity, and cost of transport, and resale prices according to type of material (only valuable residuals).

Step 6. Accounting for asbestos, this intermediate step consists on distinguishing buildings constructed before and after 1997. Table 3.5 presents a reference found on literature that provide average ratios that weight the risk of asbestos presence. From the list of buildings built before 1997, experts of the VoCI were asked to identify the buildings for which there is evidence or suspicion of existing asbestos. Experts stressed that the presence of asbestos was the major source of uncertainty within the estimation of deconstruction costs. Finally, experts signalled that it was reasonable to establish intervals of uncertainty whenever the presence of asbestos was identified: lower bound = zero additional cost; upper bound = 25% to 50% additional costs according to subjective perception of the expert.

In % of buildings built before 1997	Asbestos type flocking, insulation and false ceiling		Other materials containing asbestos	
	Average presence rate	Average presence rate of degraded material	Average presence rate	Average presence rate of degraded material
Non-domestic buildings	6,4%	1%	53,1%	11%

Table 3.5 - Average presence rates of asbestos in buildings prior to 1997.
From Michel et al. (2017: 35).

- *Estimating the costs of deconstruction waste management*

Step 7. Reference values of deconstruction waste management costs. As the common practices in France include recycling construction materials, the market for such secondary products are now relatively developed. This step encompasses finding waste management price rates. Table 3.6 shows price references for some recycling chains. Then, an additional table of material composition references was elaborated to establish a correspondence with the costs of waste management chains (Table 3.7). This table was also validated by the experts. The estimation of waste management costs was then easily estimated by multiplying the volume of the materials with the cost references of each chain (average value).

	N*	Median	Average
Chain 1: Concrete, bricks, tiles and ceramic.	62	6,70 €	15,50 €
Chain 2: Mix of inert materials.	120	4,20 €	7,00 €
Chain 3: Mix of non-inert materials.	37	9,30 €	39,10 €
Chain 4: Soils.	20	8,00 €	12,00 €
Chain 5: bitumen and bituminous mixture.	4	4,60 €	8,04 €
Chain 6: Asbestos.	6	122,75 €	154,04 €

* N is the number of collected references for the estimation
Monetary unit: € HT per Ton

Table 3.6 - Price rate references for recycling deconstruction waste materials.
From ADEME (2012).

	Correspondance Table 3.4	Office buildings		Storage buildings		Industrial buildings	
Chain 1:	Concrete						
Concrete, bricks, tiles and ceramic.	Masonry	1,773	68,2%	1,460	58,4%	1,427	59,5%
	Metals						
Chain 2:	Building boards						
Mix of inert materials.	Wood, engineered woods	0,073	2,8%	0,088	3,5%	0,037	1,5%
	Plaster, screed, mortar						
Chain 3:	Roof coverings						
Mix of non-inert materials.	Floorings, sealing sheetings	0,709	27,3%	0,938	37,5%	0,925	38,5%
	Other materials						
Chain 4:							
Soils.		-	-	-	-	-	-
Chain 5:							
bitumen and bituminous mixture.		-	-	-	-	-	-
Chain 6:							
Asbestos.	Insulation materials	0,045	1,7%	0,014	0,6%	0,011	0,5%

Table 3.7 - Material composition indicators by building typology. Expressed in tons per m² of floor space and proportions.

3.2.3. Costs of soil functions reconditioning

Reconditioning soil qualities such as depth, filtration, hydro-morphology, pH, and humidity are only relevant for future uses that require soil fertility, i.e. biomass production, phytoremediation, and urban farm. By contrast, the reuse of brownfields for redeveloping industrial activities does not require soil reconditioning. The estimation of soil functions reconditioning costs includes the following steps:

Step 1. *Characterization of current soil quality indicators for the brownfields of VoCI.* Current soil quality is characterized using the study of soil quality of VoCI made by SolPaysage (2016). The access to the GIS database allowed distinguishing five soil conditions for each site: (1) artificialized soil (concrete); (2) soil with potential to accommodate a limited range of plants with minimum reconditioning effort; (3) soil with potential to accommodate a wide range of plants with minimum reconditioning effort; (4) soil directly suitable to accommodate a limited range of plants; (5) soil directly suitable to accommodate a wide range of plants Figure 3.11.

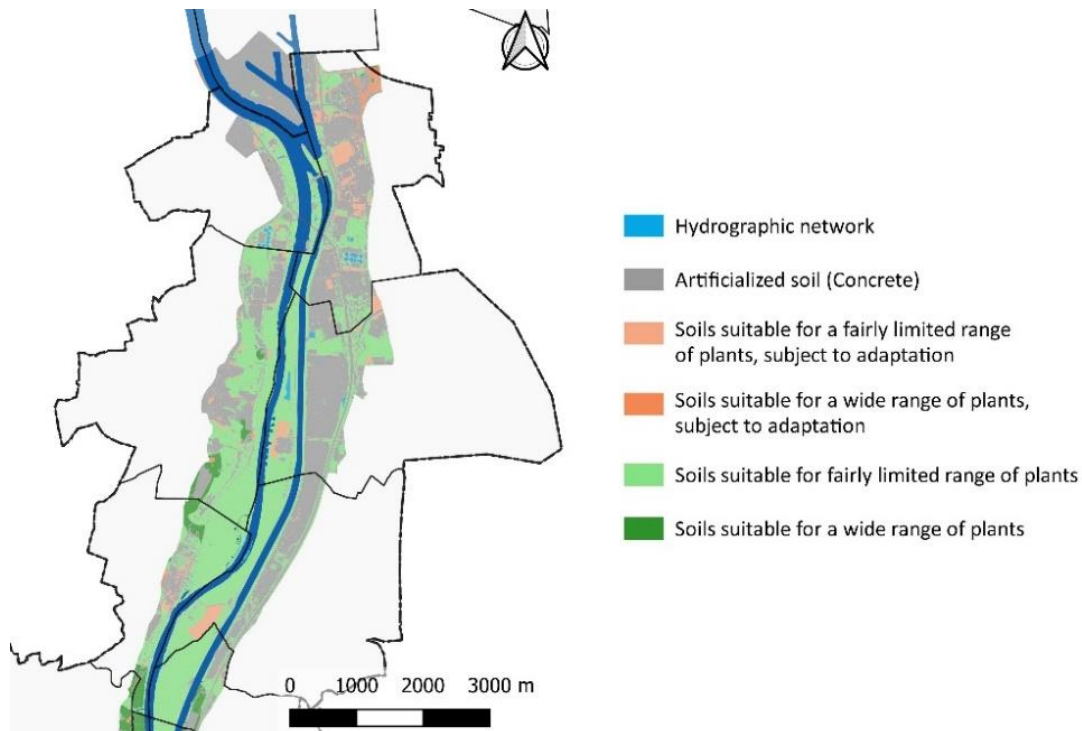


Figure 3.11 - Soil quality database (based on Sol Paysage 2016).

Step 2. Evaluation of the compatibility of future land-use with soil quality indicator. Mainly consists in identifying the species considered in each future land-use³, and then asking the experts to determine which soil quality indicator is required for each species (Table 3.8).

- Biomass production. According to the description of the activity within the framework of A30! and after consulting the experts, three species were selected for the estimation: Acacia, poplar, and willows.
- Phytoremediation. The choice of species for phytoremediation depends on the type of contaminants. To illustrate this future land use activity, the estimation accounts for phytovolatilisation and phyto-extraction. For such types of phytoremediation poplar and willows also happen to be suitable (Pulford and Watson 2003).
- Urban farms. As described in the previous chapter, this future land use activity involves cultivating ex-situ, which does not depend on the soil quality of the site. However, to illustrate the approach an implementation of an in-situ urban farm (i.e. using the soil existing at the site) was also considered, this would involve two technical requirements: the management of health risks (contaminants in soil or groundwater) and good soil fertility. As the stigma of potential pollution may represent an obstacle for societal acceptability on implementing in-situ farms in

³ Some spaces adjacent to the Rhône river in VoCI could be used for ecological compensation by recreating ecosystems that have been endangered or diminished elsewhere. The landscape type of these spaces is known as alluvial forest, for which the species considered include: mesophilic to mesohygrophilous meadow, helophytic and hydrophytic vegetation, and submerged willow.

VoCI, only three sites, exempted of contamination, were included in the analysis. The approach is illustrated with the production of lettuce on these three sites.

Future use activities	Specie	Quality Index 1	Quality Index 2	Quality Index 3	Quality Index 4	Quality Index 5
Biomass	Acacia		✓	✓		
Biomass & Phytoremediation	Poplar			✓		
Biomass & Phytoremediation	Willow			✓		
Urban farm	Lettuce				✓	

Table 3.8 - Compatibility of the considered species concerning the soil quality index.

Step 3. *Establishment of a reference cost for improving soil quality from one index to another.* Two alternatives were evaluated: in situ soil reconditioning, and the importation of fertile soil. However, experts were unable to establish intervals of time and cost for in situ soil reconditioning. They argued that these techniques are still under research and so far experiences varied significantly on each context. Thus, only the importation of functional soil (natural or recycled) was ultimately included in the estimation. Table 3.9 shows costs reference found in literature.

€/ton	Recycled soil	Natural soil
Angers	4,88	22,98
Nancy	10,13	24,19
Paris	4,60	30,35

Table 3.9 - Reference costs of importing functional soil.
From Bataillard et al. (2016: 144).

Experts elicitation included cost references and establishing an interval of the required quantity of functional soil to improve soil quality Table 3.10. Since this implies soil importation, these intervals represent the cost of directly improving soil quality from its initial condition to the required quality without any further calculation.

Required importation of soil		
Lower bound	50 cm deep	≈ 8000 ton/ha
Upper bound	100 cm deep	≈ 16000 ton/ha
Costs of soil importation		
Natural soil	20 €/ton	
Recycled soil	15 €/ton	

Table 3.10 - Elicited intervals of required importation of soil and reference values of costs.

Thus, whenever the soil quality requirements of a future land use activity exceed the soil quality of a site, an interval of soil reconditioning cost is estimated using the lower and upper bounds of required importation of soil and multiplied by a cost of 20 €/ton (current practices) or 15 €/ton if the soil recycling factory is implemented.

3.3. Results

The elicitations and methodology allowed estimating rehabilitation costs for all the identified sites. Although the calculations were internalized within the digital programming of the regional model in GAMS, this section illustrates results by applying the methodology to one site (Figure 3.12).



Figure 3.12 - Site cartographic characterization used to estimate rehabilitation costs.

- *Decontamination and management of excavated soil costs:*

The size of the site is 0,9 ha, and the subjective elicitation of rehabilitation costs for this site is 'very low' both for pollution and landfills. Thus, using the corresponding interval of reference (lower bound: 0€/ha; upper bound 50 000€/ha), the estimation of expected costs is calculated as in Table 3.11.

	Site size	Elicited cost per hectare	Lower bound	Upper bound
Decontamination cost	0,9 ha	[0 – 50 000 €/ha]	0 €	45 000 €
Managing excavated soil cost	0,9 ha	[0 – 50 000 €/ha]	0 €	45 000 €

Table 3.11 - Illustrative estimation of decontamination and excavated soils management costs.

- *Deconstruction costs:*

Due to a commitment to keep parameters confidential, the detailed estimation of the cost of deconstruction service is not shown in this table (but the value has been incorporated in the model database). Table 3.12 shows the estimation of deconstruction waste management costs and the overall information of the deconstruction service cost.

Deconstruction service		Deconstruction wastes management		
Number of identified buildings	4			
Buildings typology	Storage (predominance metal)	Chain 1 Concrete, bricks, tiles and ceramic.	1 786 ton	27 686 €
Overall volume of buildings	103,28 m ² fs	Chain 2 Mix of inert materials.	9 ton	64 €
Expected presence of asbestos	None	Chain 3 Mix of non-inert materials.	98 ton	3 844 €
Concrete slabs surface	3 662 m ²			
Deconstruction service cost	[72 297 – 84 770 €]	Waste management cost		31 594 €
Overall deconstruction cost	[103 891 – 116 364 €]			

Table 3.12 - Illustrative estimation of deconstruction costs.

- *Soil conditioning costs:*

The estimation of soil reconditioning costs is illustrated with regard to a future land use activity requiring a minimal soil quality of index 3 (acacia, poplar, willow). This means that only the surfaces with an index beneath 3 are required to be improved. This estimation is shown in Table 3.13.

Soil quality surfaces		Soil importation	
		Lower bound	Upper bound
Soil quality 1	0,38 ha	3 040 ton	6 080 ton
Soil quality 2	0,13 ha	1 040 ton	2 080 ton
Soil quality 3	0,00 ha	0 ton	0 ton
Soil quality 4	0,40 ha	0 ton	0 ton
Soil quality 5	0,00 ha	0 ton	0 ton
Overall soil importation		4 080 ton	8 160 ton
Natural soil cost (20 €/ton)		[81 600 - 163 200 €]	
Recycled soil cost (15 €/ton)		[61 200 - 122 400 €]	

Table 3.13 - Illustrative estimation of soil reconditioning costs.

Finally, the overall rehabilitation cost of the site can be delimited using an interval built through the addition of lower and upper bounds of each source of cost. For example, if soil conditioning is accounted as in Table 3.13, using the reference value of natural soil importation (i.e. 20 €/ton), the overall expected rehabilitation cost of the site (including all sources of cost) would lie between 185 491 € and 369 564 €.

3.4. Conclusion

The subjective elicitation and cost references approach (i.e. possibilistic approach) can be an effective tool to enable the design and application of a thorough methodology for the estimation of rehabilitation costs at a regional scale. It provided a robust, coherent and unique basis for rehabilitation cost estimation at regional scale.

The approach has allowed the estimation of rehabilitation costs in the form of intervals that account for uncertainty. It is however clear that the estimation of rehabilitation costs intervals at a regional scale can hardly be compared to precise results obtained with site-specific approaches. However, having delimited the uncertainty with intervals can already be considered a progress with respect to the generation of data for each site. In addition, these intervals can be used for further analysis, for example by using random drawings or by setting scenarios (See chapter 6).

This novel approach could benefit of further improvement and development by increasing the number of consulted experts could in order to improve the reliability of the subjective approach, perhaps even generating specialized discussion groups for each step of the estimation instead of individual interviews as it has been the case in this study. In this research, we were grateful to find experts who have great knowledge of the case study as well as of the disciplines concerning rehabilitation costs. Benefiting for the very helpful expert support we had in VoCI could be complex for any other case study with a similar or higher dimension. In this case, additional environmental and technical support may be sought and planned to reach the comprehensive expert level understanding. Nevertheless, the implementation of the approach can still be improved by including more steps, and adjusting the reference parameters.

In conclusion, the development and application of a methodology for the estimation of rehabilitation costs at a regional scale has effectively allowed producing the required data for the modelling purpose of this research. Herein, the participation and validation of experts in the process has been a valuable asset for the study. The next chapter describes the stage of the research addressing the identification and monetary estimation of the benefits of brownfield redevelopment in VoCI.

Chapter 4. Estimating BFR benefits at a regional scale

This chapter focuses on the estimation of the benefits of BFR future land use activities for multiple sites of the VoCI. Standard economic valuation methods rely on assessments conducted at the site level, are often based on surveys (e.g. choice experiments) or econometric analyses of market data (hedonic pricing). They are not adapted to current research which deals with a regional scale and aims to encompass a wide range of benefits. Indeed, the deployment of these methods in several dozens of sites would require human and financial resources beyond the reach of stakeholders. A simpler but robust alternative approach is therefore needed. This chapter presents the result of a reflection undertaken in this direction.

The content of the chapter includes a description of the different types of benefits, a discussion of the methodologies for the economic valuation of BFR benefits at a regional scale, the identification and estimation of benefits of the VoCI BFR portfolio, and lastly, a discussion on the advantages and disadvantages of the approach.

4.1. Methodology

This methodology elaborates on the feasibility of applying the economic valuation methods presented on Chapter 1 to evaluate the benefits of implementing the future land use activities on the brownfields of VoCI as identified in Chapter 2. The main aim is to test an approach that embeds a suitable perspective of replicability.

4.1.1. Multiplicity of benefits, future land use activities and sites

BFR projects generate benefits at different spatial scales, ranging from the project site to the metropolitan territory to which the redeveloped site belongs (Figure 4.1). At the local scale (depicted with zone ① in Figure 4.1), BFR generates direct benefits most often associated with the rise of property values and the creation of added value by the new activities established there (commercial, residential, services, etc.). These are mainly private benefits for the investors of BFR projects. If the site is reconverted into a recreational park, it can generate non-market benefits for the local population who will be able to access this space – often nearby residents (De Sousa 2003).

In the immediate proximity of the brownfield (depicted with zone ②), BFR reduces or eliminates health and/or environmental risks and various nuisances for local residents and workers. This generates indirect benefits, i.e. those that manifest themselves off-site, which often also materialize through a rise of

surrounding property values. Economists have traditionally measured these benefits using hedonic pricing (Haninger et al. 2012; Linn 2013).

BFR projects also generate benefits beyond this scale: they can also contribute revitalizing the economy of peripheral neighborhoods (3), by attracting investment and creating jobs on the periphery of redeveloped areas (Jenkins et al. 2006; Paull 2008).

On the scale of the urban or metropolitan territory (4), BFR makes it possible to densify urban planning, which indirectly avoids the construction of public infrastructures such as water, electricity, sanitation, public transport and road networks, reduces transport costs (Mashayekh et al. 2012), energy consumption and air pollution. When BFR is used to recreate urban ecosystems, it can contribute to the city's climate change adaptation objectives (e.g. controlling urban heat), to ensure the preservation of green and blue ecological spaces, and reduce air pollution (Zhong et al. 2020). Thus, BFR makes it possible to avoid costs, both financial and environmental, which globally benefit the entire population of the metropolitan area.

BFR can also generate environmental benefits outside the metropolitan perimeter (5) by avoiding external urban growth. This contributes to reducing the consumption of natural and agricultural areas, enabling the preservation of numerous ecosystem services associated with these areas.

Finally, BFR can also help eliminating environmental nuisances which, depending on the case, can extend beyond the sites and their immediate proximity (6), as contaminants present in the soil can, for example, migrate through groundwater several dozen kilometers away from the sites, generating diffuse risk in regard to human health and the environment.

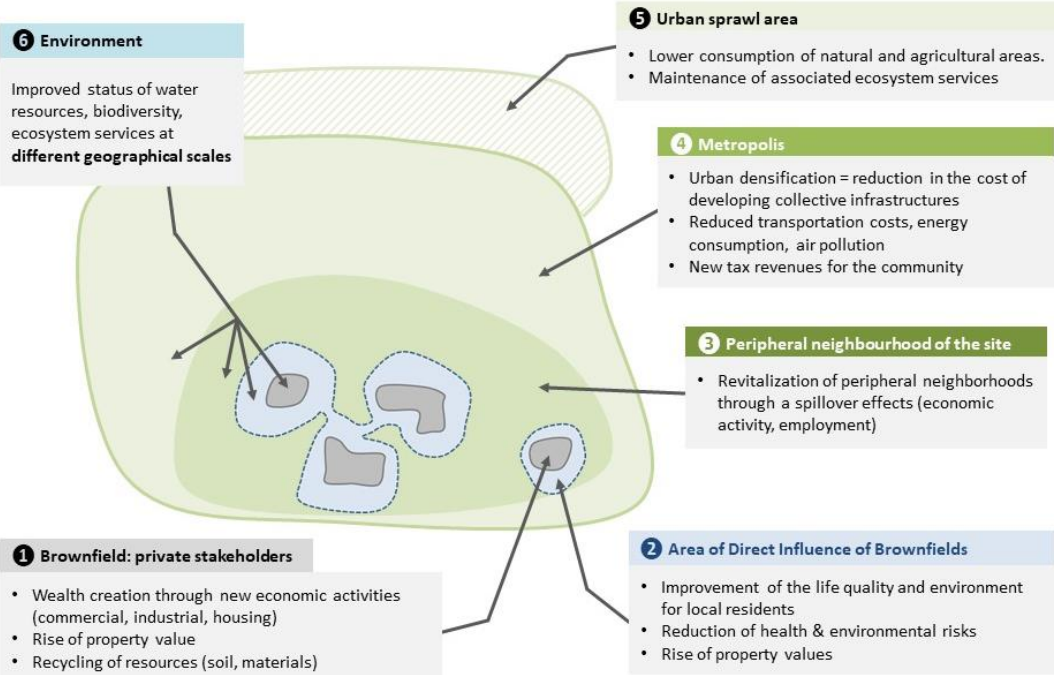


Figure 4.1 - The spatial scales and nature of benefits associated with BFR.

4.1.2. Which economic evaluation methods are suitable for a regional scale approach?

The most widely used method to value the impacts of BFR is that of hedonic pricing (Ameller et al. 2020), which consists on identifying statistical differences between property values impacted by brownfields and others. Hedonic pricing studies are arguably better suited for residential zones due to the number of properties and frequency of transactions. However, property values hardly reflect global BFR benefits such as improved water regulation, reduced GHG emissions or avoided negative externalities of urban sprawl. The hedonic pricing method would not be suited to assess the benefits of BFR in the case study of this research for several reasons: (1) sites considered in the redevelopment program are relatively distant from residential zones ($\geq 500\text{m}$); so their improvement would thus probably not generate significant increase in real estate values; (2) hedonic pricing allows evaluating benefits of projects that have already been implemented (ex-post) while this study needs to evaluate potential future benefits of projects which have not yet been conducted (ex-ante evaluation); (3) benefits have to be evaluated for several benefits in a large matrix of future land use activities and sites.

The second economic method that can be used to value BFR benefits is the avoided cost method (Farber et al. 2002; Christie et al. 2012). An example of avoiding costs through BFR is accounting for the opportunity to reduce urban sprawl. Costs of urban sprawl include expenditures on creating public infrastructure and services, transport costs due to longer distances, GHG emissions, and even health-related costs (Trubka et al. 2010a; Trubka et al. 2010b; Trubka et al. 2010c). For instance, De Sousa (2002) carried a CBA concerning industrial and residential development on brownfields and greenfields in the Greater Area of Toronto. The author concluded that both industrial and residential scenarios resulted in significantly higher net benefits by redeveloping brownfield sites as compared to greenfield development, where transport costs played a substantial role. Other studies indicate that compact city development report savings as high as 20 to 45% in land resources, 15 to 25% in the construction of local roads and 7 to 15% in the provision of water and sewage facilities, as compared to market driven suburbanization (EEA 2006). In a general note, it is clear that avoided costs can help assessing some of the BFR benefits (but not all of them). At the same time, the approach for estimation remains affordable even within the territorial scope, and results can be reliable.

Both property values and avoided costs are known as revealed preferences methods because they use market information to deduce (or ‘reveal’) the monetary value of benefits. On the other hand, stated preferences directly ask individuals to elicit their willingness to pay for a certain benefit. This is the case of the contingent valuation and choice modelling approaches (See Chapter 1). For example, stated preferences approaches have been used to estimate the monetary values of preferences for reducing the human health risks associated to contaminated sites (Alberini et al. 2007a; Tonin et al. 2012). Furthermore, Powell (2002) used a contingent valuation survey to complement results of a property values study on the preferences of proximity to a hazardous waste site. Stated preferences are knowingly useful and well suited to explore non-market values, especially in absence of prior information. Although there is current need to continue carrying stated preferences studies to improve data availability (Ameller et al. 2020), such methods were not suitable for this case study as there exists a significant multiplicity of sites and benefits that need to be evaluated separately. This requirement rules out the relevance of carrying a contingent valuation, and significantly complicates the design and implementation of a choice experiment.

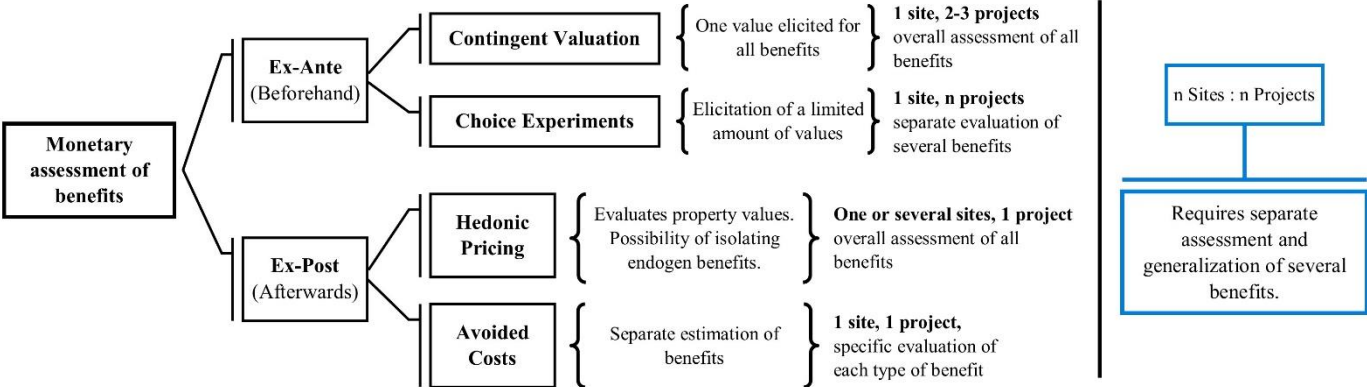


Figure 4.2 - Typology of economic methods used to evaluate the benefits of BFR.

None of the previously described methods is in itself designed to evaluate all the potential benefits of implementing various project alternatives at different sites (Figure 4.2). In consequence, an effort on this scale would require the use of several evaluation methods simultaneously.

4.1.3. Using reference studies and simple benefit transfer functions to assess benefits of multiple BFR projects on multiple sites

The approach used in this study relies on the use of simple benefit transfer functions⁴. Figure 4.3 provides an overview of this 3 steps approach. The first step consisted in identifying the main benefits (b₁ to b_k) that would be generated by each possible future land use activity (j₁ to j_n) on each site (i₁ to i_n).

⁴ Benefit transfer uses economic information obtained at one case study to make inferences about the economic value of environmental goods and services at another place and time. Using this approach, economic estimates are either transferred as monetary value units or as value functions conditioned on explanatory variables that define the attributes of the new case study (Wilson and Hoehn 2006).

This was organised using a set of matrixes -one per site- to represent the expected benefits of each future use activity. Thus, each cell $[b, j]$ taking the value 1 if the concerned benefit is expected to appear with the implementation of a certain future land use activity, and zero otherwise. Step 2 consisted in establishing a coherent way for valuing the benefits of each future land use activity using references in literature and the data obtained from the interviews described in Chapter 2. Finally, the third step consisted in constructing simple benefit transfer functions (as a function of the size of the site) to assess a monetary value for each cell with expected benefits within the matrixes. The resulting matrixes of estimated benefits were then used as input to the optimisation model. The three steps of this approach (identification, estimation and extrapolation) were presented and discussed with the experts of the Metropolitan Council.

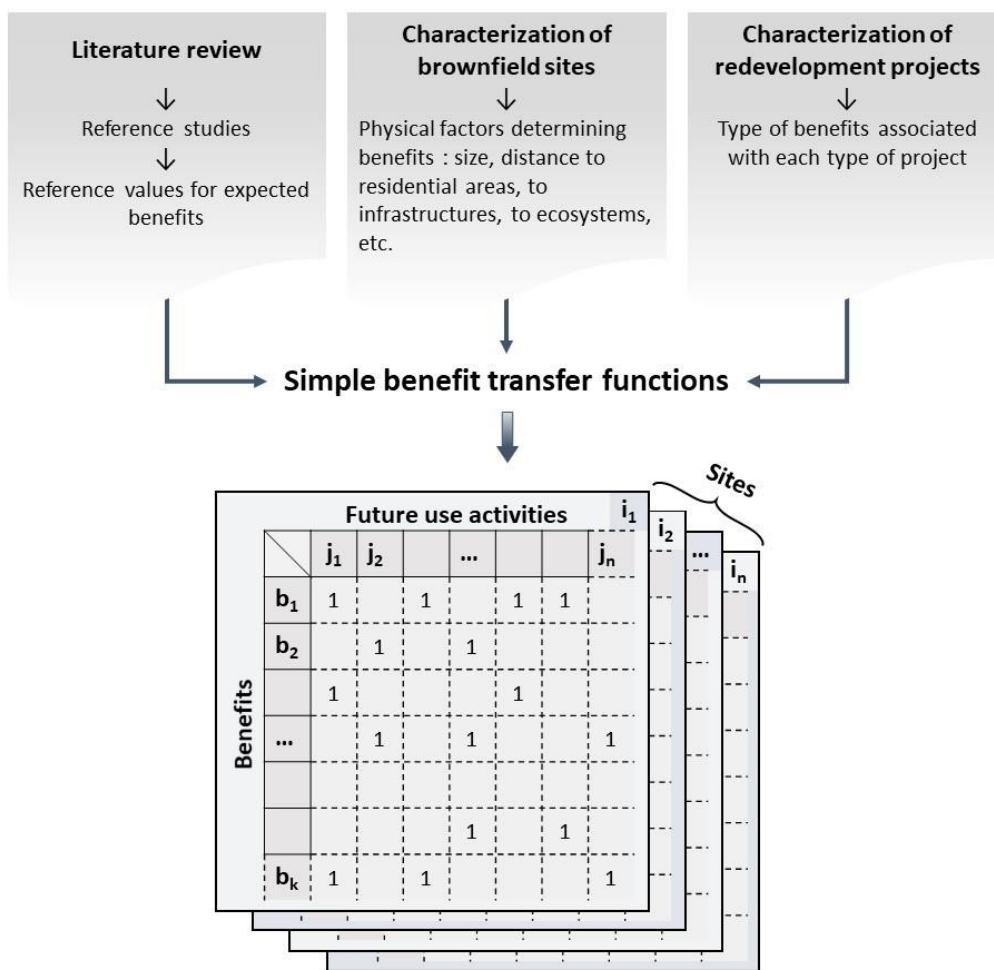


Figure 4.3 The benefit transfer approach and the matrix of expected benefits.

4.2. Results

This section details the identification, estimation and valuation of each type of benefit, using the approach described above.

4.2.1. Identifying the benefits of BFR opportunities in VoCI

Table 4.1 presents and organizes the list of identified benefits of each future land use activity, classifying them into private, social or environmental.

	Soil recycling factory	Biomass growing	Phytoremediation	Urban Farm	Solar energy farm	Biomass energy plant	Big factory	Medium factory	SME
Private benefits									
Private revenues / Added Value	✓	✓	✓	✓	✓	✓	✓	✓	✓
Reduced transport costs	✓	✓		✓					
Biomass recovery		✓	✓						
Image/Reputation*					✓				
Social benefits									
Local tax revenues	✓			✓		✓	✓	✓	✓
Job creation*	✓			✓		✓	✓	✓	✓
Environmental benefits									
Reducing CO ₂ emissions	✓	✓		✓	✓	✓			
CO ₂ sequestration		✓	✓						
Reducing urban sprawl	✓	✓		✓		✓	✓	✓	✓
Water regulation		✓	✓						
Reducing the import of fertile soil	✓								
Biodiversity*		✓							

* Image, job creation, and biodiversity benefits were identified but remained separate indicators with no monetary quantification.

Table 4.1 - List of identified benefits.

The use of in-depth interviews for the qualitative identification of the benefits was a key element of the research. The territorial approach requires accounting for values involving multiple stakeholders. Within the context of an industrial zone as VoCI, this study aims at including all benefits accruing to private investors and the community. For the former, the analysis accounts for the creation of value as an important element for a healthy growing economy. This also allows assessing the financial viability of the activity. As for the latter, this study includes the community by accounting for the budget of public institutions. Certain benefits such as the value of existence of biodiversity, the improvement of aesthetic characteristics of the area, or enhancing quality-life by suppressing nuisances were initially identified as potential benefits, but were later excluded from the estimation because existing reference studies were generally not transferable to the VoCI case study (See Chapter 2).

4.2.2. Estimating Private benefits

The estimation of private benefits of the six first re-use activities include the net revenue for investors which was evaluated using data provided in their proposals to A30! (2018). Reduction in transport costs (avoided cost) and valorisation of biomass as a by-product of phytoremediation are also estimated as side-benefits.

The soil-recycling factory was the only activity with a detailed business plan available, with a detailed financial proposition for a 4.5ha project. Table 4.2 displays the financial flow planning for a period of 20 years and for a private actualisation rate of 6%. For sake of comparison, the total net value is divided by 20 and by 4.5, which equals an average private revenue of 925€/ha/year. The soil recycling expert validated the estimated value explaining that the dynamics of the activity are still at a research and redevelopment stage, for which investors were satisfied with a balanced net value.

As for another example, the installation cost of a solar farm of 100 kWc (minimum 0.5 ha) can vary from €78500 to €120000 excluding taxes⁵. According to the interviews, this alternative reaches financial equilibrium in approximately 12 years and the return rate over investment lays around 3% for a period of 20 years. Mean indicators also help assessing the annual revenue of solar farms, the average capacity of the equipment is 1658.92 kWc/ha, the mean solar energy production in France is 900kWh/kWc, and the reference of market price for solar energy is 0.2617 €/kWh. This adds up to an annual revenue of 390725 €/ha. More information on the potentials of renewable energy on brownfields is available in literature (Adelaja et al. 2010).

The description of the three industrial land use activities is too general to expect any specific estimation of net revenue. Given that urban-planners had an expected density of employment for each category of industrial activity, the statistical indicators of added value and employment were used as proxy for measuring direct private benefits⁶. Current prices of 2016 were actualized to 2019 by a factor of 1.04.

In addition to the expected cash flows stemming from main activities, some redevelopments can produce side-line financial benefits such as reducing transport costs. Implementing a soil-recycling factory, urban farms, or producing biomass in the VoCI help reducing transport distances. Table 4.3 shows how transport costs savings are calculated using production estimations, average distances, and references for fuel consumption and price⁷. Another side-line benefit identified is the recovery and sale of biomass resulting from phytoremediation. Although this practice is usually not the purpose of phytoremediation and its viability is not guaranteed, biomass can be used either for combustion or industrial

⁵ Source : <https://terresolaire.com> – Accessed 10/09/2020.

⁶ Source : www.insee.fr – Slate: ‘6.209D Emploi intérieur total par branche en nombre d'équivalents temps plein’, and ‘6.201D Valeur ajoutée brute par branche à prix courants’ – Accessed 30/07/2019

⁷ Formula and reference values of fuel consumption based on the formation available in: Guide méthodologique ‘Information CO2 des prestations de transport’. Octobre 2012. Ministère de l'écologie, du Développement durable et de l'Énergie. p. 76-82.

transformation. In addition, phyto-extraction may occasionally allow recycling certain chemical components. As for illustration, this study includes benefits resulting from selling biomass for combustion. According to the findings of Witters et al. (2012), phytoremediation (willows) can yield around 5Mg dm/ha/year (4 to 12Mg dm/ha/year), which can be sold for 50€/Mg dm, giving 250€/ha/year.

Year (n)	Annual cash flow	$i=6\%$ $(1+i)^n$	Actual flow
1	- 89 250 €	1,060	-84 198 €
2	- 42 679 €	1,124	-37 984 €
3	21 321 €	1,191	17 902 €
4	21 321 €	1,262	16 889 €
5	21 321 €	1,338	15 933 €
6	21 321 €	1,419	15 031 €
7	21 321 €	1,504	14 180 €
8	21 321 €	1,594	13 377 €
9	21 321 €	1,689	12 620 €
10	21 321 €	1,791	11 906 €
11	21 321 €	1,898	11 232 €
12	21 321 €	2,012	10 596 €
13	21 321 €	2,133	9 996 €
14	21 321 €	2,261	9 430 €
15	21 321 €	2,397	8 897 €
16	21 321 €	2,540	8 393 €
17	21 321 €	2,693	7 918 €
18	21 321 €	2,854	7 469 €
19	21 321 €	3,026	7 047 €
20	21 321 €	3,207	6 648 €
Total net value			83 283 €

Table 4.2 - Financial cash flow of a soil-recycling factory.

The following table presents the main direct financial benefits for the future land use activities considered in the model as well as the assumptions made to value those benefits.

Future use alternative	Primary private benefit	Secondary private benefit
1. Soil recycling factory	Private revenue 83 000 € net cumulated private benefit over 20 years (according to business plan of the company, see table 4.2) 925 € year ⁻¹ ha ⁻¹	Reduced transport costs Δ distance travelled (≈150000 km/year) × average consumption of the reference vehicle (0,27 ℓ/km) × fuel prices (1,51 €/ℓ) 61 155 € year ⁻¹ ha ⁻¹
2. Biomass growing	Private revenue [selling price (30 €/MWh) - cost (18€/MWh)] × yearly production (10 tn/ha) 247 € year ⁻¹ ha ⁻¹	Reduced transport costs Δ distance travelled (≈91 km/year) × fuel consumption (0,3ℓ/km) × fuel prices (1,51 €/ℓ) 42 € year ⁻¹ ha ⁻¹
3. Phytoremediation	Private revenue Δ Rehabilitation costs (Less expensive remediation actions) Site-specific	Biomass recovery Yearly biomass production (5 Mg dm/ha) × value (50 €/Mg dm) 250 € year ⁻¹ ha ⁻¹
4. Urban Farm	Private revenue Average net revenue (5 €/ton) × expected production (4997 ton/ha/year) 24 985 € year ⁻¹ ha ⁻¹	Reduced transport cost Δ distance travelled (≈112000 km/year) × fuel consumption (0,34 ℓ/km) × fuel prices (1,51 €/ℓ) 57 163 € year ⁻¹ ha ⁻¹
5. Solar energy farm	Private revenue Nominal power (1658,92 KWp/ha) × expected performance (900 kWh/ KWp) × expected selling rate (0,262 €/kWh) 390 725 € year ⁻¹ ha ⁻¹	
6. Biomass energy plant	Added value Expected added value (306 885,3 €/FTE/year) × expected number of employees (24 FTE) 7 365 247 € year ⁻¹ ha ⁻¹	
7. Big factory	Added value Expected added value (183 041,6 €/FTE/year) × expected number of employees (17 FTE) 3 111 707 € year ⁻¹ ha ⁻¹	
8. Medium factory	Added value Expected added value (183 041,6 €/FTE/year) × expected number of employees (12 FTE) 2 196 499 € year ⁻¹ ha ⁻¹	
9. SME Small & Medium Enterprises	Added value Expected added value (183 041,6 €/FTE/year) × expected number of employees (20 FTE) 3 660 832 € year ⁻¹ ha ⁻¹	

Table 4.3 - Summary of the private benefits estimation.

4.2.3. Social benefits

During the interviews, the direct social benefits of BFR for the community involving the enhancement of neighbourhood life-quality was considered marginal by the interviewee, as brownfields are nested within a large industrial zone, and their redevelopment only marginally improves the quality of life of residents. Moreover, the literature search did not allow finding any study assessing BFR social benefits for a similar context, which impeded the use of literature references to approximate the value for this benefit.

As discussed on chapter 1, BFR also contributes to social benefits by increasing employment and tax based revenues. For the former, Table 4.4 displays the average ratio of direct jobs creation for each future land use activity as expected by local urban planners. This was not monetized but kept as a separate indicator in the optimisation model (see chapter 5).

	Jobs creation per hectare
Soil recycling factory	0.7
Biomass growing	0.1
Phytoremediation	0.1
Urban Farm	4
Solar energy farm	0.3
Biomass energy plant	24
Big factory	17
Medium factory	12
SME	20

Table 4.4 - Expected job creation per hectare by future land use activity.

- *Increased tax incomes*

Concerning tax-base revenues, this study accounts for local taxes only, which include the real estate taxes (built and not built), the real estate business contribution (CFE) and business contribution on added value (CVAE). The estimation of taxes relies firstly on the relevance of taxes for each future land use activity, this was validated by urban planning administration as shown in Table 4.5. This under the assumption that sites are currently uniquely paying for the unbuilt real estate tax and once the future land use activity is implemented, all the surface is accounted for as built real estate (if it corresponds with Table 4.5). The gain on local taxes is thus calculated by adding the CFE, CVAE and the difference between built (B) and not-build taxes (NB). The estimation of these taxes are detailed in box 5. Table 4.8 displays the final estimation of gain on local taxes for each futures land use activity.

	NB Real estate	B Real estate	CFE	CVAE
Soil recycling factory	✓	✓	✓	✓
Biomass growing	✓			
Phytoremediation	✓			
Urban Farm	✓	✓	✓	✓
Solar energy farm	✓			
Biomass energy plant	✓	✓	✓	✓
Big factory	✓	✓	✓	✓
Medium factory	✓	✓	✓	✓
SME	✓	✓	✓	✓

Table 4.5 - Legal correspondence of taxes according to the urban planning administration.

Box 5. Overview of taxes calculation:

- *Built and Not-Built real estate taxes*

According to the information given by the urban planning managers, the not-built real estate tax (82.19%) can be estimated under the base of a referential rental value of land ($\lambda = 4000\text{€}/\text{ha}$). As for the built real estate tax (37,46%), on top of rental value of land, the calculation also includes the value of the buildings, interest rate (8%), abatement rate (50%), and a revaluation factor of 1.018 (+0.0004 each year). Table 4.6 presents the estimation of building values for each re-use activity using the building standards of A30! proposals and average cost values for each type of building.

	Building type distribution			Building cost value
	%office	%factory	%hangars	€/ha*
Average cost values	1500-3000€/m ² ~2000€/m ²	400-500€/m ² ~450€/m ²	45-100€/m ² ~75€/m ²	
Soil recycling factory	0%	0%	10% **	75 000
Biomass growing	0%	0%	0%	-
Phytoremediation	0%	0%	0%	-
Urban Farm	0%	0%	50%	375 000
Solar energy farm	0%	0%	0%	-
Biomass energy plant	10%	65%	10%	9 925 000
Big factory	20%	50%	30%	12 725 000
Medium factory	20%	50%	30%	12 725 000
SME	30%	60%	10%	17 475 000

*Building cost values approximations are estimated under the assumption that storage hangars have 1 floor, whilst offices and factories have 2 floors.

Table 4.6 - Buildings value approximations according to each future land use activity.

- *CFE*

The real estate business contribution is imposed to the rental value of the building and the land using a revaluation factor of 1.018 (+0.0004 each year), an interest rate (8%), and an abatement rate (30%). The tax rate varies according to the different municipalities, the estimates shown in Table 4.8 account for a referential rate of 28.62% (Municipality of Feyzin).

- *CVAE*

The business contribution on added value is calculated in function of the net benefits of the firm. Table 4.7 shows the legal formula to find the corresponding tax rate.

Net benefit (β)	Tax rate
$\beta < 500\,000\text{ €}$	0%
$500\,000\text{ €} \leq \beta \leq 3\,000\,000\text{ €}$	$0.5\% \times [(\beta - 500\,000\text{ €}) / 2\,500\,000\text{ €}]$
$3\,000\,000\text{ €} \leq \beta \leq 10\,000\,000\text{ €}$	$0.5\% + [0.9\% \times (\beta - 3\,000\,000\text{ €}) / 7\,000\,000\text{ €}]$
$10\,000\,000\text{ €} \leq \beta \leq 50\,000\,000\text{ €}$	$1.4\% + [0.1\% \times (\beta - 10\,000\,000\text{ €}) / 40\,000\,000\text{ €}]$
$\beta > 50\,000\,000\text{ €}$	1.5%

Table 4.7 - Legal formula of CVAE estimation.

	Net Benefit (β) €/ha	Building cost value (C) €/ha	NB Real estate (NBRE)	B Real estate (BRE)	CFE	CVAE	Gain on tax revenue
			$t = 82.19\%$ $\lambda = 4\,000\text{ €/ha}$	$t = 37.46\%$ $i = 8\%$ $r = 1.018$ $a = 50\%$ $(C + \lambda) \times r \times i \times (1 - a) \times t$	$t = 28.62\%$ $i = 8\%$ $r = 1.018$ $a = 30\%$ $(C + \phi) \times r \times i \times (1 - a) \times t$	$t = 0 - 1.5\%$ $\beta \times t$	$BRE - NBRE + CFE + CVAE$
Soil recycling factory	925 €	75 000 €	3 288 €	1 184 €	3 606 €	-	1 502 €
Biomass growing	247 €	-	3 288 €	-	-	-	-
Phytoremediation	-	-	3 288 €	-	-	-	-
Urban Farm	24 984 €	375 000 €	3 288 €	5 679 €	8 414 €	-	10 806 €
Solar energy farm	390 725 €	-	3 288 €	-	-	-	-
Biomass energy plant	7 365 247 €	9 925 000 €	3 288 €	148 776 €	161 474 €	36 826 €	343 789 €
Big factory	3 111 707 €	12 725 000 €	3 288 €	190 731 €	206 350 €	15 559 €	409 352 €
Medium factory	2 196 499 €	12 725 000 €	3 288 €	190 731 €	206 350 €	10 983 €	404 776 €
SME	3 660 832 €	17 475 000 €	3 288 €	261 905 €	282 479 €	18 304 €	559 401 €

Table 4.8 - Gain on tax revenues.

- *Life quality improvements*

A point of impasse was found when trying to assess benefits concerning the quality of life of inhabitants such as: suppression of brownfield nuisances, health improvement, and aesthetic and/or cultural values. The difficulty is that no references were found suitable to transfer the value of these benefits due to the particular context of the VoCI case study.

The literature provides several studies addressing the evaluation of social values. For instance, Letombe and Zuindeau (2001) carried a hedonic pricing study on the districts of Lens, finding that visibility of industrial brownfields may reduce residential property values by 10%. A different model of the same study evidenced that homes increased their value when they were far away from brownfields by approximately 1% for a distance of 100 meters. Similarly, another study concerning transactions of apartments on the city of Angers, found that proximity of green spaces (less than 500m) increased the value of property values by approximately 50€/m² (Choumert 2010; ASTERES 2016). A study carried in Lyon (Roebeling et al. 2017), used a model based on property values to find that brownfield redevelopment can increase real estate (rental) value by around 22% (this varied among a set of scenarios). Social values can also be approached using other valuation methods. Alberini et al (2007b) used a choice experiment to estimate the willingness to pay for clean-up programs for sustained health-risk reductions in Venice, Milan, Bari and Naples. Other literature examples also show how willingness to pay surveys can be used to elicit the recreational values (e.g. implementation of parks and vegetation areas Harnik and Crompton 2014).

However, none of the references found in literature provided values for a context similar to the VoCI case study. In fact, brownfield sites (depicted with ① in Figure 4.4) only represent a fraction of the VoCI industrial zone (②), which means that improvements remain relatively marginal at the level of the whole valley (since most industrial sites and landscapes will in operation). On top of that, brownfields are frequently distanced by more than 500m (③) from residential zones (④), which exceeds the thresholds parameters signalled within the references found in literature. Also, the residential zones and brownfields are frequently separated by some type of physical barrier such as difference in elevation, vegetation, railway lines, or highways (⑤), which also isolates the effects of BFR. It was therefore uncertain to determine whether inhabitants would actually perceive the isolated impacts of BFR or if these impacts would remain mitigated by the overall perception of the industrial zone. In view of this, values concerning life quality improvements were estimated to be negligible.

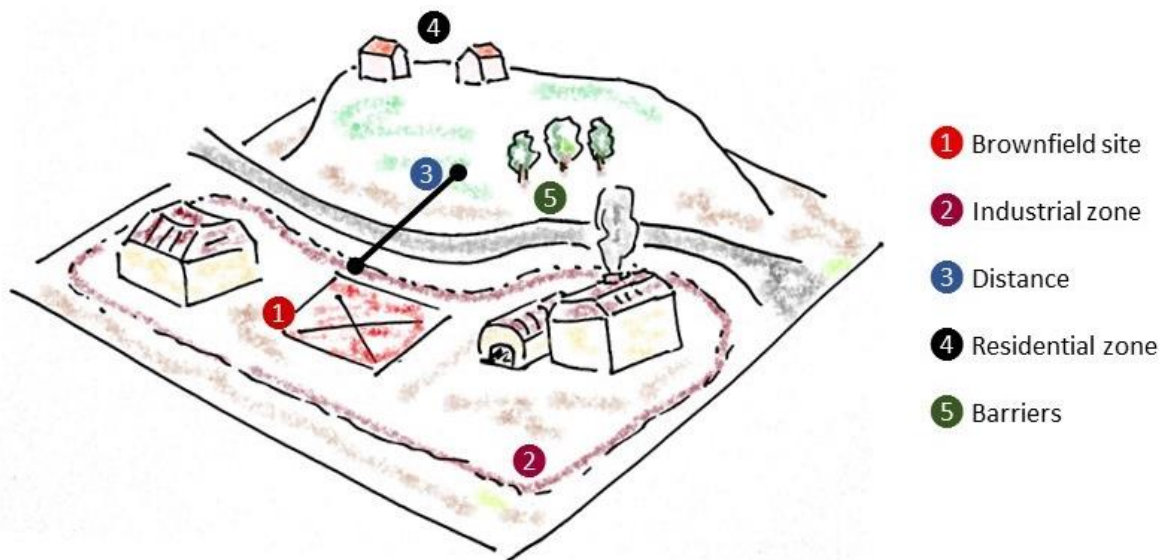


Figure 4.4 VoCI characteristics that condition the evaluation of social values.

4.2.4. Environmental benefits

- *Reduction of net CO₂ emission*

Avoided cost is the conventional approach to value reduction of CO₂ emissions (De Valck et al. 2019). The future land use activities considered for BFR in VoCI offer three different sources for this benefit: CO₂ sequestration from growing plants (Biomass growing & Phytoremediation), lesser emission of CO₂ due to a net gain in comparison to the emissions of traditional energy production (Solar power plants & Biomass energy plant), and lesser emission of CO₂ due to reducing transport distances. Generally, the monetary value for a tonne of CO₂ is estimated from the results of different climate models, the marginal cost of 20 €/ton/CO₂ in 2010 is expected to rise up between 95 €/ton/CO₂ and 320 €/ton/CO₂ equivalent by 2040 (Aertsens et al. 2013). For the scope of the study, the following estimations use a reference value of 40 €/ton/CO₂.

For example, 1 hectare of willow plantation stores approximately 7 ton/CO₂/year in the aerial parts, and 4 ton/CO₂ in the roots, or 0.2 ton/CO₂/year considering a 20-year plantation (INNOBIOMA 2019). If the biomass production is orientated towards energy production (biomass incinerator), this means that the carbon stored in the aerial parts is released during combustion, so only 0.2 ton/CO₂/year are truly being stored. However, producing energy at a neutral CO₂ emission still represents a net gain in comparison to fossil fuel combustion, this allows reducing 15 ton/CO₂/ha/year (INNOBIOMA 2019). In addition, setting biomass growing and incineration in the same territory may reduce the distances of transport between these activities. If the status-quo reference of distance is 50km, knowing that the average distance between sites lays around 4.5 km, the production requires transporting around 15 ton/ha/year, and an appropriate vehicle for that volume emits 156 g CO₂/t.km (MEDDE 2012: 78). Reducing transport distances would avoid an approximate of 0.213 t CO₂ emissions per hectare per year.

One limitation of this study is that benefits associated with reducing carbon emissions and sequestration do not account for other important anthropogenic greenhouse gases (e.g. CH₄ & N₂O; See Forster et al. 2007).

- *Reducing urban sprawl*

In the metropolitan area of Lyon, inhabitants travel in average 3.6 times per day, for which 23 km is the average distance travelled per person per working day (SYTRAL 2016). The corresponding aggregated emissions lay around 1780 t per day, individual emissions are 2.51 kg/day in average for all active individuals, and 4.5 kg/day for individuals that go to work by car (Bouzouina et al. 2013). On this regard, reducing urban sprawl through BFR in VoCI can help avoiding transport costs including expenditures, time, and GHG emissions. Furthermore, urban -planners had no means to estimate ex-ante the travelling times or distances of future employees. Avoided transport costs through reducing urban sprawl was therefore not accounted for.

Notwithstanding, BFR reducing the pressure on greenfields outside the city also allows preserving ecosystem services. In the previously referred study of De Sousa (2002), the author argued that it was difficult to place an economic value on natural regions, and used the value of agricultural lands instead. In 2019, France average agricultural added value is about 1159€ per hectare. For the time being, there are studies that estimate the lower bound of French meadows environmental value between 600 and 1000€/ha/year (Puydarrieux and Devaux 2013: 27; CEV 2019). On top of that, the ratio of greenfields surface saved through BFR is arguably higher than 1, as there is also need for roads and public services. Sherk (2002) place this ratio at 4.5 hectares saved from being converted from rural to urban uses per hectare of BFR, as for industrial purposes, one brownfield hectare redeveloped would protect 6.2 greenfield hectares. This study includes these ratios and a conservative reference value of 600€/ha/year of ecosystem services (Table 4.9). With the exception of the urban farm, as it was expected that one hectare of this activity equals the productivity of 180 hectares of conventional agriculture.

	Factor	Avoided costs
Soil recycling factory	4.5	2 700 €
Biomass growing	1	600 €
Phytoremediation	0	-
Urban Farm	180	108 000 €
Solar energy farm	0	-
Biomass energy plant	6.2	3 720 €
Big factory	6.2	3 720 €
Medium factory	6.2	3 720 €
SME	6.2	3 720 €

Table 4.9 - Avoided costs, preserving Ecosystem Services by reducing urban sprawl

- *Ecosystem Services: Water regulation*

Regulating ecosystem services helps maintaining the quality of air, water and soil. These services are often taken for granted, but when they are damaged, the resulting losses can be substantial and difficult to restore. Regulating services include carbon sequestration, improving local air quality, moderation of extreme events, wastewater treatment, erosion prevention and maintenance of soil fertility, pollination, biological control, and regulation of water flow (Gundimeda et al. 2018). In this regard, redeveloping brownfields into green-oriented activities results in improvements of regulating services (Elmqvist et al. 2015; Cundy et al. 2016; Livesley et al. 2016). Besides carbon sequestration, which has already been addressed, biomass production and phytoremediation are the two future land use activities evaluated in this study that can actively provide other regulating ecosystem services. Table 4.10 recalls the findings of Elmqvist et al. (2015) on the monetary benefits of urban green spaces.

Service	Studies reviewed (n)	Range	Average value (€/ha/y)
Pollution and air quality regulation	9	59 - 2085	641 €
Carbon sequestration (annual flow)	5	57 - 695	391 €
Carbon storage (stock value)	3	1898 - 5127	3 094 €
Storm water reduction	6	609 - 2515	913 €
Energy savings/temperature regulation	4	34 - 1889	1 398 €
Recreation and other amenity services	2	2112 - 10413	6 263 €
Positive health effects	1		18 684 €
Total (excl. health effects and carbon storage)		3180 - 17597	9 606 €

Table 4.10 - Ecosystem services in urban areas. Adapted from Elmqvist et al. (2015: 103).

Water regulation is accounted for by adapting the estimates of McPherson et al. (2005). The authors estimated the avoided costs by virtue of municipal forests in five cities in USA, for which benefits included energy savings, CO₂ sequestration, air quality, storm water reduction, property increase and aesthetics. The estimation adapts low and upper bound estimates concerning water regulation (per tree), which were updated and converted to €₂₀₁₉, giving 2.02 up to 32.46 € per tree per year. Then, these values were aggregated to a reference of 15000 plants/ha. In order to maintain a conservative approach, only the lower bound was taken, this equals 30 300€/ha. As this result concerns a relatively dense vegetation, it is natural that monetary value results higher than the references shown in Table 4.10, which concerns urban forests among others such as parks, gardens, landfills, campus areas, lakes, and ponds.

Ecosystem services concerning air quality, pollution and heat regulation were excluded from the study due to the abovementioned isolation of the sites (previous section). Both activities provide habitat for biodiversity: a small range of species such as rabbits, birds and insects (supporting services). As these species are not particularly rare and would also be isolated from inhabitants, it was considered that the marginal monetary value of option (inheritance or existence) of this service is close to zero.

- *Reducing the use of vegetable soil*

Population growth and the accompanying construction of housing, infrastructure and landscaping generate a high demand for topsoil in Lyon metropolitan area. That demand is currently met with importing fertile soil which often provides from agricultural land stripping. As part of its sustainable development policy, Lyon Metropolitan Council has decided to fully stop the import of agricultural topsoil for all works commissioned or financially supported by the Council. The proposed strategy consists in substituting imported topsoil with artificial soils produced in soil recycling factories located within the boundaries of the metropolitan area. Hence, installing such soil recycling factories in brownfields of the VoCI would reduce the stripping of agricultural land outside the city, preserving ecological services provided by those soils. Soil functions include: biodiversity pool, nutrient cycling, soil formation and water cycling (Jónsson and Davíðsdóttir 2016). These functions support ecosystem services such as biological control of pest and diseases, climate and gas regulation, hydrological control, filtering nutrients and contaminants, recycling wastes and detoxification, biomass production, clean water and raw materials provision, and cultural services. The preservation of natural topsoils in their initial location outside the city thus represent an environmental benefit associated with the construction soil recycling factories in brownfields of VoCI.

Quantifying this benefit has proven to be difficult, mainly due to lack of existing studies that could be used for a benefit transfer approach. The only study found was conducted in China, which sets limits on the possibility to transfer results. Xiao Yu et al. (2003) estimated the conservation value of soils in Qinghai-Tibet Plateau taking into account the protection of soil fertility, reduction of soil disuse and decrease of soil deposit. The final estimates of the authors rise up to 559.01 Million of 2003 Yuan, for saving a total amount of 377 tons of soil, which is roughly equivalent to 0.28 €₂₀₁₉ per ton. Considering that each hectare dedicated to soil recycling stations would avoid the extraction of approximately 14 000 tons of fertile to soil per year. These estimates would set the benefits of soil conservation to 3920€/ha/year.

Given the very specific context of this study, it was considered not possible to extrapolate these results to the VoCI case study. Instead, the reference which assesses at 600€/ha/year the value (lower bound) of ecosystem services of French meadows (Puydarrieux and Devaux 2013: 27) was used to estimate the value of topsoil conservation. Knowing that greenfield stripping yields 4800 tons of vegetable soil (by digging 30cm deep), each hectare of soil recycling station would save 2.91 hectares of greenfields each year, which avoids an environmental cost of 1790€/ha/year.

4.2.5. Aggregation of benefits

The benefits identified in this study have been estimated in monetary values per hectare and per year (with a horizon of 20 years) to enable comparison. Table 4.11 display all the final estimates that were

included in the regional economic model (See next Chapter). Then, the calculations of net present value (as illustrated in Table 4.2) were directly integrated in the script of the model. This includes the available reference costs of investment of each future land use activity, and the discount rates. Following the guidelines agreed with the experts of VoCI, discount rates were fixed at 6% for private benefits, 7% for social benefits, and 4% for environmental benefits. On another note, the aggregation of the benefits estimated in this chapter might contain a caveat for the case of the industrial activities, since the estimation of private benefits is based on added value, there might exist a double counting issue concerning the taxes included as social benefits.

Re-use alternative (Size of reference)	Benefits (€ ha ⁻¹ year ⁻¹)		
	Private	Social	Environmental
1. Soil recycling factory (4.5ha)	Private revenue	Tax revenues	Reducing the use of vegetable soil
	925 €	3690 €	1 790 €
	Reduced transport costs	Job creation	Reducing CO₂ emissions
	61 155 €	0.7 FTE	2 520 €
			Reducing urban sprawl
			2 700 €
2. Biomass growing (10ha)	Private revenue	Tax revenues	Water regulation.
	247 €	- €	30 300 €
	Reduced transport costs	Job creation	Biodiversity
	42 €	0.1 FTE	- €
			Sequestration & reducing emissions of CO₂
		608 €	
		Reducing CO₂ emissions (√ transport distances)	
		9 €	
		Reducing urban sprawl	
		600 €	
3. Phytoremediation (1ha)	Private revenue (√ Rehabilitation costs) Site-specific	Tax revenues	Water regulation.
		- €	30 300 €
	Biomass recovery	Job creation	CO₂ sequestration
	250 €	0.15 FTE	160 €
4. Urban Farm (1ha)	Private revenue	Tax revenues	Reducing CO₂ emissions
	24 984 €	6 062 €	376 €
	Reduced transport cost	Job creation	Reducing agriculture sprawl
	57 163 €	3 FTE	108 000 €
5. Solar energy farm (1ha)	Private revenue	Tax revenues	Reducing CO₂ emissions
	390 725 €	- €	282 480 €
		Job creation	
		0.3 FTE	
6. Biomass energy plant (3ha)	Added value	Tax revenues	Reducing CO₂ emissions
	7 365 247 €	251 458 €	800 000 €
		Job creation	Reducing urban sprawl
		24 FTE	2 700 €
7. Big factory (15ha)	Added value	Tax revenues	Reducing urban sprawl
	3 111 707 €	291 378 €	3 720 €
		Job creation	
		17 FTE	
8. Medium factory (2ha)	Added value	Tax revenues	Reducing urban sprawl
	2 196 499 €	286 802 €	3 720 €
		Job creation	
		12 FTE	
9. SME Small & Medium Enterprises (0.5ha)	Added value	Tax revenues	Reducing urban sprawl
	3 660 832 €	397 925 €	3 720 €
		Job creation	
		20 FTE	

Table 4.11 - Benefits of BFR in Vallée de la Chimie, Lyon.

4.3. Discussion and conclusion

The main methodological challenge addressed in this part of the research was to perform an ex-ante evaluation of the multiple benefits associated with several types of projects that can be implemented on a significant number of sites. The proposed approach consisted of three stages: 1) identifying and characterizing the various benefits of the projects under consideration; 2) identifying economic studies in the literature that have evaluated these benefits in similar contexts; and 3) deducing reference values (standardized) that would allow extrapolation to VoCI case study.

The completion of the work revealed many difficulties at each of these stages, not all of which could be resolved. The first concerns the quantification of the impacts of the BFR projects under consideration. For example, the available expertise was insufficient to specify the characteristics of ecological compensation projects, since these depend on the damaged sites to be compensated (which are unknown in an ex-ante approach). Furthermore, literature does not provide enough reference studies to cover all the types of benefits in contexts comparable to the VoCI case study. In some cases, these contexts were very different from that of the chemical valley and were not transposed (e.g. Chinese study on the use of vegetable soils). Another limitation of the benefit transfer approach is the uncertainty linked to choice when several reference values are available, e.g. the choice of carbon price (40€/ton CO₂), for which market values can be found as low as 5 €/tCO₂, while other studies place a value of 90€/ton CO₂ (See Therond et al. 2017). Finally, the transfer of values had to be carried out in a very crude way - i.e. on a per hectare basis - due to the absence of meta-analysis for more detailed transfer functions, and this even for the benefits best documented in literature. For all these reasons, the results obtained in this chapter are partly unsatisfactory and invite to further research on the use of the benefit transfer approach for BFR benefits at a regional scale (see general discussion at the end of the thesis).

In spite of these limitations, the methodology portrayed in this chapter does exhibit how regional ex-ante approaches can be approached, especially for types of case studies that are well documented in literature. A very recent study also demonstrates that benefit transfer can be viable and helpful to support urban planning decision-making (Chateau et al. 2020). Hence, more site-specific studies valuing the benefits of brownfield redevelopment are required to improve availability of references for regional scale evaluations.

Considering that the evaluation of benefits is only one stage of this PhD research, the core of which is the development of an economic optimization model, these results were presented to the experts of the VoCI redevelopment task force and, although imperfect, were judged overall sufficient to proceed and carry out the methodological development in the field of modelling. This work is presented in the following chapter.

Chapter 5. Designing a regional economic model to optimize BFR

Urban planners may have to deal with a portfolio of brownfields. Hence, BFR management can benefit from a regional perspective. Most of regional approaches include analyses that are limited on determining a priority order. This chapter presents an economic model based on mathematical programming aiming to optimize BFR at a regional scale.

The model is based in the theoretical framework of cost-benefit analysis (Hanley 2001). The main idea is to devise the optimal redevelopment program that maximizes the outcome for society. The model is designed as an ex-ante decision support tool. It relies on a thorough analysis of each site characteristics and its redevelopment opportunities, along with a number of assumptions that help describing the context of the region. BFR decision-making depends heavily on three main stakeholders: site owners, investors, and the governmental authorities, but also concerns funding agencies, consultants, and, often sensitively, near inhabitants (Yousefi et al. 2007; BenDor et al. 2011). The role of our economic model is to find the BFR allocation that maximizes the total net benefit, without looking at the distinctions between the aforementioned stakeholders. This means that the model accounts for private, social, and environmental costs and benefits emanating from BFR (i.e. rehabilitation and future use), and assigns optimal redevelopment options to each site.

The development of this model can result in a useful decision-support tool for urban planners, giving solid economic arguments for defining a redevelopment strategy at the metropolitan (or regional) area. However, it remains clear that such an approach requires significant availability of information in order to assess costs and benefits of various redevelopment options for a large number of potential sites. Regional approach inherently leads too less specificity than site-specific analyses. Nonetheless, we argue that in some cases regional and site-specific analyses should be carried complementarily. Otherwise, we may be overlooking at synergy potential between projects in different sites that could provide extra benefits. This chapter presents the development of the model, tests its validity, and discusses why regional urban planning may enable higher economic outcomes. The empirical application of the model is illustrated on the VoCI case study (See chapter 2).

5.1. Conceptual overview of the model

The modelling framework with the inputs and outputs of the model is shown in Figure 5.1. The inputs of the model are: i) brownfield sites database and ii) database of the future land use activities. The model itself is a set of equations that represent the BFR optimization problem. The objective function of the model maximizes the sum of individual net revenues stemming from BFR at the regional scale, including expected costs (estimated in chapter 3) and benefits (chapter 4). The main decision variable is the

allocation of future land use activities on the sites. This is modelled through constraint equations that define sites-activities compatibility and global constraints set by local policies. As optimization is performed at the regional scale, it enables interaction between sites and activities, and also defining the overall minimum and maximum production of some activities (set by territories needs and demands). The outputs of the model are the optimal allocation of activities to each site and the calculation of the optimum total benefit and others global indicators.

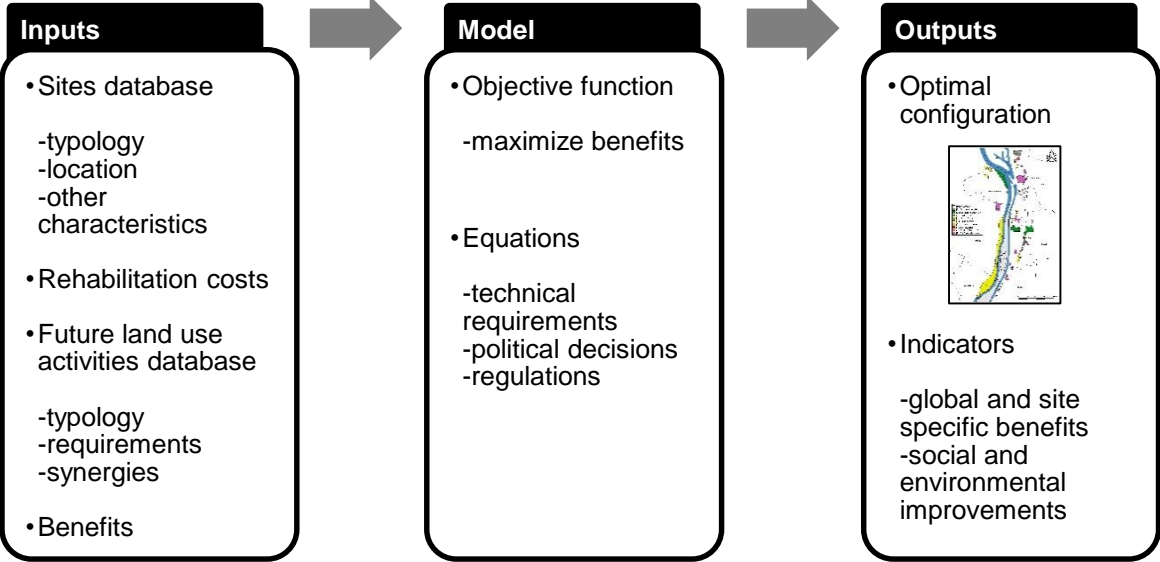


Figure 5.1 - Conceptual structure of the model.

5.2. Model inputs

5.2.1. Sites database

A geographic database of the brownfields is developed to characterize the sites and provide all necessary information to further evaluate redevelopment options. The database includes information concerning site location, size, soil conditions, environmental state, soil permeability, current buildings, availability of industrial services, proximity to residential areas and to the river, and urban regulatory zoning restrictions. The final list of available sites includes 29 brownfield sites and 3 derelict open spaces, but some heterogenous sites were later split into different plots to better depict their specificity. The final version of the database characterizes 71 plots. For more details on the sites database, please see Chapter 2.

5.2.2. The rehabilitation costs

The evaluation of the rehabilitation costs of those sites accounts for four sources of costs: remediation of contaminants, management of excavated soils, deconstruction of existing buildings, and soil

reconditioning. The study allowed eliciting intervals of minimum and maximum rehabilitation costs with triangular distribution for each site (See Chapter 3). The center of the intervals was used to run a deterministic model named the model of reference, under the assumption that the center of the interval would be the less surprising cost. A second phase of the study includes a stochastic analysis to test the sensibility of the outcomes to this uncertainty (See next Chapter).

5.2.3. Future land use activities database

The future land use activities database includes information concerning compatibility requirements such as minimum size, soil conditions, public infrastructure, and urban planning security requirements. Additional information concerning market potential, political preferences, and possible interactions between activities were also described in the database. For more details on the characterization of the redevelopment alternatives, see Chapter 2.

5.2.4. Redevelopment benefits

The identification and monetary valuation of the benefits of BFR in VoCI presented in chapter 4 includes the expected private revenues, taxes, and environmental values generated by the envisaged future use activities. These benefits were then aggregated and discounted over an implementation of 20 years. The net present value per hectare of each activity was thus included in the CBA of the model.

5.3. The Model

The model optimizes the allocation of space for the implementation of future land use activities in each site. The decision variable of the model, expressed in hectares, is noted X_{ij} , where i represents the site, and j the future land use activity. The model includes the use of a binary variable noted ρ_{ij} that activates X_{ij} when constraints related to that activity are satisfied. In this regard, the model uses the auxiliary variable Y_{ij} . Hence, the decision variable is defined as shown in equation 1, where ρ_{ij} is the aforementioned binary variable.

$$X_{ij} = Y_{ij} * \rho_{ij} \quad (1)$$

5.3.1. The objective function

The objective function of our regional brownfield redevelopment model is designed to find the optimal allocation of redevelopment (X) considering j future uses, for all available sites (i) at the regional scale of VoCI. This is obtained from the maximisation of the total net benefit Z , which is the sum over the net benefits (benefits minus costs) resulting from costs (C) and benefits (β) of brownfields redevelopment

on a 20-year horizon. This cost benefit analysis assumes that rehabilitation costs are one time immediate expenditures, estimated for each site (C_i), whilst benefits are yearly incomes, estimated for each redevelopment option (β_j), for which 20 years were actualized to present value.

Note that there are different ways of formulating the objective function. For example, if we assume that each site owner takes his decision independently from others (individual maximisation approach), by maximising his own net benefits in his site, the objective function writes as shown in equation 2.

$$\sum_i MAX (Z = \sum_j [X_{ij}(\beta_j - C_i)]) \quad (2)$$

If we assume that a regional planner takes the decision (regional maximisation approach), or if there is perfect cooperation between all individual site owners, the objective function writes as shown in equation 3.

$$MAX (Z = \sum_i \sum_j [X_{ij}(\beta_j - C_i)]) \quad (3)$$

As aforementioned, a regional maximisation approach can also include adding benefits stemming from synergies or interactions (noted δ) between X_{ij} . A synergy means that the total net benefit stemming from two redevelopment projects X_{nm} and X_{tk} implemented jointly is greater than the sum of their individual benefits. The objective function shown in equation 4 includes the possibility of synergies, whose value is subject to certain conditions.

$$MAX Z = \sum_i \sum_j [X_{ij}(\beta_j - C_i + \delta_{ij})] \quad (4)$$

Furthermore, the objective function can be formulated differently to account for different regulatory contexts. This is illustrated with a simplified situation depicted on Figure 5.2, which displays three situations, the boxes represent three different sites, the yellow area represents the allocation of a future use (generating benefits), pattern filling represents the area remediated (generating costs), and empty represents unchanged areas.

In situation depicted in row A, the regulation imposes that redevelopers entirely decontaminate the sites they want to redevelop, irrespective of their plans to develop new activities (even if it is only on a fraction of the site). So the decontamination cost is fixed and the model simply looks for activities that generate the higher total benefit possible, as shown in equation 5.

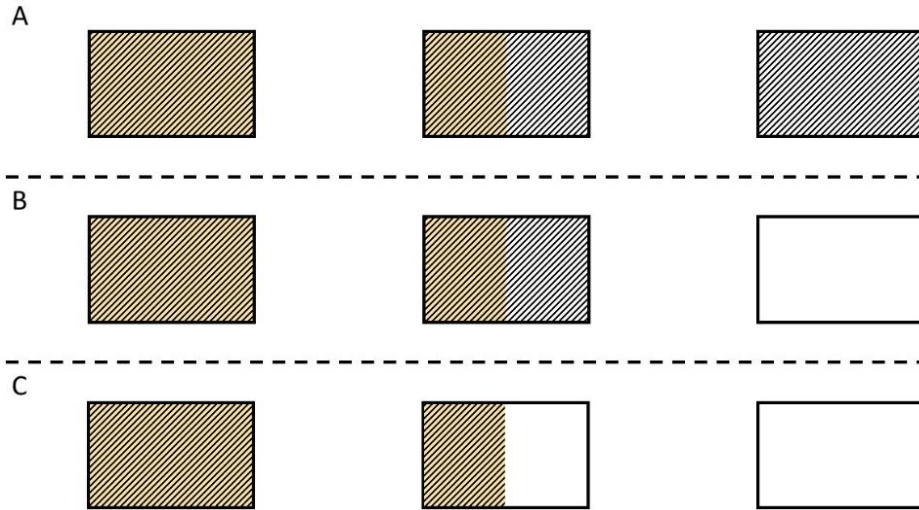


Figure 5.2 - Illustration of different brownfield rehabilitation decision-making situations.

$$MAX (Z = \sum_i \sum_j [X_{ij}(\beta_j + \delta_{ij}) - C_i]) \quad (5)$$

In situation B, the regulation imposes that the entire site is decontaminated if redeveloped, irrespective of the size of the new activity. In this situation the objective function includes a binary variable (φ) denoting the activation of such site and therefore its rehabilitation cost (equation 6). Where φ_i would be defined in an auxiliary equation (Eq. 7)

$$MAX Z = \sum_i \sum_j [X_{ij}(\beta_j + \delta_{ij}) - \varphi_i(C_i)] \quad (6)$$

$$\varphi_i \in \{0,1\}, \text{ and } \varphi_i = 1 \leftrightarrow X_{ij} > 0 \quad (7)$$

In situation C, the regulation only requires decontaminating the portion of the site that will be redeveloped, the rest can remain in its initial (polluted) condition. Put differently, only the surface that is allocated for future re-use (X_{ij}) needs to be rehabilitated. Within the context of the VoCI, the objective function corresponds to situation C, which is expressed in equation 8. Where $Size_i$ is the size of each site.

$$MAX Z = \sum_i \sum_j [X_{ij}(\beta_j - (C_i/Size_i) + \delta_{ij})] \quad (8)$$

5.3.2. The constraints

Whereas the objective function determines the use of X_{ij} as a decision variable to maximize the total benefit, other equations are required to constraint the allocation as ‘shaping’ the reality of the case study.

- *Size constraints*

Allocations (X_{ij}) need to be limited to the size of the sites. In parallel, allocations need to respect the minimum sizes to satisfy technical requirements of the different activities. The allocated area is thus constrained in two different ways, as shown in equations 9 and 10.

$$\forall i \sum_j X_{ij} \leq Size_i \quad (9)$$

$$\forall ij Y_{ij} \geq RSize_j * \rho_{ij} \quad (10)$$

where

X_{ij} is the area allocated of activities j in sites i .

$Size_i$ is the size of each site.

Y_{ij} is an auxiliary variable also representing the surface of allocated activities on each site.

$RSize_j$ is the minimum size determined as a technical requirement for each activity.

ρ_{ij} is a binary variable that activates the right-side constraint in equation 10, if $X_{ij} > 0$.

Clearly, all combinations of activities and sites entailed in X_{ij} cannot always be higher than the technical requirements and lower than the sites size at the same time. For instance, if the total area of a small site is designated to produce solar energy, this automatically means that there is no room for allocating other activities. This is why one of the equations is controlled by ρ_{ij} . Thus, $RSize_j$ is only really required whenever ρ_{ij} equals 1, and since X_{ij} is also determined by ρ_{ij} (Eq 1.), the model will seek to assign $\rho_{ij} = 1$ in order to maximize the allocation.

- *Compatibility constraints*

Technical requirements were identified, discussed and validated with project managers and urban planners of the case study. A set of equations was then implemented to control the allocation of BFR in accordance with site-activity compatibility. Practically, both sites and activities databases included parameters defined within discrete scales, and allocations were conditioned to satisfy compatibility requirements. For instance, sites accessibility was described as low (0), intermediate (1), or good (2) in function of the site distance to highways, whether it was surrounded by transport facilities (bus or train stations), or it was enclosed within intricate locations. In turn, some future land use activities such as solar farms required low accessibility, whereas soil recycling stations and incineration plants required good accessibility mainly to facilitate truck traffic (Eq. 11).

$$\forall ij \quad A_i \leq ARq_j \rightarrow X_{ij} = 0 \quad (11)$$

in which

A_i is the parameter characterizing accessibility for each site i .

ARq_j is the parameter describing accessibility requirement for each activity j .

The same logic is applied to all compatibility conditions. Namely, rehabilitation requirements, distance to the river, distance to residential zones, electricity lines, and existence of pipelines (chemical products, gas, or hydrocarbon). The complete list of compatibility equations is given in the Appendix A.

- *Energy production constraint*

Given that two of the activities are orientated towards renewable energy production, the model includes specific constraint equations that bound minimum and maximum production of energy. Authorities stressed that a minimum production of energy is mandatory because the life-span of one of the Lyon's electrical power plants will soon come to an end, generating need for energy supply exceeding demand, therefore an upper-bound is also needed (especially knowing that the estimations of benefits for these activities are relatively high so the model might maximize energy production activities). Equations 12 and 13 set the boundaries of energy production of the territory, where the parameter ' $ProdE_j$ ' denotes the energy production capacity per hectare for each activity, ε_{min} was set to 20 MWh and represents the minimum production required and ε_{max} denotes the maximum (70 MWh).

$$\sum_{ij} X_{ij} * ProdE_j \geq \varepsilon_{min} \quad (12)$$

$$\sum_{ij} X_{ij} * ProdE_j \leq \varepsilon_{max} \quad (13)$$

5.3.3. Inclusion of spatial considerations and synergies

The equations described hereafter specify if certain activities are restricted to a certain zone of the site (due to risk management and associated restrictions). To cope with this, the different zoning categories, noted p , are included within the definition of the auxiliary variable of the model (Y_{ijp}), so that Eq. 1 is replaced by equation 14.

$$X_{ij} = \sum_p Y_{ijp} * \rho_{ij} \quad (14)$$

Synergies are defined as the creation of a whole that is greater than the sum of its parts. Within the model, this means that the interaction between sites and activities can enable the creation of a higher total benefit. In this regard, developing a regional model makes it possible to include some type of

interaction. From a theoretical perspective, it can be argued that if analysed separately, each stakeholder will choose the higher return over investment alternative for his own site, but interaction between actors can bring pareto improvements that can justify changes in decision-making. Within the context of the case study, we identified three types of interactions, these stem from interaction between activities, interactions between sites and activities, and interactions between sites.

- *Industrial risk zoning constraint*

Some of the factories within VoCI industrial zone represent a source of technological risks (e.g. explosion). For this reason, public administration enforces a regulatory industrial risk zoning to prevent accidents. Sites can therefore intercept different risk zones with different regulatory constraints that allow (or not) some activities (See Figure 5.3).

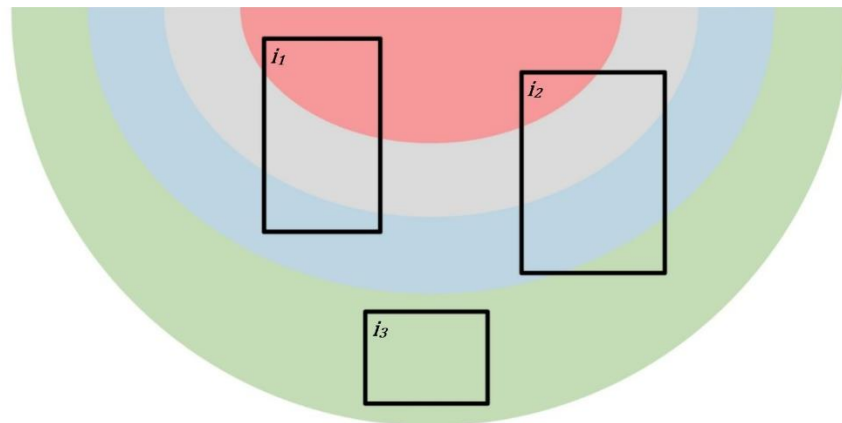


Figure 5.3 - Illustration of sites (squares) within urban regulating zones (coloured areas).

To deal with this, the maximum size constraint (Eq. 9) needs to be adapted. To do this, we have subdivided each site “*i*” in sub-site which are homogeneous in terms of risk zone. Allocation size can be defined and restricted according to the sites sub-surfaces and its regulation zone classification as shown in equations 15 and 16.

$$\forall ipj \quad Y_{ipj} \leq SizeTP_{ipj} \quad (15)$$

and

$$\forall ip \quad \sum_j Y_{ipj} \leq SubSurfacesP_{ip} \quad (16)$$

In Eq. 15 the allocation of BFR activity is specified to the scale of sub-surfaces, and its upper bound is restricted to $SizeTP_{ipj}$, which is the size of surface of each site (*i*), compatible with each activity (*j*) in regard to the tolerance with the regulating zones (*p*). In turn, Eq. 16 allows avoiding double-counting

zones (p) which may be compatible with more than one activity. Thus, the sum of the space allocated activities in each site subsurface, cannot be higher than the size subsurface itself ($SubSurfacesP_{ip}$).

To illustrate this constraint, Table 5.1 displays the zoning parameter for 3 hypothetical sites. Let activity j_1 be compatible with zones p_1 and p_2 , and j_2 be compatible with p_1 only. Eq. 15 implies that allocations in site i_1 are bounded up to 0.5 hectares for j_1 ($p_1 + p_2$), and 0.3 hectares for j_2 . Eq. 16 complements the constraint by bounding the sum of allocations up to the size of the subsurface, meaning that $j_1 + j_2$ cannot be higher than 0.3 in the green zone of i_1 .

		<i>p</i> Zones				Total Size
		p_1 : Green Zone	p_2 : Blue Zone	p_3 : Grey Zone	p_4 : Red Zone	
<i>i</i> Sites	i_1	0.3	0.2	1	0.5	2
	i_2	1	0	0	0	1
	i_3	0.5	1	0	1.5	3

	i_n

Table 5.1 - Sub-zones size control parameter.

- *Activity-to-activity synergy*

Two main interactions between activities were identified. First, between biomass production and the incineration plant, where the former enables a significant part of the latter environmental benefits. The carbon sequestration impact of biomass growing was estimated at 600€ per hectare per year, and becomes neutral if we consider that this biomass becomes fuel for the incineration plant. However, by using locally produced biomass instead of fossil fuel energy, the incineration plant reduces CO₂ emissions as compared to emissions using fossil fuel alternatives. This CO₂ emissions reduction was estimated at 800k€ per hectare per year. It depends on whether the biomass is produced for this purpose or if it is entailing deforestation. Moreover, biomass growing does not need to happen in VoCI in order to enable this benefit. Within the model, interaction between biomass growing and incineration plant will be taken into account by dedicating a set surface area of biomass growing to feeding incineration plant (minimum 5 hectares).

Interaction between activities were modeled using binary variables. For instance, the binary variable ' $B_{\delta 1}$ ' activates the benefit stemming from reducing CO₂ emissions by using biomass as compared to fossil fuel alternatives ($\beta_{j_6_CO_2} = 800k \text{ €/ha/year}$). Equation 17 determines that $B_{\delta 1}$ can equal 1 only if the sum of allocations of j_2 within VoCI is higher than 5 hectares. Complementarily, equation 18 activates the benefit whenever $B_{\delta 1}$ equals 1.

$$5 * B_{\delta 1} \leq \sum_i X_{ij_2} \quad (17)$$

$$\delta 1_{ij} = X_{ij} * B_{\delta 1} * \beta_{j6_CO2} \quad (18)$$

Following a similar logic, the second activity to activity interaction entails that the existence of a soil recycling plant can reduce soil reconditioning costs of other activities that can be implemented in other sites. The model assesses whether the allocations require soil reconditioning, which is generally true for biomass growing and phytoremediation in sites with poor soil quality, and adjusts this cost when maximizing the overall net benefit. On average, the soil conditioning cost parameter equals 20€/Ton ($Px_{Soil} = 20$), and can be reduced to 15€/Ton if using the output of the soil recycling plant ($Px_{j1_{Soil}} = 15$). In addition, the parameter eSQ_{ij} denotes the expected soil quantity that needs to be reconditioned for each site (i) taking into account soil quality requirements of each activity (j). Thus, costs due to soil conditioning ($\delta 2_{ij}$) are estimated as shown in equation 19, where the binary variable ‘ $B_{\delta 2}$ ’ determines which price needs to be activated. In turn, equation 20 determines that the binary variable ‘ $B_{\delta 2}$ ’ can equal 1 only if the sum of allocations of j_1 within VoCI is higher than 5 hectares (half an hectare more than $RSize_{j_1}$).

$$\delta 2_{ij} = -eSQ_{ij}[Px_{Soil}(1 - B_{\delta 2}) + Px_{j1_{Soil}}(B_{\delta 2})] \quad (19)$$

$$5 * B_{\delta 2} \leq \sum_i X_{ij_1} \quad (20)$$

- *Site-to-activity interactions*

This interaction basically denotes that even if two sites are compatible with an activity, certain characteristics can make one site more attractive than an other (due to reduced installation cost for instance). Thus, if choices need to be made, this enables the model to allocate on optimal sites so the overall benefit is being maximized. In practice, the incineration and the industrial factories benefit from the existence of the industrial pipelines network. Hence, even if the presence of such industrial infrastructure is not required to determine compatibility, it may represent a bonus benefit (or avoided installation cost). Urban planners we interviewed confirmed that firms often invest to connect their factories to this type of industrial infrastructure, for which the costs can reach a million euros per kilometer. For sake of simplicity, the analysis assumes that all factories connect to the pipeline network. Therefore, the proximity to the pipelines is accounted as a bonus due to avoided costs.

This interaction is modeled using a discrete parameter (τ_i) describing whether sites contain the required pipelines ($\tau_i = 2$), are in proximity (Distance < 150m $\rightarrow \tau_i = 1$), or relatively far (Distance > 150m $\rightarrow \tau_i = 0$). In return, the discrete parameter $R\tau_i$ describes whether activities require pipelines ($R\tau_j = 1$) or not ($R\tau_j = 0$). As connection costs go up to a million euros per kilometer, the value of the pipeline network proximity ($\delta 3_{ij}$) can be roughly defined in function of τ_i using a referential value of 150,000€, whenever pipelines are required (See Eq. 21). As in the objective function synergies are ultimately multiplied by the decision variable (Eq. 8), the required size for activities is included in equation 21 to

provide the synergy with dimensional relativity. Thus, if there are multiple activities in one site, each allocation would separately benefit from this interaction. This is also valid if the model allocates relatively large areas to a single activity, as it can arguably be interpreted as multiple investments of the same activity within a single site.

$$\forall ij \quad \delta 3_{ij} = \frac{150,000 * \tau_i}{RSize_j} \leftrightarrow R\tau_j = 1 \quad (21)$$

Conversely, sites can also be compatible but relatively unattractive. The industrial zone of VoCI is regulated by zones aiming to prevent technological risks. These zones can determine site-activity compatibility or demand for extra safety measures such as reinforcement of building, airtightness of buildings, etc. Thus, in certain cases, the redevelopment of a site i with an activity j can be possible but requiring extra investment. Extra-cost in building constructions due to safety measures vary from 10% to 20% according to the zones.

These extra-costs in building constructions due to safety measures ($\delta 4_{ij}$) can be modelled as in equation 22, which uses the approximated value per hectare of investment in buildings construction for each activity ($BuildingCost_j$), adding 10% if it concerns p_3 , and 20% if allocations happen in p_4 .

$$\forall ij \quad \delta 4_{ij} = - \left(\sum_{p_3} Y_{ipj} * BuildingCost_j * 0.1 \right) - \left(\sum_{p_4} Y_{ipj} * BuildingCost_j * 0.2 \right) \quad (22)$$

- *Site-to-site synergy*

In VoCI, the main interaction between sites is the mutualization of their area in regard to the minimum size constraints. This means that considering sets of adjacent or very close sites (which together reach the minimum size limit) enables accounting for more redevelopment options. For instance, the activity characterized as ‘Big factories’ demand sites of at least 15 hectares. This minimum size requirement automatically discards most sites. However, the possibility of grouping adjacent sites may lead to reach site size of 15ha which makes the activity becomes feasible.

Site mutualization also allows separating two types of size requirements for the activity of solar energy farms. Investors were interested in sites with areas higher than three hectares, but negotiation drove stakeholders to accept redeveloping several sites with a minimum surface of one hectare, whenever the sum of allocated sites equaled a total surface of at least 3 hectares. Noteworthy, herein sites do not need to be adjacent.

The identified interaction between sites basically means joining their attributes to meet requirements (i.e. the constraint of size). In Figure 5.4, patterns in part A show groups of sites which are all mutually adjacent. However, in reality adjacency of sites can be more complicated, as it is shown in Figure 5.4,

part B. For instance, in the triplet in part B, i_1 is adjacent to i_2 but not to i_3 , yet linking the three sites is viable because i_2 is adjacent both to i_1 and i_3 .

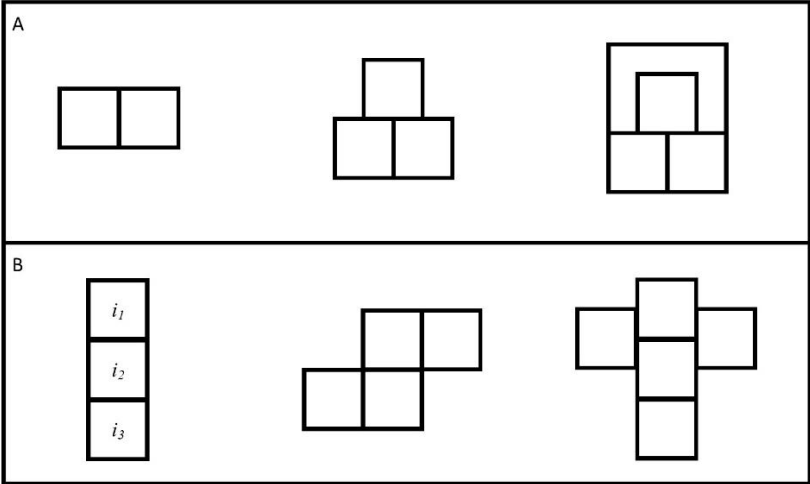


Figure 5.4 - Adjacency patterns.

Two alternative strategies were considered to model adjacent (or near) site mutualization. The first, consists in defining all feasible combinations of sites (g) and controlling which combinations are being used by extending the definition of the auxiliary decision variable (Y_{gipj}). However, this caused a significant rise in the number of equations required to solve the model. The other strategy consists in modifying the sites database, merging the data of sites that can be mutualized. The downside of the second option is that merged sites acquired the most restrictive feature of each of its sub-parts (e.g. the lowest soil quality, the highest remediation cost, etc.). Also, this alternative may result in loss of precision, for instance in the estimations of rehabilitation costs.

For the scope of this research, the two alternatives are exhibited hereafter. The first with an illustrative simplified model with limited number of sites and future land use activities, and the second using the VoCI case study databases.

- Illustrative model -

In this first model, any type of mutualisation condition can be easily included. The main feature is that the auxiliary variable of allocations (Y) also defines which combination of sites is being used (g). A parameter (M) of viable combinations of sites is created. M is a table that determines which sites (i) correspond to each combination (g), where ‘1’ means yes and ‘0’ means no. Table 5.2 depicts 5 illustrative sites, where i_1 , i_2 and i_3 are adjacent as the triplet of Figure 5.4 part B. Separately, i_4 and i_5 are also adjacent. Thus, g_4 groups three sites for which the maximum size of allocation can be expanded to 6 hectares, same happens with g_9 where joining two sites broadens size availability up to 2.5 hectares.

			<i>g</i> Combinations of sites									
		Size (<i>i</i>)	<i>g</i> ₁	<i>g</i> ₂	<i>g</i> ₃	<i>g</i> ₄	<i>g</i> ₅	<i>g</i> ₆	<i>g</i> ₇	<i>g</i> ₈	<i>g</i> ₉	... <i>g</i> _{<i>n</i>}
<i>i</i> Sites	<i>i</i> ₁	2	1	0	1	1	0	0	0	0	0	...
	<i>i</i> ₂	1	0	1	1	1	1	0	0	0	0	...
	<i>i</i> ₃	3	0	0	0	1	1	1	0	0	0	...
	<i>i</i> ₄	2	0	0	0	0	0	0	1	0	1	...
	<i>i</i> ₅	0.5	0	0	0	0	0	0	0	1	1	...
Maximum size (<i>g</i>)			2	1	3	6	4	3	2	0.5	2.5	

Table 5.2 - Illustration of parameter *M_{ig}*.

Incorporating this feature requires including equation 23, where the upper bound of the sum of allocations is restricted to the size of each site whenever it belongs to the combination (and zero otherwise). Note that aforementioned equations need to be updated to cope with ‘*g*’. For instance, Eq. 10 is replaced by Eq. 24, which allows adding up allocations over sites (*i*) in order to cope with activities size requirements. The use of the binary variable ‘*ρ_{ij}*’ remains unchanged.

$$\forall gi \quad \sum_p \sum_j Y_{gipj} \leq Size_i * M_{gi} \tag{23}$$

$$\forall gj \quad \sum_i \sum_p Y_{gipj} \geq RSize_j * \rho_{ij} \tag{24}$$

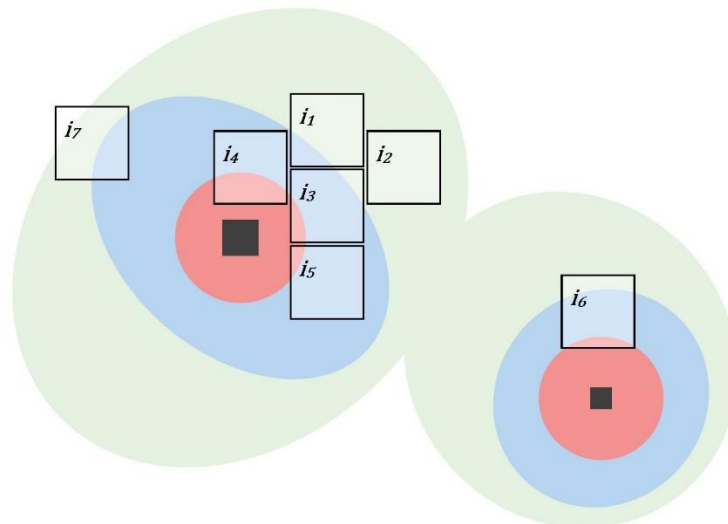


Figure 5.5 - Illustrative model.

Figure 5.5 represents an imaginary case (inspired from the VoCI) used for illustrating the model. All sites have equal size, but adjacency allows different grouping combinations of sites *i*₁ to *i*₅, the broader

viable combination being linking the five sites through i_3 . On the other hand, sites i_6 and i_7 are isolated sites. In addition, sites contain different regulating zones, the black squares being the sources of technological risks, the red zone is the most restrictive zone, blue is intermediate, green is the less restrictive zone, and blank is out of the regulating restrictions. On the other hand, there are three competing activities, j_1 is suitable in any zone, has the lower size requirement and lower expected benefit, j_2 is suitable in blue, green and white and has an intermediate size requirements and benefits per hectare, and j_3 is feasible in red and blue zones only, requires the higher size and yields the higher expected benefit per hectare. Table 5.3 displays sites size characteristics and activities size requirements.

Sites (i)	Total Size	Regulating Zones Surfaces (p)				Activities (j)			
		None	Green	Blue	Red	j_1	j_2	j_3	
i_1	1	0	0.8	0.2	0	Required Size	0.85	1	1.25
i_2	1	0	1	0	0		Benefit	1	1.5
i_3	1	0	0.125	0.775	0.1	<i>Zoning Tolerances:</i>			
i_4	1	0	0	0.65	0.35	None	Yes	Yes	No
i_5	1	0	0	0.94	0.06	Green	Yes	Yes	No
i_6	1	0	0.26	0.615	0.125	Blue	Yes	Yes	Yes
i_7	1	0.2	0.5	0.3	0	Red	Yes	No	Yes

Table 5.3 - Parameters of the illustrative case.

- The VoCI model -

To solve the adjacency problem applied to the VoCI case study, the approach consisted in merging sites that can be combined, sometimes keeping the most restrictive features of each original site, carefully adapting the zoning data, and accepting that it reduces the quality of rehabilitation costs estimation (See Figure 5.6).

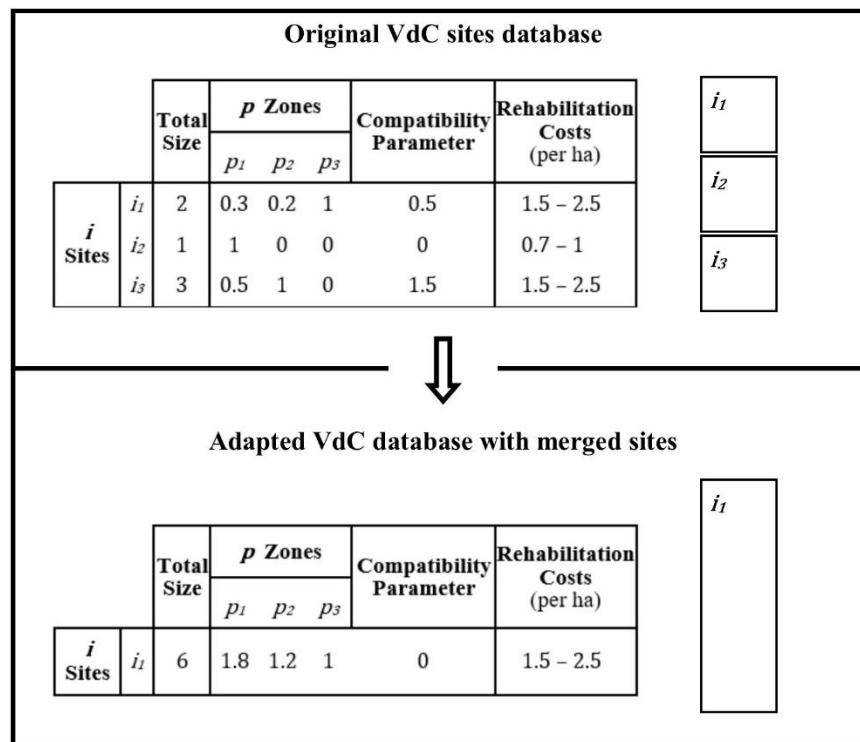


Figure 5.6 - Adaptation of VoCI database to include mutualisation of sites.

The adapted database includes 7 merged sites that group up to 19 different sites, reducing the initial number of 71 to 58. The final list of equations applied to VoCI case study is presented in Appendix B.

5.4. Model outputs

5.4.1. Solution of the illustrative model

The model has been coded on GAMS and ran as a mixed-integer non-linear problem. The main output of the model is a table with the optimal levels of allocation X_{ij} (Table 5.4). This can easily be presented in geographic representations using color code for activities (See Figure 5.7).

X_{ij}	j_1	j_2	j_3
i_1	0	0.831	0.169
i_2	0	1	0
i_3	0	0.143	0.857
i_4	0	0.009	0.991
i_5	0	0.018	0.982
i_6	1	0	0
i_7	0	1	0

Table 5.4 - Solution of the illustrative model.

Note that j_1 and j_2 required a minimum size of 0.85 and 1 respectively (See Table 5.3), the model effectively added up the sub-surfaces of i_6 and i_7 to cope with this size constraint while respecting the compatibility considerations of the risk management zones. Also, as j_3 requires at least 1.25 ha of surface and all sites sizes are 1, it is clear that the mutualization of sites has enabled the inclusion of that activity in the solution. The model found a combination of sites and sub-surfaces that maximizes the allocation of j_3 because is the activity that yields the higher benefit. The solution includes very small allocations of j_2 within i_4 and i_5 although it could allocate the whole site to j_3 . This can be seen as a minor margin of error stemming from the characteristics of the solver. However, it helps noticing that $X_{i_5j_2}$ in this solution is not reasonable since it is not adjacent to $X_{i_3j_2}$, which is not a problem within the scope of this research, but it can become an issue if the model is replicated within a case study with intricate zoning patterns.

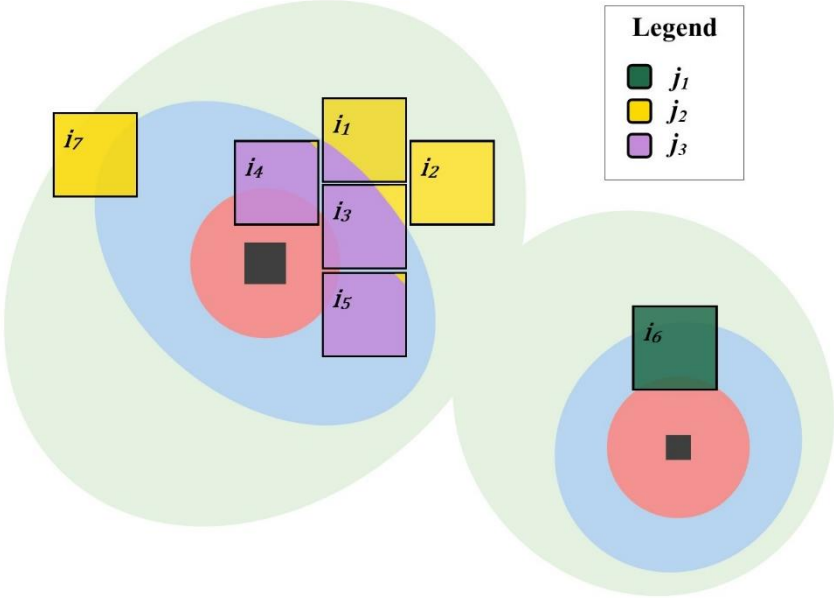


Figure 5.7 - Solution of the illustrative model.

The values in Table 5.4 allow calculating general indicators and subtotals sorted by activities. This can be very useful for larger scales, specially to contrast results between different scenarios. For instance, Table 5.5 clearly shows that all sites have been redeveloped, it also shows allocated areas per activity and the total benefits yielded by each activity. One can therefore easily perceive that j_2 and j_3 have been allocated equally, and j_3 alone yields the 52% of the total benefits.

Sites redeveloped = 7/7		
	<i>Surface</i>	<i>Benefits</i>
<i>j₁</i>	1	1
<i>j₂</i>	3	4.5
<i>j₃</i>	3	6
TOTAL	7	11.5

Table 5.5 - General indicators of the illustrative case study solution.

5.4.2. Solution of VoCI case study

The model for VoCI case study was also coded on GAMS and ran as a mixed-integer non-linear problem. Table 5.6 presents the indicators that summarize the outcome of the model. Straightforward, one can see that 32 out of 58 sites were allocated with a redevelopment activity (55%), representing 212.6 hectares (26 sites were not redeveloped). This solution would generate 2943 employments and 70 MWh of energy during the 20 years of the redevelopment program. The model mainly allocated j_9 (146,42 hectares). Concerning interactions, the synergies of reducing CO₂ emissions and soil rehabilitation costs (synergy 1 and 2 noted S1 & S2) were not activated, the existing industrial infrastructure (S3) results significantly valuable (538,6 M€), and extra safety measures in blue Risk Management Zones (S4) involve extra costs for no less than 167,6 M€.

Sites redeveloped	32/58	Activities	Surface	Benefits
Total rehabilitation costs	144.193.587 €	j₁	0,00	- €
		j₂	23,91	10.734.149 €
		j₃	0,00	- €
Employment generation	2943	j₄	0,06	142.959 €
		j₅	42,19	368.904.900 €
		j₆	0,00	- €
S1 : reducing CO₂ emissions	- €	j₇	0,00	- €
		j₈	0,00	- €
S2 : reducing soil rehabilitation costs	- €			
S3 : industrial network avoided costs	538.677.060 €	j₉	146,42	7.185.285.845 €
S4 : security measures extra costs	167.658.623 €	Total	212,6	7.565.067.853 €

Table 5.6 - Summary of VoCI allocation results.

It is natural that the results in VoCI prioritize allocating small and medium enterprises (j_9), as the expected benefits per hectare for this activity are the highest after incineration plants (j_6). On top of that, j_9 is also relatively flexible in terms of compatibility constraints. For instance, it does not require minimum distances with residential zones nor high accessibility standards, and yet it is compatible with most regulating zones. However, it is unlikely that, in real life, the offer for investments in j_9 can cope to redevelop up to 146 hectares in VoCI. In a way, this optimization result can be seen as an ideal outcome that may not be reached in reality. Urban planners might be interested in seeing outcomes that cap the maximum offer of j_9 , which in theory would open space to share allocations with other activities such as big and medium sized factories.

The model solution excludes the activity j_1 because all sites that were compatible with the soil recycling factory were also compatible with other activities that generate higher benefits per hectare. The synergy of reducing soil rehabilitation costs is not big enough to compensate, for example, the revenue over 20 years of allocating 5 hectares of SMEs or urban farms. Once again, the model can be used to test different contexts, it can be argued that at least one soil recycling station is needed in order to be consistent with sustainable development objectives, in which case it should be imposed using a lower-bound constraint for this activity.

Phytoremediation (j_3) was included within future use alternatives in the sense that it would occupy space. However, the hypothetical implementations of phytoremediation considered in this study were not creating value other than reducing rehabilitation costs (i.e. by implementing phytoremediation instead of other remediation techniques). Only a few sites were characterized as suitable for phytoremediation, and it is not clear that phytoremediation techniques enable other allocations in the future, so this alternative is actively competing with other activities with higher net benefits. In that sense, it is not surprising that results excluded allocating phytoremediation.

Even though there is enough allocation of biomass production to activate the synergy of reducing CO₂ emissions of the incinerators, results also excluded j_6 , which is the activity with the highest expected revenue per hectare. Clearly, the reason is that limiting the production of energy creates competition between solar energy and incinerators. Producing the cap of energy (70MWh) requires 42.2 ha of j_5 or 4.2 ha of j_6 . The model compares the outcome of these allocations in terms of overall benefits taking into account costs of opportunity. In that sense, implementing 4.2 ha of j_6 would liberate 38 ha for other allocations, but these spaces might not be suitable for other activities.

In addition to overall results, the allocation variable is informative by itself, giving an idea of which activities should be allocated on each site. As the model includes 58 sites, the table of allocations is very extended. Figure 5.8 shows resulting allocations in VoCI, which can also be seen in Table 5.7.

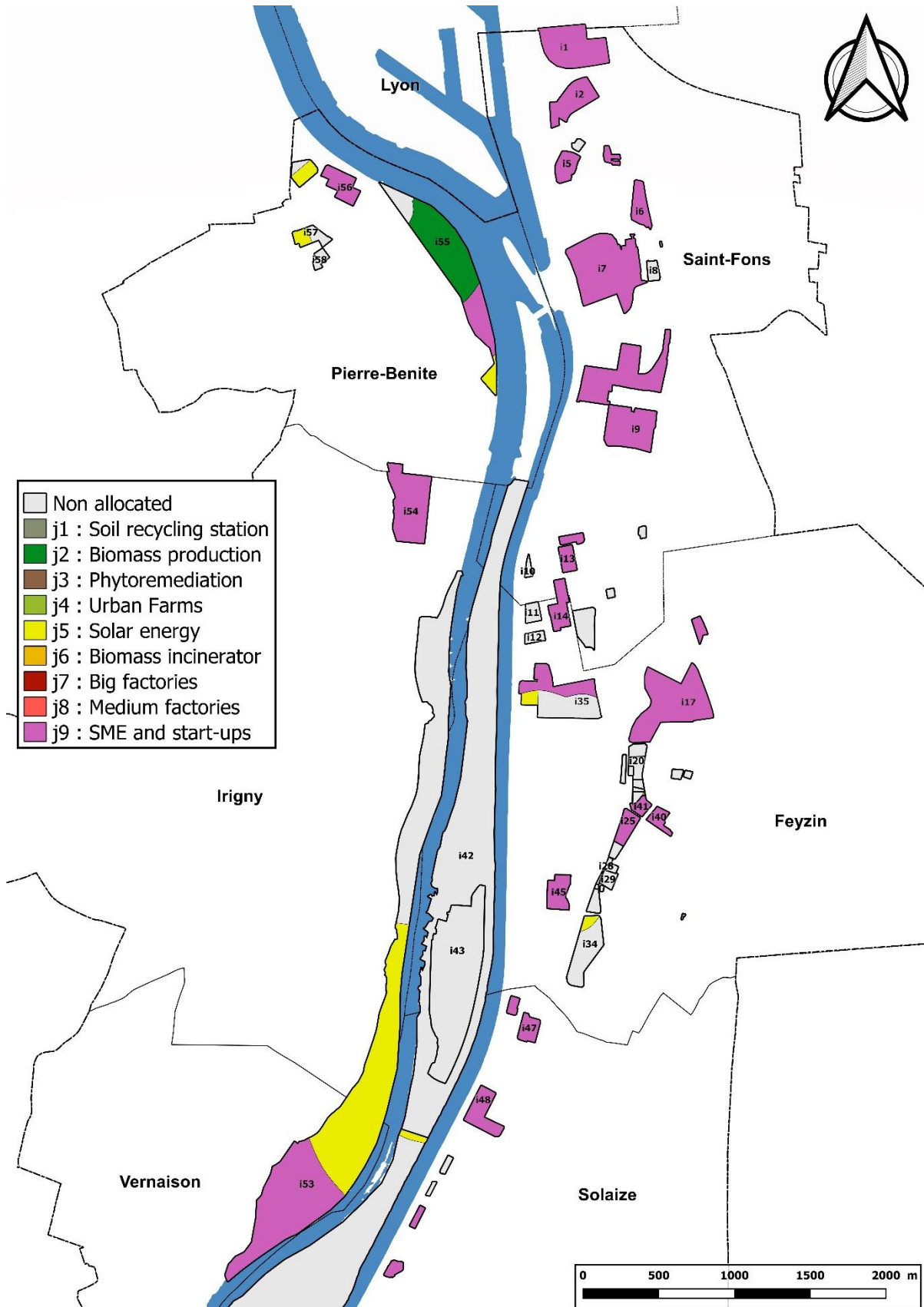


Figure 5.8 - Allocation results in VoCI.

X_{ij}	j_1	j_2	j_3	j_4	j_5	j_6	j_7	j_8	j_9
i_1									9,76
i_2									5,04
i_3									0,72
i_5									2,37
i_6									2,63
i_7									17,21
i_9									19,92
i_{13}									2,41
i_{14}									5,87
i_{17}									14,13
i_{18}									0,91
i_{24}				0,01					
i_{25}									2,03
i_{34}					1,00				
i_{35}					1,00				4,855
i_{37}				0,05					
i_{40}									1,39
i_{41}									1,02
i_{44}					1,00				
i_{45}									2,89
i_{46}									0,69
i_{47}									1,91
i_{48}									4,02
i_{51}									0,57
i_{52}									0,88
i_{53}					36,19				29,42
i_{54}									10,80
i_{55}		12,92			1,00				4,72
i_{56}					1,00				3,96
i_{57}					1,00				

Table 5.7 - Allocation results in VoCI.

Results displayed in Figure 5.8 and Table 5.7 show that most allocations in north VoCI were attributed to j_9 because of its relatively high expected revenue. However, some sites were not allocated at all. For instance, i_4 and i_{36} have areas of 0,41 and 0,034 hectares respectively, which is too small regarding minimum size requirements of most activities. Thus, i_4 is only big enough for urban farms and phytoremediation and i_{36} for urban farms uniquely. Unfortunately, i_4 is not suitable for phytoremediation, and both sites are located within the blue risk zone, which excludes the possibility of allocating urban farms. Similarly, i_{58} is not suitable for phytoremediation, and is big enough for allocating urban farms and SMEs, but these activities are excluded because the site is located within light red risk zone. As for i_8 , the site is not suitable for phytoremediation, it is only big enough for urban farms and SMEs, but these alternatives are excluded because the site is given with very low accessibility.

The allocation of i55 is clearly conditioned their location vis-à-vis risk management zones. The north part of the site is located within dark red zone, which excludes 2,9 ha of any allocation. Then, the site contains two sections of light red zones that adds up 13,92 hectares, which were attributed to biomass production. Lastly, the centre of the site contains 1,18 ha within green zone, and 3,55 ha with no zoning restriction, these zones were allocated with activity j_9 .

Site i56 encompasses two separate plots, one of which is located within grey zone and was allocated with j_9 (right side). The other plot (left side), is located within light red regulating zone, but was only partially allocated with solar energy because of the limitation set for electrical energy production. The same happens with i57, which was also attributed with one hectare of solar energy.

5.5. Discussion

In this chapter, we demonstrated the feasibility of the regional optimization approach and we illustrated the type of outcomes of the model. Members of the VoCI task force found that the results were interesting and could support discussion for decision-making, in particular if used to simulate and compare several scenarios. However, they stressed that the model should not be used as a prescriptive tool, as the optimal solution identified does not account for all real-life constraints. First, the model can only be as good as the quality of the data and we saw in the previous chapter that cost and benefit estimates are difficult to assess precisely at regional level. The model presented in this chapter includes rehabilitation costs that were initially approximated with triangular distributions yet included in the model as values fixed in the center of the intervals.

Secondly, there is more than only one way to model the context of a case study. As for VoCI, the approach to model the problem resulted well suited for case study. That being said, there are several perspectives that can result viable. Namely, setting a maximal surface for SMEs, adjusting the parameters of energy production, orienting the valley to the creation of employment, forcing the valley to manage a certain amount of soil recycling, and even relaxing constraints such as minimum distances to residential areas and the urban zoning restrictions. The next chapter also includes the use of the model to set different scenarios.

At this point, the modelling process not only concerns equations but also the construction of the databases. For example, although this was not a major issue for VoCI case study, it was not clear which is the best scale to characterize the sites. A balance has to be found between describing specific attributes of sites that are relatively big (i.e. sites with multiple sub-zones defined by urban zoning restrictions) and dividing sites into several plots with single attributes. In the former alternative, the model has to be adapted to read a number of sites that contain different attributes, as it was the case of VoCI in this chapter. For the latter, the model needs to be able to join the specific plots in order to give the sense of

the actual sites. This alternative requires an approach similar as in the illustrative model presented in this chapter. This could solve issues of intricate zoning patterns as for example i55, where the model allocated two separated areas of red zoning regulation with biomass production. However, this choice entails more resources, both for collecting data and for solving the model. Furthermore, it can result challenging in case studies with more than one zoning criteria if these overlap (e.g. technological risk prevention zoning and inundation prevention zoning). Sometimes this issue will be conditioned to data availability, but it is worth analyzing different modelling approaches even before ending the phase of database construction.

Finally, there are other components that can also condition results. The modelling environment includes the choice of software, the choice of algorithms for solving the model, and even choosing starting points for decision variables. In this research, the model was coded in GAMS. Several tests were done to see how results reacted to changes of the solver and decision variables starting points, then choosing what seemed more adapted to the model. However, only BONMIN and COUENNE solvers were tested. Although testing the model in different modelling environments and deepening an analysis of its effects may be relevant, this was beyond the scope of this research.

5.6. Conclusion

Preliminary results presented in this chapter can be seen as the results of a model of reference, a starting point to compare different scenarios including assumptions on energy production objectives, employment creation, available offer of investment, or ensuring a chain of soil recycling in line with sustainable development objectives. Therefore, the model can simulate the impact of changes in the regulatory or redevelopment policy contexts.

The model can be used to test several scenarios by modifying some of the most restrictive constraints such as distance to residential zones, constraints imposed in risk management zones, etc. Also, the model can be used to run stochastic simulations, using randomly drawn values of uncertain parameters such as costs and benefits. This would allow assessing the sensibility of the solution to the uncertainty entailed in the parameters, and assessing how reliable are the outcomes of the current model. In a way, the difference in overall benefits between this model of reference and the different scenarios can be seen as an approximate estimation of the benefits or costs of implementing such scenario. In the case of testing the consequences of uncertainty these differences could be interpreted as a proxy of the value of information.

Chapter 6. Model implementation and simulations

This chapter discusses the implementation of the model and its use for simulating various scenarios. The first section addresses computational problems encountered when implementing the model with GAMS using solvers that do not guarantee finding the optimal solution for non-convex problems. The second section of the chapter presents a stochastic approach implemented to test the sensibility of the outcomes in regard to the uncertainty of the input data, and presents an example of sensibility test concerning the uncertainty embedded in the intervals of rehabilitation costs that were estimated in chapter 3. Finally, the third section presents simulations ran for different scenarios, for which the outcomes are compared to the results of the reference situation presented in the last chapter.

6.1. The complexity of solving non-convex problems

Optimization problems can be usefully classified into convex and non-convex problems. In a convex optimization problem all of the constraints are convex functions, and the objective is a convex function if minimizing, or a concave function if maximizing. On the other hand, non-convex problems may have multiple feasible regions and multiple locally optimal points within each region. Figure 6.1 displays typical graphic examples of convex and non-convex functions. Such non convex problems are much more complicated to solve, from a computational point of view, than convex problems. For deeper considerations on non-convex problems and solving algorithms please see Burer and Letchford (2012).

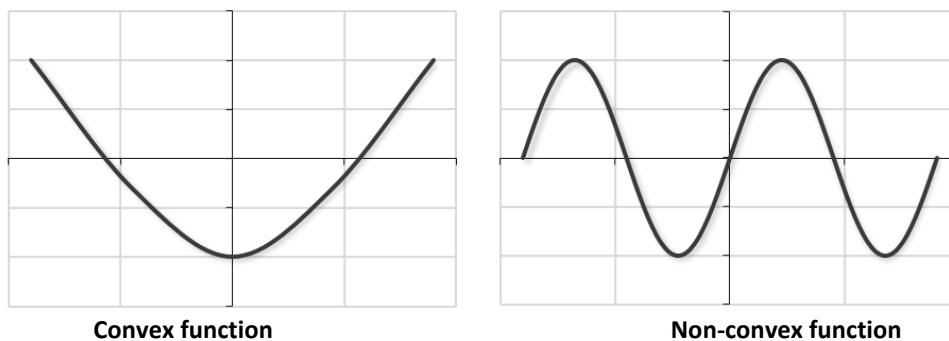


Figure 6.1 - Illustration of convex and non-convex functions.

The ‘regional portfolio’ nature of the VoCI model required indexing the decision variable (X) into multiple sites (i) and future land use activities (j), which involves an objective function with ‘multiple’ feasible regions. In addition, the feasible regions include disjoint regions that are specified by the binary variables included in the system of inequalities (thus including complex interactions between variables).

Hence, the overall feasible region does not meet the notion of convex sets⁸. The model is therefore dealing with a non-convex problem.

Multiple scientific efforts have helped developing computational methods to deal with complex, time-consuming problems. A variety of effective exact solution methods have been devised to solve convex problems, see for example Interior Point and Barrier. In contrast, it results far more complicate to find exact solutions for non-convex problems, meaning that not only it requires more resources (e.g. calculation time, number of iterations), but in some specific cases existing methods can be unable to solve problems to optimality.

In essence, the shape of convex functions allows finding optimality in a relatively reduced sequence of computational actions, whereas similar efforts in non-convex problems may only find locally optimal values. Local optimums are optimal solutions within a segment of the feasible region, but are not the best solution (or Global optimum) within the entire feasible region. This is illustrated in Figure 6.2. Therefore, non-convex problems usually require more sequences of computational actions in order to find the global optimum. Solving methods that are able to find the global optimal within non-convex problems are called global optimizers.

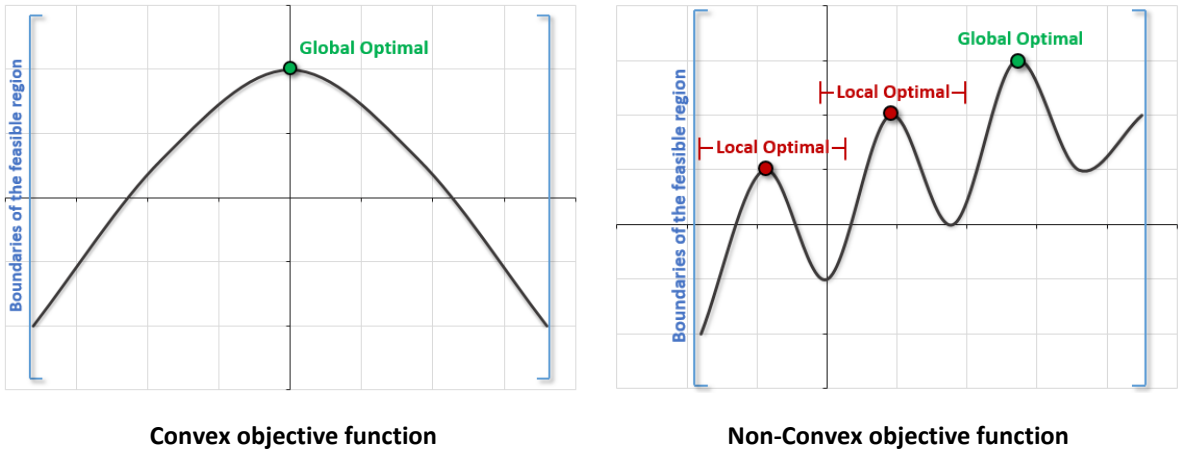


Figure 6.2 - Finding the global optimal in convex and non-convex functions.

The research exercise of this thesis includes the development of the model within the GAMS modelling language. In GAMS, as in other softwares, the algorithms that enclose solving methods are embedded in software packages called solvers. Each solver has its own limitations concerning the number of variables, constraints and iterations that can be dealt with. With the GAMS version used in this research, only the BONMIN solver was able to solve the non-convex MINLP problem of the VoCI case study.

⁸ Definition of convex set: A set of points C is called convex if, for all λ in the interval $0 \leq \lambda \leq 1$, $\lambda a + (1 - \lambda)b$ is contained in C whenever a and b are contained in C (Bradley et al. 1977: 571).

BONMIN stands for Basic Open-source Nonlinear Mixed INteger programming. It is an open source code to solve MINLPs, and it implements four different algorithms. Namely, branch-and-bound algorithm, outer-approximation based decomposition algorithm, outer-approximation based branch-and-bound algorithm, and a hybrid outer-approximation/nonlinear programming based branch and-cut algorithm (Bonami et al. 2008). All in all, the different methods that BONMIN implements are exact algorithms for convex problems but are only heuristics when this is not the case, which means that BONMIN is not a global optimizer (Bonami and Lee 2007). In consequence, it does not ensure finding the global optimum for a non-convex problem.

To solve the non-convex problem of brownfield redevelopment in the VoCI using the BONMIN solver, we designed a methodology to improve the possibility of finding the global optimum, or at the very least, reduce the gap between the best-known solution and the global optimum. This methodology consists in running the model several times with different algorithm initial conditions (decision variables starting points).

Basically, the sequence of actions to solve the problem begins by assigning zero as the initial value by default to all decision variables. Our computational strategy consists in assigning different initial values (i.e. starting points) to begin the assessment of the decision variable. Figure 6.3 illustrates this strategy: the model is run seven times, the comparison of local optimum shows that the best solution is found using the 6th starting point, it will thus be considered as “best known solution” and assimilated as a global optimum.

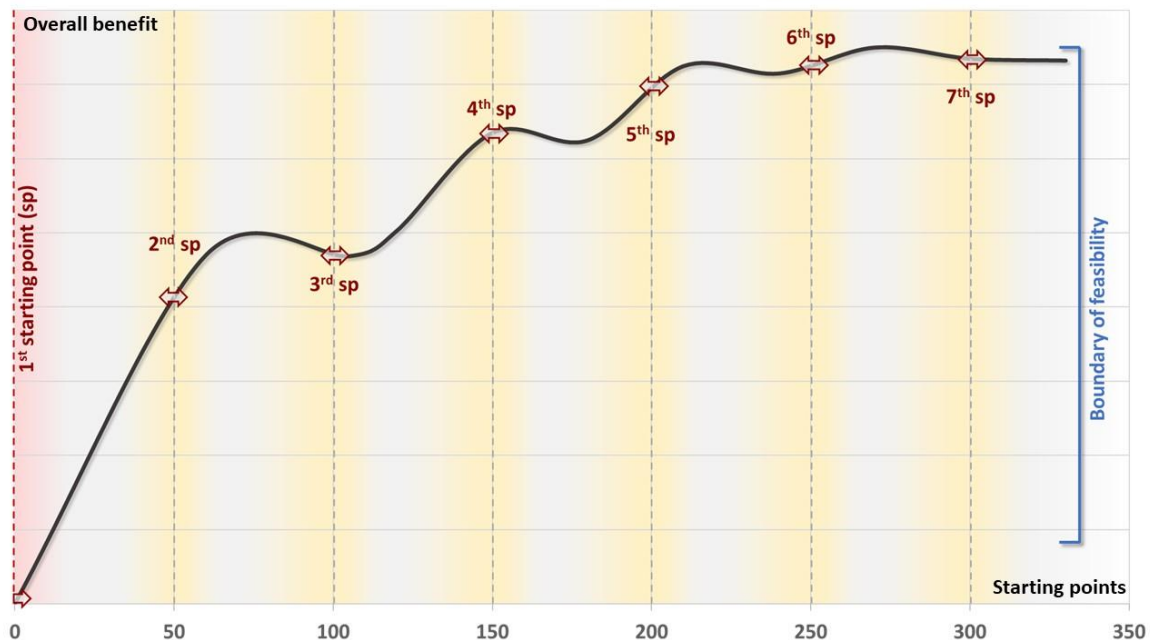


Figure 6.3 - Illustration of modifying the starting points strategy.

Naturally, as the decision variable ‘X’ is indexed to 59 sites and 9 future land use activities and there are multiple feasible regions, the objective function of the VoCI problem cannot be represented as easily

as the illustrative function in Figure 6.3. An exhaustive approach testing all possible combinations of starting points was discarded by lack of computational resources. The chosen strategy consisted in changing starting points for the binary variables (i.e. 0 and 1) and testing seven starting points for all X_{ij} with no discrimination between sites and future use activities. In addition, more tests including starting points that prioritized the two activities with the highest benefits per hectare (i.e. j_6 and j_9) were also conducted. Overall, more than 50 different combinations of starting points were tested.

The analysis of results shows that the solution was clearly sensitive to the value attributed to starting points. Concerning the binary variables, all tests generated better results with the three integer-constrained variables starting at one. Figure 6.4 shows the results of the application of the aforementioned strategy. Among the non-discriminating starting points, the model responded the better to the 200 starting point (dark green). This result was slightly outperformed by two specific tests prioritizing j_6 and j_9 (+1.07% and +1.53% respectively). These specific tests (blue) included a non-discriminating starting point at zero for all future land use activities with the exception of the referred ones (j_6 and j_9 respectively). Finally, the latter was ultimately retained as the best-known solution to the VoCI problem as shown in chapter 5 (dark blue)⁹.

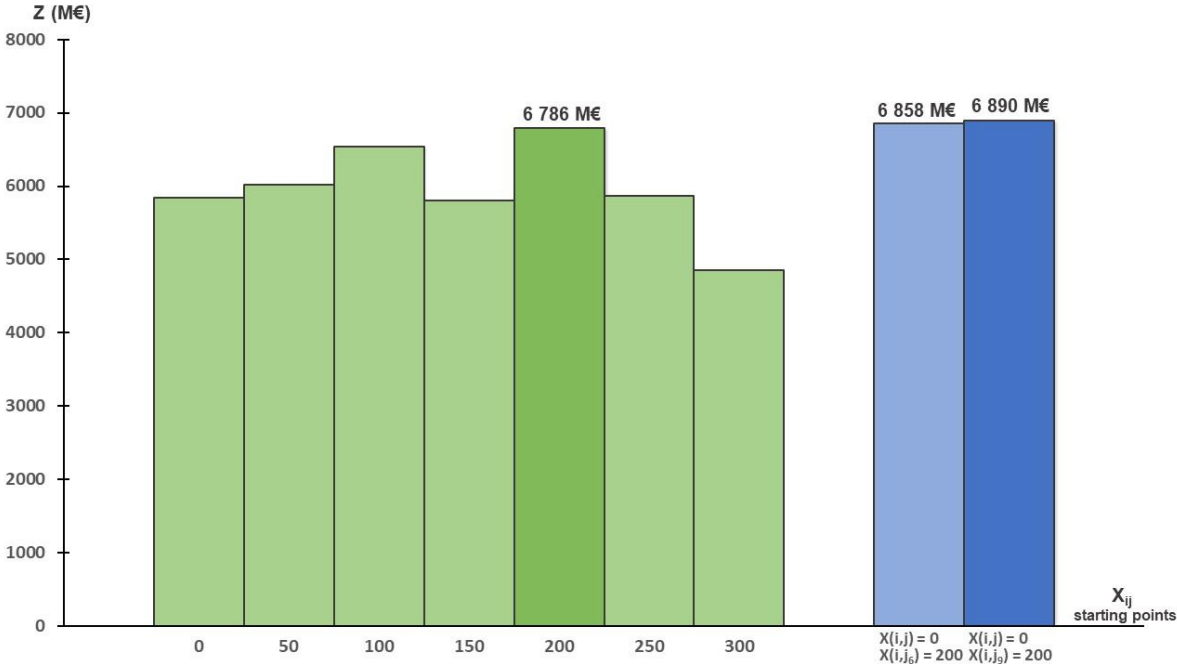


Figure 6.4 - Results of the starting points strategy.

⁹ Manual scrutiny of results allowed verifying that all results remained consistent in regard to the constraints, and that the establishment of starting points did not condition its value within the outcomes. For instance, even though the model presented better results by setting binary variables starting points at one, all results excluded the synergy between j_2 and j_6 ($B_{\delta_1} = 0$), this is mainly due to the fact that the model does not allocate j_6 (not even within the test setting a starting point prioritizing j_6). Hence, the role of the strategy is limited to set different angles to start the assessment, which does not necessarily compromise the outcomes, but allows tracing results and identifying the best-known solution.

Please note that although this strategy helped improving the quality of the results, herein it is not claimed that it ensures finding the global optimum. Overall, the non-availability of a global optimizer prevails as a caveat of this study. In view of the scope of this study, the strategy presented in this section has nevertheless sufficiently helped to improve the quality of results. Results presented in the upcoming sections also include the application of this strategy.

6.2. Dealing with uncertainty: a stochastic approach

The reliability of the outcomes of an optimization model are heavily determined by the quality of its inputs. It is therefore very important to acknowledge whenever input data entail a certain degree of uncertainty. Running sensibility tests can be an effective way to manage uncertainty. If uncertainty concerns little changes within a reduced number of parameters, such tests can be carried with single-run scenarios. This section raises attention to more important sources of uncertainty. In particular, to the limitations embedded in the evaluation of benefits and costs. The research therefore includes using a stochastic approach to test the sensibility of the model in regard to uncertainty. Herein both benefits and costs evaluations conceded uncertainty. For instance, the evaluation of benefits adopted a number of assumptions that could be approached differently (i.e. modifying expected benefits). However, since rehabilitation costs were outlined as intervals from the very beginning of their estimation, it was convenient to illustrate the application of this approach using these intervals with triangular distributions. The scope of this study only included testing sensibility in regard to rehabilitation costs.

Inspired in the Monte-Carlo method, the approach uses random drawings of cost values to test the behavior of the model. The approach consists in running the model 1000 times letting the costs be randomly determined from their triangular distribution.

Two paths were considered to execute the random drawing (See Figure 6.5). The first consists in simply drawing a value from the intervals of each of the four sources of rehabilitation costs (remediation, managing excavated ground, deconstruction and its wastes, and soil reconditioning). The second consists in an addition of the four intervals to establish a single broader triangular distribution to draw from. A priori, the former would deal with scenarios whose added costs would tend to the average (because there are chances of high cost drawings being compensated by low drawings), whereas the latter has better chances to showcase what happens with extremely low and high cost scenarios. As the addition of the intervals entailed the complication of adding the triangular distributions, it was decided that the first path was more appropriate.

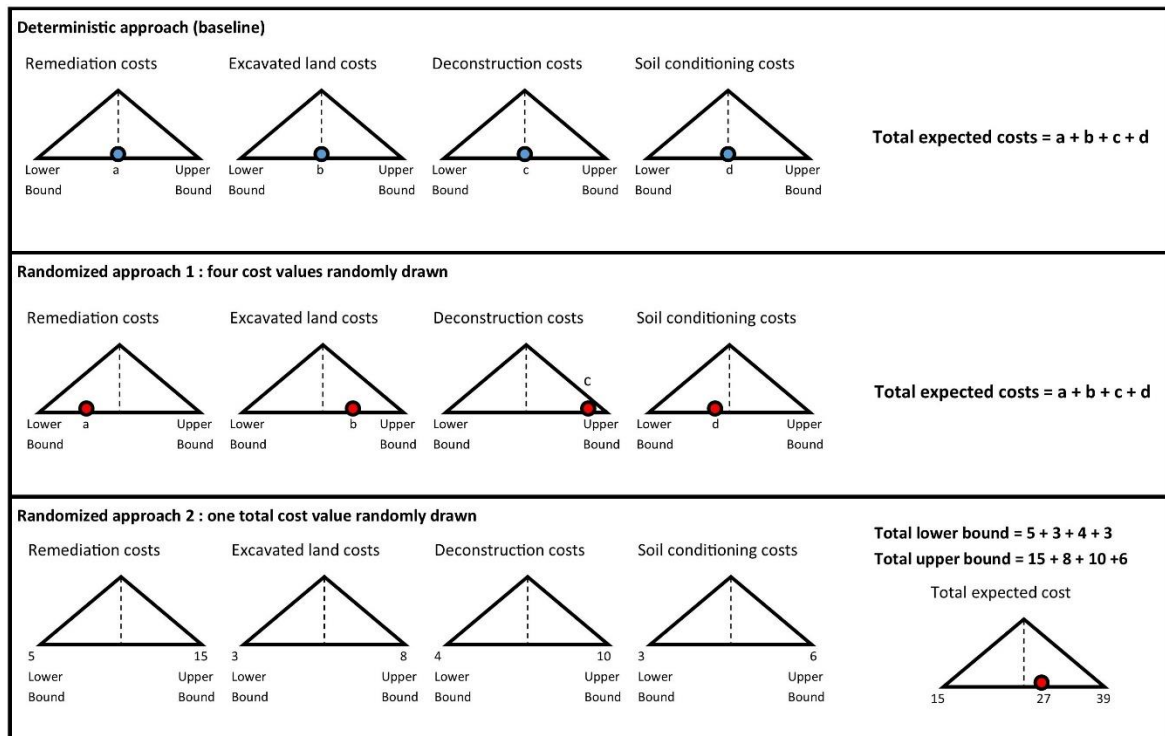


Figure 6.5 - Two approaches to deal with random drawing.

The application of the approach included three phases (See Figure 6.6). The first phase is the random drawing itself (a). As all the inputs of the model, the intervals of costs are stored in EXCEL files. This data is then incorporated to GAMS, where the thousand random drawings are conducted, generating a thousand variants of the VoCI problem. The second phase consists in running the model (a), this includes applying the strategy of starting points discussed in the previous section. Herein, seven non-discriminating starting points were used (0, 50, 100, 150, 200, 250, and 300), generating 7000 solutions of the problem. As each solution includes the allocations of each site, the database of results included 406000 lines (number of sites * number of solutions), stored in EXCEL files. The third phase consisted in selecting the best-known solution of each variant of the problem (c), which reduced the database back to 1000 solutions of the problem. The analysis of sensitivity is then carried based on these 1000 best-known solutions.

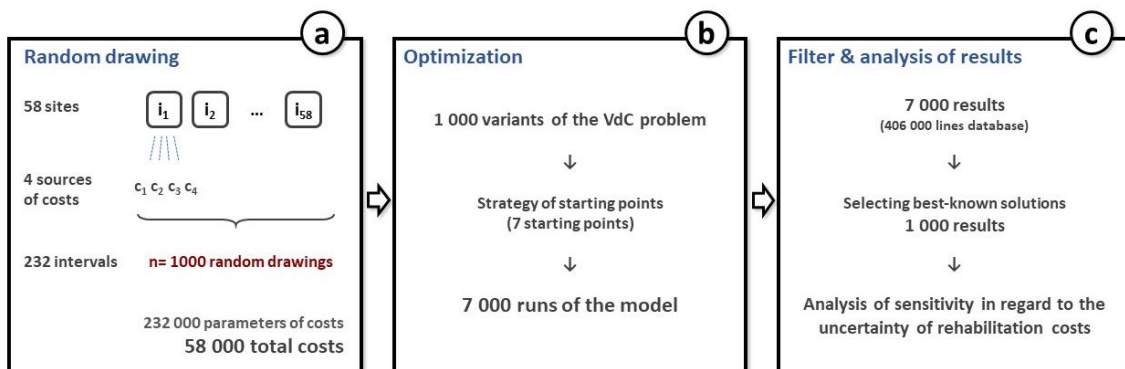


Figure 6.6 - Procedure of the stochastic approach.

The filter of best-known solutions allowed to compare the results obtained with different starting points. As shown in Table 6.1, 200 is the initial value that generated most of the best-known solutions. However, the best-known solution was repeatedly found with more than one starting point. Overall, all the starting points -except zero- presented very good possibilities of finding the best-known solution.

Starting Points	Number of times finding the best-known solution	%
0	691	69,1%
50	984	98,4%
100	985	98,5%
150	895	89,5%
200	991	99,1%
250	984	98,4%
300	984	98,4%

Table 6.1 - Performance of the starting points strategy.

Results of the random drawing of rehabilitation costs and optimization are displayed in Figure 6.7, where units are expressed in millions of euros (M€). Blue dots represent the overall net benefits resulting from the optimizations (left side axis). Conversely, red dots represent the total rehabilitation costs resulting from random drawing (right side axis), and the yellow line represents the deterministic value obtained with cost values equaled the center of the intervals.

Only one observation resulted particularly low (6031,78 M€, n=1). The difference of this isolated outcome stems from being the sole optimization that did not allocate j_9 in two specific sites (i_1 and i_{55}). A close examination of data allowed verifying that there were no particularly high rehabilitation costs on these two sites. If anything, the overall expected costs of this variant of the problem are relatively low. Therefore, this can only be explained as a matter of under optimization due to the limitation of the solver discussed in the previous section. A small group of results (2,3%) lay slightly below 6800 M€. Finally, the vast majority of results (97,6%) are relatively homogenous, laying between 6869,97 M€ and a maximal value of 6909,7 M€. Overall, these results clearly show that the outcomes of the model of reference were not very sensitive to the uncertainty embedded within the intervals of rehabilitation costs.

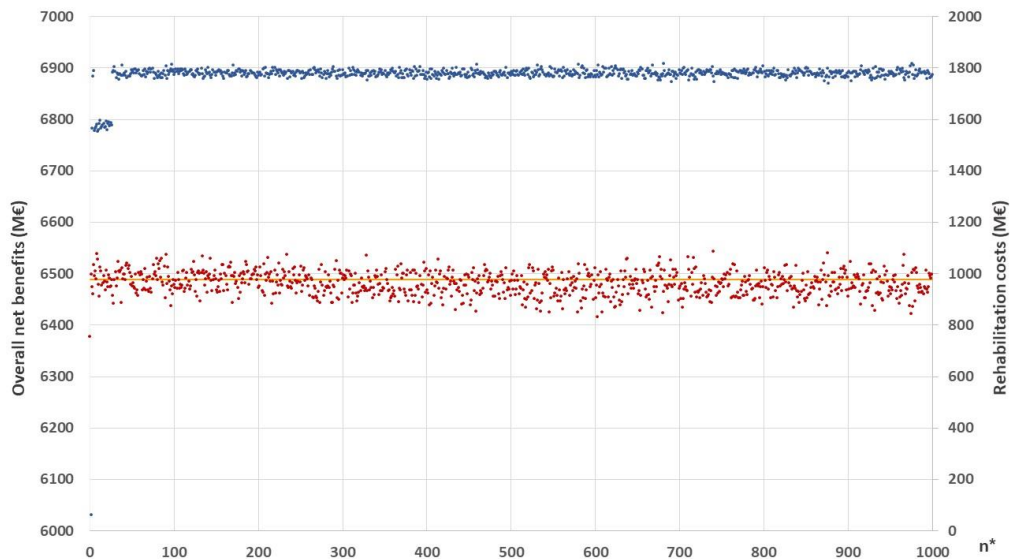


Figure 6.7 - Random rehabilitation costs and total net benefits. *n represents the number of random drawings.

The test of sensibility also showed that optimizations consistently selected which sites were preferable for redevelopment and which sites should –within the scope of this analysis- remain non-redeveloped. This is shown in Figure 6.8, where shaded sites were allocated 100% of the times, blank sites were non-allocated 100% of the times, and yellow colored sites were very rarely allocated (< 0.5%). This information gives useful hints on BFR prioritization, specially to help understanding why some sites are preferable, or at least raising attention on certain elements of the analysis that could be causing unexpected results.

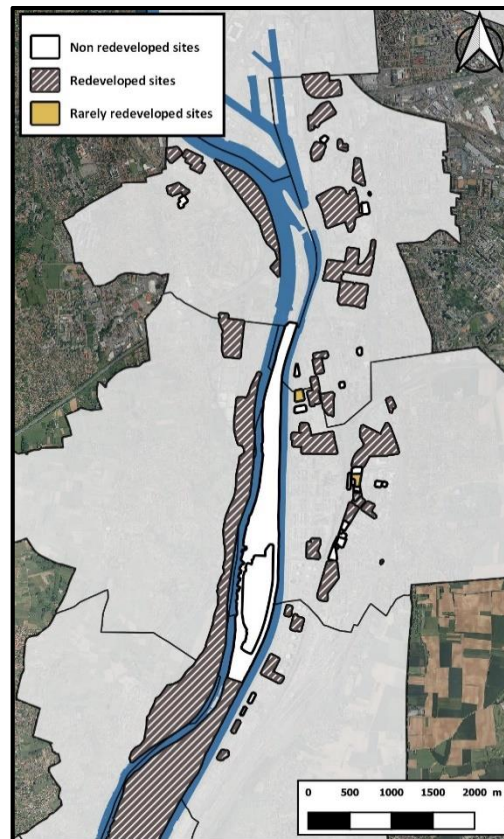
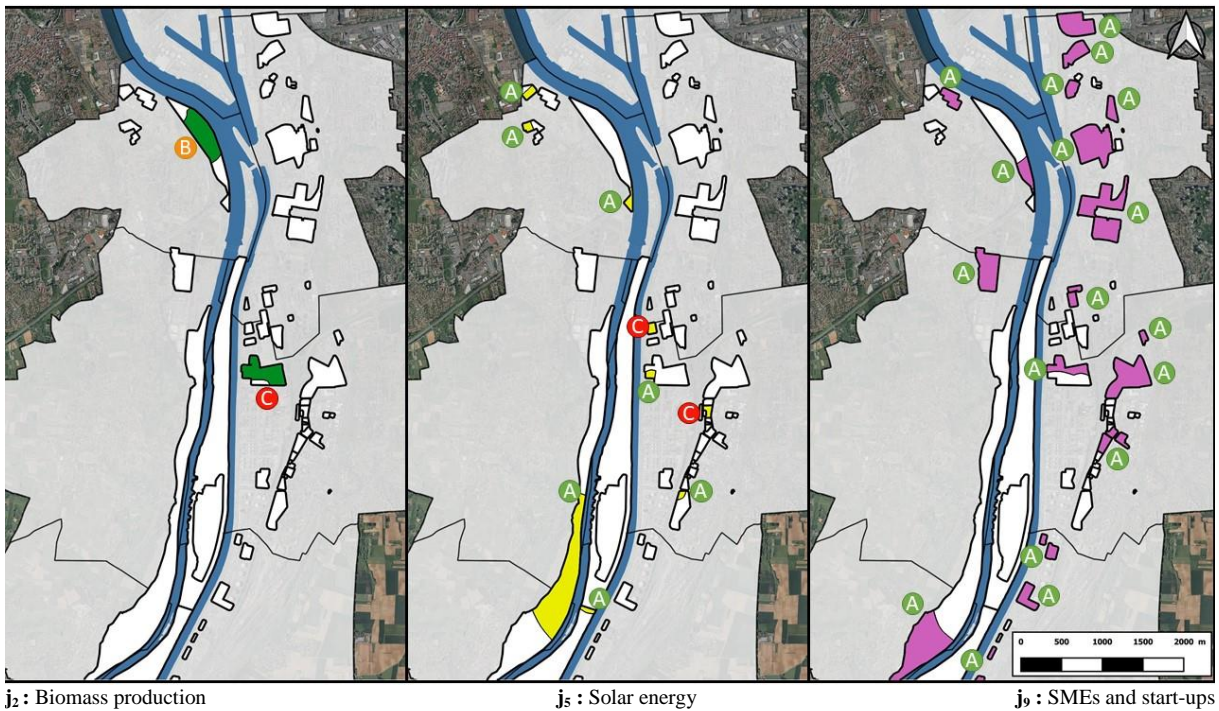


Figure 6.8 - Sites redeveloped despite uncertainty.

Allocations (i.e. activities selected in each site) also were very consistent throughout the test. Figure 6.9 displays the allocations of three future land use activities and it also provides indicators of confidence based on how often these allocations selected. More specifically, **Ⓐ** indicates the allocations with the highest stability (above 99,5%), **Ⓑ** indicates allocations that are sensible to uncertainty, and **Ⓒ** indicates allocations with very low stability in the solution (beneath 0,5%). Concerning biomass production (j_2), the allocation in i_{55} was rated B supported with the 48% of the solutions. This was the only allocation that was found sensitive to rehabilitation costs. The allocation of biomass in i_{35} was rated C because it is only present within n_1 (the case of under optimization). Soil recycling station (j_1) was only allocated once, also in n_1 . Urban farms (j_4) were consistently allocated in the two smallest sites of the VoCI portfolio (100%, i_{24} and i_{37}). The allocations of solar energy and SMEs was very consistent (center and right on Figure 6.9).



j_2 : Biomass production

j_5 : Solar energy

j_9 : SMEs and start-ups

Figure 6.9 - Allocations of future land use activities in regard to uncertainty.

Overall, results allowed concluding that the specific context of the VoCI problem that was tested in this section was robust in regard to the uncertainty embedded within the estimation of rehabilitation costs. This conclusion however only applies to the reference situation simulated here, which assumes a given set of parameters and constraints. The sensitivity analysis should be repeated with each scenario simulated – scenarios that are now discussed in the following section.

6.3. Testing scenarios

The development of scenarios involved changing some of the policy and urban planning assumptions made in the reference situation that was discussed in the previous section and in chapter 5. These changes are summarized in Figure 6.10.

Baseline	Energy production	Prioritizing employment	Soil recycling	Relaxing compatibility constraints																				
<ul style="list-style-type: none"> • Max energy: 70MWh • Min energy: 20MWh • Min employment: unrestricted • Min soil recylement: unrestricted • Max $\sum j_s$: unrestricted • Compatibility parameters: <table border="1"> <tr> <td>Distance to residential zones</td> <td>j_r</td> </tr> <tr> <td>Max regulation zone</td> <td>Blue</td> </tr> </table>	Distance to residential zones	j_r	Max regulation zone	Blue	<ul style="list-style-type: none"> • Max energy: 140MWh • Min energy: 50MWh • Min employment: unrestricted • Min soil recylement: unrestricted • Max $\sum j_s$: unrestricted • Compatibility parameters: <table border="1"> <tr> <td>Distance to residential zones</td> <td>j_r</td> </tr> <tr> <td>Max regulation zone</td> <td>Blue</td> </tr> </table>	Distance to residential zones	j_r	Max regulation zone	Blue	<ul style="list-style-type: none"> • Max energy: 70MWh • Min energy: 20MWh • Min employment: 3500 • Min soil recylement: unrestricted • Max $\sum j_s$: unrestricted • Compatibility parameters: <table border="1"> <tr> <td>Distance to residential zones</td> <td>j_r</td> </tr> <tr> <td>Max regulation zone</td> <td>Blue</td> </tr> </table>	Distance to residential zones	j_r	Max regulation zone	Blue	<ul style="list-style-type: none"> • Max energy: 70MWh • Min energy: 20MWh • Min employment: unrestricted • Min soil recylement: 40 000 m²/yr • Max $\sum j_s$: unrestricted • Compatibility parameters: <table border="1"> <tr> <td>Distance to residential zones</td> <td>j_r</td> </tr> <tr> <td>Max regulation zone</td> <td>Blue</td> </tr> </table>	Distance to residential zones	j_r	Max regulation zone	Blue	<ul style="list-style-type: none"> • Max energy: 70MWh • Min energy: 20MWh • Min employment: unrestricted • Min soil recylement: unrestricted • Max $\sum j_s$: 80 ha • Compatibility parameters: <table border="1"> <tr> <td>Distance to residential zones</td> <td>j_r</td> </tr> <tr> <td>Max regulation zone</td> <td>Red</td> </tr> </table>	Distance to residential zones	j_r	Max regulation zone	Red
Distance to residential zones	j_r																							
Max regulation zone	Blue																							
Distance to residential zones	j_r																							
Max regulation zone	Blue																							
Distance to residential zones	j_r																							
Max regulation zone	Blue																							
Distance to residential zones	j_r																							
Max regulation zone	Blue																							
Distance to residential zones	j_r																							
Max regulation zone	Red																							

Figure 6.10 - Setting scenarios.

Baseline settings include a minimum and maximum electrical energy production (20-70 MWh), unrestricted amount of soil recycling, unrestricted amount of available hectares for redevelopment into SMEs (j_9), and site-activity compatibility of big factories (j_7) is restricted to sites located more than 500 meters away from residential zones (0), and classified as maximum as blue zones.

6.3.1. Energy production

This scenario assumes that the Metropolitan Council gives priority to renewable energy production in the choice of redevelopment options in the VoCI. That policy assumption is reflected in the model by increasing energy production upper and lower bounds to 50 and 140 MWh respectively. This upper bound is set at a level which would allow producing energy equivalent to the energy produced by the two aging power plants of Lyon (whose life-cycle is coming to an end).

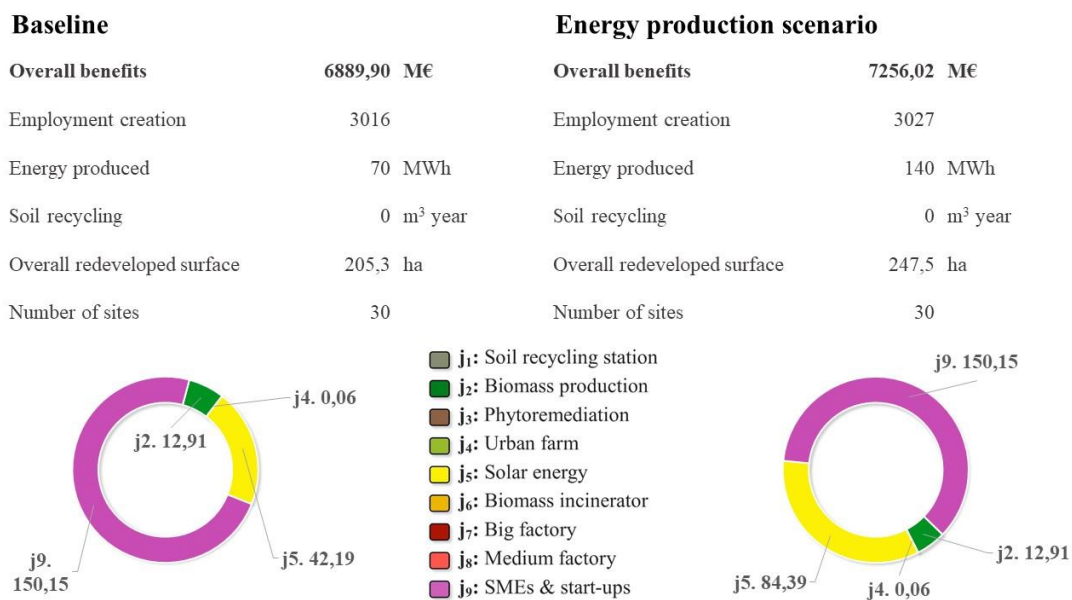


Figure 6.11 - Energy production scenario results.

Figure 6.11 displays the results of the energy production scenario. Raising the cap of energy production to 140 MWh allows increasing 5.31% of the overall benefits. Slightly reducing the creation of employment (-0.39%) and augmenting the overall redeveloped surface (+20.55%). Allocations of biomass production and SMEs remain, and redevelopment into solar energy generation doubles its surface (+100%).

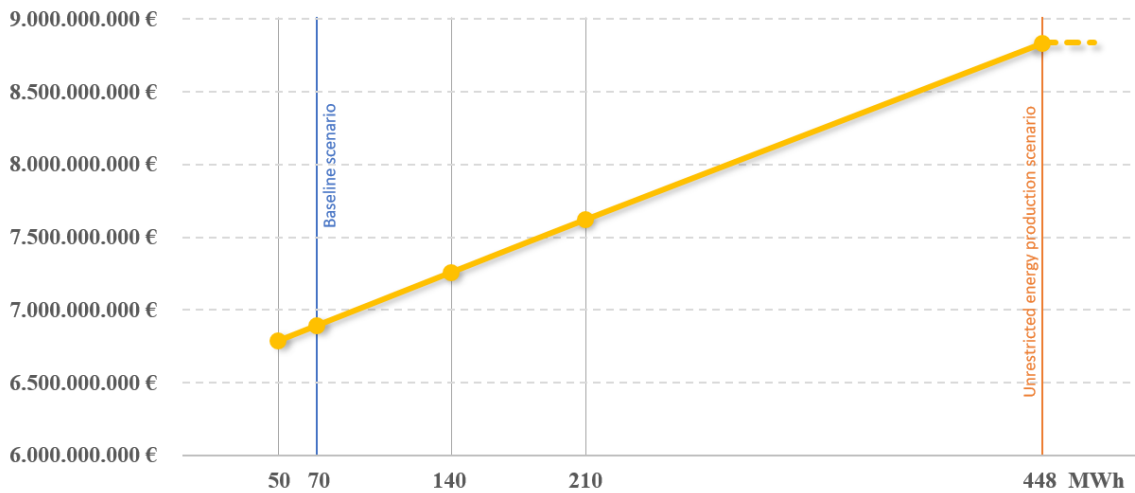


Figure 6.12 – Comparing energy production scenarios.

Figure 6.12 presents simulation results with 5 variations on the cap of energy production. The figure depicts the value of results with maximum energy production cap set at 50, 70, 140, 210 and unrestricted production. Clearly, the cap of energy production has a positive relation with the overall benefits. However, despite the growing trend on renewable energy demand, forecasts on energy requirements for upcoming years do not go beyond 210MWh. In addition, these results remain under the assumption that there is enough demand of energy to maintain the context of the estimation of benefits, this can be used as support for analysis and decision making. On another note, 100% of the energy is produced using solar energy allocations. Given the high returns and compatibility, results maximized the production of energy up to 448 MWh within the unrestricted scenario, which means that beyond point the optimal remains stable. Imposing a minimum production higher than 448 MWh would incur into a negative slope on the curve.

6.3.2. *Prioritizing employment*

The second scenario assumes that the Metropolitan Council wants to use BRF as a way to generate employment in the valley. This policy assumption is incorporated in the model by setting a minimum target for total employment equal to 3500 Equivalent Full-Time jobs. The model then looks for an optimal allocation that satisfies this minimum employment constraint.

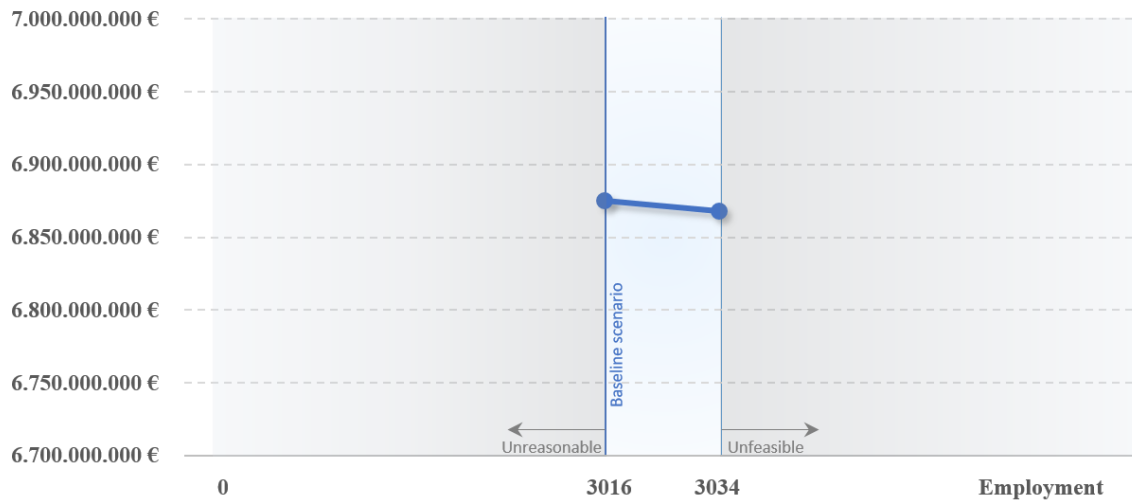


Figure 6.13 - Prioritizing employment scenario.

Meeting this employment constraint resulted unfeasible. This means that there is not enough room for changes in allocations so the outcome increases employment creation up to 3500. This is reasonable since baseline results maximized the allocation of j_9 which is also the activity with the higher employments per hectare estimations. Figure 6.13 displays results of the baseline scenario (3016 employments created) and a less ambitious scenario of increasing employment (3034). The curve clearly depicts that this change (+0.59% employment) had a slight negative impact on the overall benefit (-0.32%). The grey area between 0 and 3016 denotes unreasonable changes on parameters since requiring a minimum lower than the baseline gives the same results, and there is no interest on restricting the creation of employment. On the other hand, the grey area beyond 3034 indicates that requiring more employments is unfeasible.

6.3.3. Soil recycling

The third scenario assumes that the metropolitan council puts priority on soil management issues in defining a BFR strategy for the VoCI. The assumption is that the valley is well located to develop soil recycling factories, considering the proximity with works generating inert soils (supply of raw materials for the factory) and the short distance with new construction site in the metropolitan area which demand high quantities of fertile soil. The scenario is depicted in the model with a new constraint that imposes a minimum allocation of soil recycling station (j_1). The works of Lyon metropolitan administration yearly requires using between 50k and 100k m³ of functional soil and roughly generates 50k m³ of soil wastes. In this scenario, the minimum amount of soil recycling is set to 40k m³.

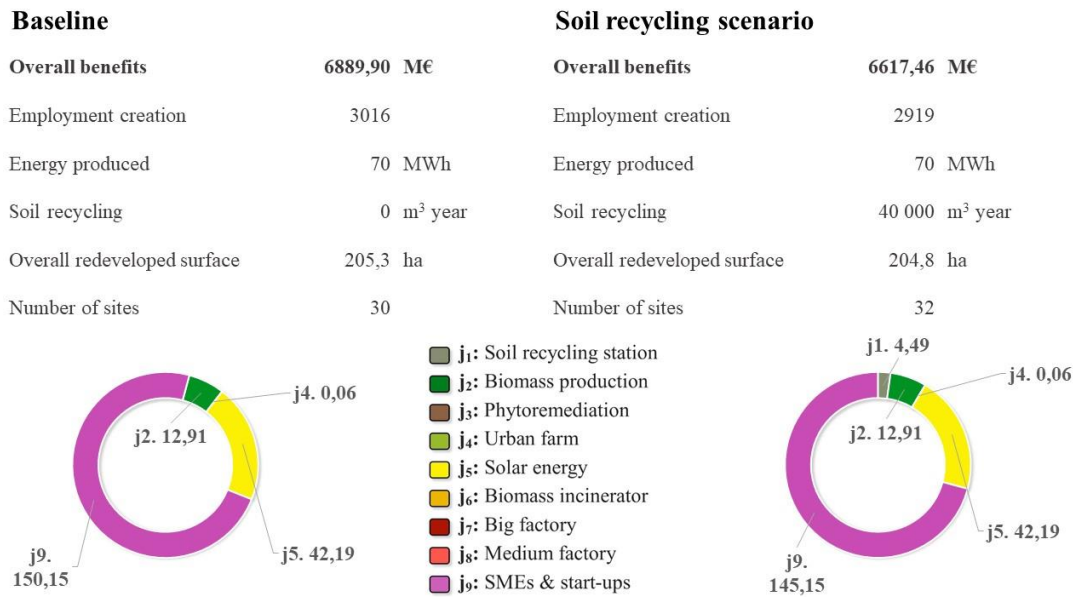


Figure 6.14 - Soil recycling scenario results.

Figure 6.14 displays results for the soil recycling scenario. Compared to the baseline settings, the 40k m³ of soil recycling scenario leads to lower overall benefits (-3.95%), and it slightly reduces the overall redeveloped surface (-0.25%), together with decreasing the creation of employment (-3.21%).

The main change in optimal solution is a reduction of the area allocated to SMEs (-3.33%) which is compensated with an increase of area dedicated to the soil recycling station (j₁). In addition, in this scenario the model reduced by 2 ha the allocation of solar energy (j₅) in i₅₃, and compensated it by allocating one hectare (of j₅) in two sites that were originally non-allocated (i₁₁ and i₂₀), which elevates the number of sites hosting redevelopment to 32. This modification is an example of having two or more available sites that offer similar economic outcomes, for which there is only one viable activity (j₅).

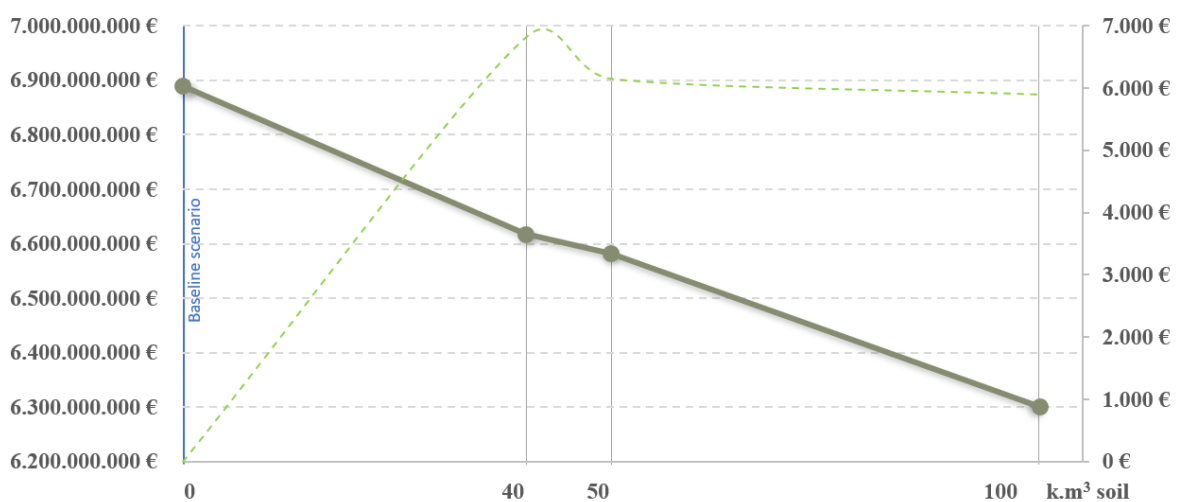


Figure 6.15 – Comparing soil recycling scenarios.

Figure 6.15 displays the outcomes of additional scenarios by varying the required amount of recycled soil. The curve shows that increasing this requirement has a negative impact on the overall benefits (supported on the left-hand vertical axis). When the constraint is increased up to 100 000 m³ of recycled soil the objective function decreases by 8.56% as compared to the baseline settings. Complementarily, the secondary curve of the figure (dotted line, scale on the right vertical axis) represents the evolution of the average cost of (€/ m³) of recycled soil. Therefore, if soil recycling must be prioritized, decision-makers might consider going straightforward for a capacity of 50 000 m³, where each m³ of recycled soil costs relatively less as compared to the 40 000 m³ scenario (-9.75%).

6.3.4. Relaxing compatibility constraints

This type of scenario illustrates how the model can be used to simulate and assess the impact of small changes in the parameters. Some initial constraints might result too restrictive, as for example the requirements of big factories (j_7) concerning the distance from residential zones and urban regulatory zoning. This section includes two scenarios relaxing these constraints. First, only the regulatory zoning constraint is relaxed. Then, both zoning and distance to residential zones constraints are relaxed. Finally, as baseline results including up to 150 ha of BFR into SMEs (j_9) seems unrealistic, in addition to the previous changes, a third scenario includes a restriction with a maximum area that could realistically be covered by j_9 within VoCI context (80ha).

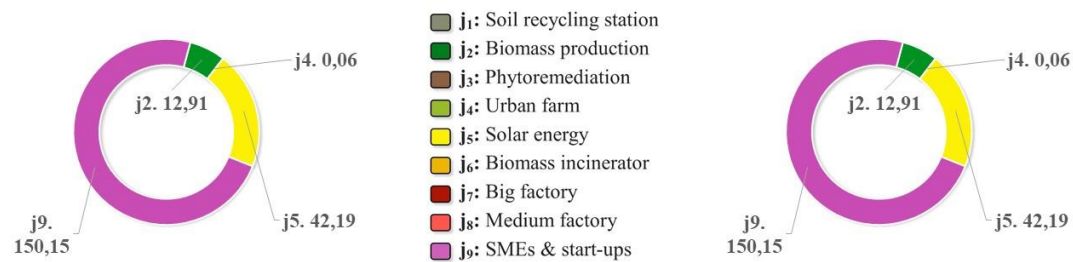
Figure 6.16 reveals that the first modification (zoning constraint only) is not enough of a change to affect the outcome. However, the second scenario (relaxing both zoning and distance restrictions) do allow allocating 15 ha to j_7 (big factory). As in the scenario of soil recycling, the modification is also produced in i_{55} . The surface originally allocated with biomass production (j_2) is entirely conceded to j_7 , one hectare allocated j_5 is transferred from i_{55} to a vacant surface on i_{53} , and only one hectare of j_9 is ceded. This scenario raises the overall net benefits up to 7449 million € (+8.12%) and creates 227 additional employments (+7.53%). On the other hand, the third scenario effectively restrains the allocation of j_9 down to 80 ha, which opens space to allocate 60,73 ha of medium-sized factories and 18,14 ha of big factories. However, this also provokes a reduction on the overall redeveloped surface of 3,8 ha (-1.85%), the overall net benefits (-10.5%), and the creation of employment (-13%).

Baseline

Overall benefits	6889,90 M€
Employment creation	3016
Energy produced	70 MWh
Soil recycling	0 m ³ year
Overall redeveloped surface	205,3 ha
Number of sites	30

1. Only zoning constraint relaxed

Overall benefits	6889,90 M€
Employment creation	3016
Energy produced	70 MWh
Soil recycling	0 m ³ year
Overall redeveloped surface	205,3 ha
Number of sites	30



2. Both constraints relaxed

Overall benefits	7449,11 M€
Employment creation	3243
Energy produced	70 MWh
Soil recycling	0 m ³ year
Overall redeveloped surface	206,3 ha
Number of sites	30

3. Constraints relaxed and j₉ maximal surface restriction

Overall benefits	6166,42 M€
Employment creation	2624
Energy produced	70 MWh
Soil recycling	0 m ³ year
Overall redeveloped surface	201,5 ha
Number of sites	30

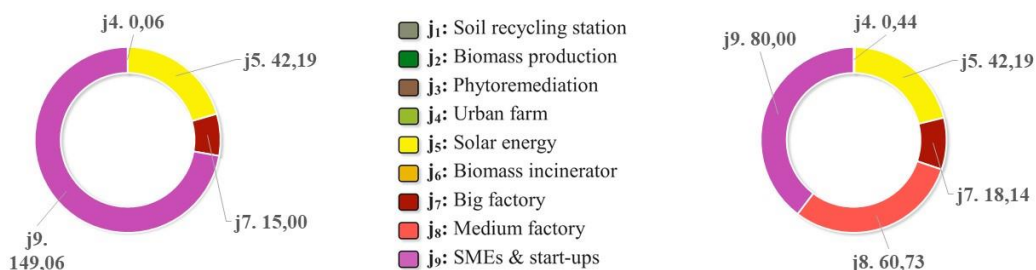


Figure 6.16 - Relaxing constraints scenarios.

6.4. Discussion and conclusion

First of all, this chapter has illustrated some simulations and applications of the economic model and its associated uncertainties. Although the strategy of starting points helped improving results, future research should include using the model with global optimizers.

Secondly, the stochastic approach portrayed an interesting representation of the sensibility of the model in regard to the uncertainty of rehabilitation costs. The findings of the test suggested very low sensitivity to this uncertainty. This present research does not include testing of uncertainty of the estimation of benefits and its sensitivity and its potential impacts on results robustness. This could be tested in future research. Moreover, future research could include a combination of the deterministic and stochastic

approaches. This would allow gradually upgrading site information as it becomes available (up to setting a known cost), and still maintain the randomized analysis for sites with less information. Results of such an approach would allow elaborating on an interpretation of changes in the total net benefits as a proxy of the value of information.

The final section shows how modifications in input parameters can alter the outcomes of model. This sheds light on the identification and analysis of decisive parameters such as the restrictions in regard to prevention zones, required distances to residential zones, or prioritizing the engagement on the management of soil importation/recycling. In essence, this proves that the model can only be used as a prescriptive tool in the measure of the certainty of the input data, but thanks to its flexibility it can effectively be used as a decision support tool to feed decision-making analysis.

General conclusion

This thesis contributes to the study of brownfield redevelopment in France by building an economic optimization model at a regional scale. To the best of my knowledge and belief, the work contained in this research explores a modelling approach that has not been previously published. The three main sources of originality of this research are the following. Firstly, the economic optimization model applied to brownfield redevelopment at regional level. It is inspired by mathematical programming approaches that are commonly used in agriculture and water management domains, but it is herein applied to the brownfield redevelopment domain where conventional approaches are mainly site-specific. Secondly, the empirical application of the model was carried out in a case study with an unusual context as compared to what is reported in the literature: a large industrial zone in which industrial activity still dominates, but which contains a multitude of small sites to be redeveloped. Also, this particular context conditioned the research decisions because, on top of a multiplicity of sites and future land use activities, sites to be rehabilitated are far from residential areas and remain embedded in an industrial zone, their redevelopment has therefore little (or no) impact on the utility function of local residents which makes it difficult to elicit their preferences either with survey methods (stated preferences) or from the revealed preferences. A third source of originality is the use of a possibilistic approach to deal with the difficulty of estimating rehabilitation costs at a regional scale, and ultimately use the resulting intervals of expected costs to illustrate an approach for testing the robustness of the solution of the model in regard to uncertainty.

In a domain where site-specific approaches are prioritized to ensure adequate decision-making in regard to the human-health and environmental risks of brownfield management, but recent multi-disciplinary efforts are trying to address the need of regional scale decision support tools, the primary goal of this research was to *develop an economic optimization model as part of an extended cost-benefit approach for brownfield redevelopment at a regional scale*. Accordingly, this study aims addressing the following research questions:

What is the optimal allocation of redevelopment for the brownfield sites in the valley of the chemical industry?

How can economic optimization on a regional scale be mobilized to support public decision-making in brownfields management?

What main factors of uncertainty compromise the application of regional economic optimization modelling approaches, and how can these factors of uncertainty be managed in order to implement robust economic assessments?

As a first contribution, the model developed in this research can help decision-making by quickly unveiling which future use activities are adequate for each site, account for interactions between sites and future land use activities that may entail additional benefits and/or costs (synergies), and test what are the most economically effective allocations under different scenarios. Solely a regional approach can provide this framework. At lower scale, it is more complicated or impossible to efficiently account for competition between redevelopment options, for example, to meet a quota for a certain objective (e.g. soil recycling) or to decide which allocations should be prioritized if there is limited budget for investment. Another contribution stems from the ability of the developed model to quickly simulate the impact of changes in different regulatory or redevelopment policy contexts, which cannot be determined beforehand since urban policies and decision-making are not driven by a single logic but are the product of deliberation integrating multiple factors. These contributions are consolidated by the urban planners' feedback on the outcomes of the model: They stressed that although in reality they need to include more intangible details in their analysis, the results of this research do match with their expectations in relative terms. Urban planners included in their feedback that testing contrasted scenarios can be particularly didactic to provide concise information to decision-makers who may have less time available to invest in knowing technical details. The solutions of the model presented in this research give solid indications to answer the question of the optimal allocation of the brownfields sites of VoCI. These results are particularly useful to explore scenarios and support public decision-making but are not prescriptive.

Imprecisions in brownfield redevelopment modelling mainly stem from epistemic uncertainty, which concerns the incomplete nature of available information. This issue is therefore magnified within regional approaches, where the cost of acquiring detailed information is substantially higher as compared to site level assessments which already deal with uncertainty. In this research, significant sources of uncertainty were encountered within setting the parameters of the model including policy context and details of sites and future land use activities, and within estimating input data concerning the costs and benefits of brownfield redevelopment.

The third contribution of the modelling approach presented in this thesis consists in demonstrating that the use of a stochastic approach can help managing the uncertainty embedded within the input data. This was illustrated by testing the robustness of a solution of the model in regard to the uncertainty of rehabilitation costs. The analysis allowed to conclude that the solution under the set of parameters and input data of the reference scenario was not very sensitive to the uncertainty of the rehabilitation costs. The same approach can be used to manage uncertainty stemming from benefits evaluation. This would require eliciting intervals of benefits, which can be done by varying the parameters of benefit transfer (using lower and upper bounds instead of averages, for instance for the value of CO₂). Benefits and costs intervals can also be used to set optimistic/pessimistic scenarios.

Another contribution of this thesis consists in the exploration of a methodological approach based on benefit transfer to extrapolate benefits references found in literature to a regional scale case study. This methodology allowed simplifying the complex (costly) task of using conventional valuation methods for the estimation of a wide range of benefits (i.e. matrix benefits-sites-future land use activities). Ideally, this approach will be based on well-adapted benefit transfer functions including several parameters to describe the specific context of each combination of sites-future land use activities. However, the literature did not provide enough references to cover all the benefits and details that were required given the specific context of the VoCI case study. This forced to apply much more simple adaptations of the references. Benefit estimation results were presented to the experts of the VoCI redevelopment task force and, although imperfect, were judged overall sufficient to proceed and carry out the methodological development in the field of modelling. This stage of the research invites to continue developing the benefit-transfer approach, and to carry more studies addressing monetary valuation of BFR benefits to provide more references for benefit transfer.

This research also contributes to literature by providing an effective illustration of using available data references and the subjective knowledge of experts to estimate the costs of rehabilitation costs. More precisely, this methodology allowed characterizing the uncertainty on rehabilitation costs by reducing it into intervals. Intervals can be nevertheless very informative, these can be used as a starting point for more detailed site level studies, and can also be used to determine which sites require more efforts to reduce uncertainty. The centre of the intervals was thereafter included in the model as a proxy for the expected rehabilitation costs of each site under the assumption that the centre of the intervals would be the least surprising values. Contribution of experts was a key resource to carry out the applied phase of this research and sets a valuable methodological precedent to build into and explore the reliability of using the possibilistic approach for the estimation of rehabilitation costs.

Concerning the replicability of the modelling approach, the model required a lot of data to give credibility to the outcomes. This was confirmed in the feedback from experts and urban planners. Since lack of data availability can compromise the proper identification and characterization of sites, future use activities, rehabilitation costs and BFR benefits, future efforts should try to identify which data is essential for carrying the model. Also, it may be possible to start with a site screening phase targeting the most sensitive sites and excluding from the analysis those sites with very little variability due to their characteristics (with little or no compatibility). This may avoid collecting information on very little variability sites.

As for perspectives, I believe that the present research could be enriched and developed by three main actions. The first path strives directly on the applied angle of the research: improving the valuation of multiple benefits in order to strengthen the model implementation. Herein I would suggest establishing a typology of sites and to devise an extended choice experiment (multiple sites – multiple future land

use activities) including an “in-built” outcome for meta-analysis (to extrapolate benefits for all sites) that feed the inputs of the model. This would first require carrying focus groups and a pilot survey. Then implementing a large survey, were several sites, attributes and scenarios would be included by using questionnaires in which the attributes have been randomly assigned to cover consistent representativeness.

Another path for further research includes an approach to continue simulations with the current model: gradually improve information according to availability in rehabilitation costs (by reducing uncertainty up to setting a known cost) and still maintain the randomized analysis for sites with less information. This approach would allow elaborating on an interpretation of changes in the total net benefits of the solution as a proxy of the value of information, and support decision-making in regard to the prioritization of efforts to reduce uncertainty.

The third way of improvement consists in taking a step back from the applied angle and emphasize from a theoretical angle on the main asset of this research: accounting for the needs and interactions of brownfield management at a regional scale (policies and synergies). Building on game-theory, I would develop a model to represent the dynamics of negotiation and decision-making of the stakeholders of brownfield redevelopment. This would allow to clearly elucidate more interactions and therefore identifying more benefits (and costs). The model could therefore be used to identify the institutional settings that are better suited to drive efficient brownfield redevelopment. A second phase could thereafter be included to test if the hypotheses made (benefits and effective policies) can be proven in reality.

As a final remark, keep in mind that brownfield management is a topical issue. This thesis is positioned in literature as an effort to improve the integration of economic sciences within the multidisciplinary efforts in the domain of brownfields management to find solutions in a sustainable development framework. While the number of brownfields is likely to keep increasing. Urban planners and decision makers are currently devising strategies to manage brownfield redevelopment at regional scales while dealing with uncertainty and scarce resources. There is therefore great scope for more studies in economics dealing with regional approaches for BFR, both for improving the modelling approach developed in this research, and for finding new ways to include economic analyses within the existing multidisciplinary stream of literature.

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