UNIVERSITE BRETAGNE LOIRE

UNIVERSITÉ DE NANTES

Thèse de Doctorat

Marjan MOUSAVI

Mémoire présenté en vue de l'obtention du
grade de Docteur de l'Université de Nantes
sous le sceau de l'Université Bretagne Loire

École doctorale : Sciences pour L'ingénieur

Discipline : Sciences pour l'ingénieur
Spécialité : Génie Civil
Unité de recherche : Génie Civil et Mécanique UMR CNRS 6183

Soutenue le **28 Novembre 2018**
Thèse N° :

Territorial Environmental Modeling of Cement Concrete Demolition Waste (CCDW) Management with a Life Cycle Approach

JURY

Président du jury	
Rapporteurs :	**Bernard CHRISTOPHE,** Professeur, Université d'Amiens
	Nicolas PERRY, Professeur, Université de Bordeaux
Examinateurs :	**Adélaïde FERAILLE,** Maître de Conférences, HDR, Ecole Nationale des Ponts et Chaussées
	Nordine LEKLOU, Maître de Conférences, HDR, Université de Nantes – Polytech (GeM)
Invité :	**Valéry FERBER,** Directeur scientifique, Charrier
	Stéphane LEPOCHAT, Directeur scientifique, Evéa
Directeur de Thèse :	**Anne VENTURA,** Chargée de recherche, HDR, IFSTTAR, Nantes
Co-directeur de Thèse :	**Nicolas ANTHEAUME,** Professeur, Université de Nantes – IAE (LEMNA)

Abstract

Recycling Construction and Demolition Waste (CDW) and conserving natural resources have become an essential issue in Europe due the huge amounts of waste generated and primary materials consumed every year in the construction sector. The aim of this PhD thesis was to evaluate the environmental performance of Cement Concrete Demolition Waste (CCDW) management in a given territory and to compare the current situation in this territory with different scenarios. The question was whether recycling would improve the environmental performance of waste management in the territory and minimize the dependence on primary materials. The territory understudy was *Loire-Atlantique* on the west coast of France. Recycled Cement Concrete (RCC) recycled from CCDW was considered to be a technically viable alternative to basic quality natural aggregates (A1- dependent co-product of the quarry process) to be used for the foundations of constructions or the sub-base of roads. Our territorial model of CCDW management was an expanded system including different processes and multiple reference flows such as: quarry process with its three co-products, recycling process, landfilling and stock of the demand-constrained materials. A combination of different methods was applied to evaluate the environmental performance of the territorial CCDW management in terms of 12 environmental impacts: Life Cycle Assessment (LCA), Materials Flow Analysis (MFA) and a local market mechanism model. LCA was used to estimate the potential environmental impacts of the territorial CCDW management. MFA provided us with information concerning the production and consumption of materials in the territory, associated with the territorial waste management, and accumulation of the materials in the territory (this issue is usually ignored in LCA studies). The local market mechanism model enabled us to investigate the possible decision procedures and parameters of buyers in the “basic quality aggregates” market. We then studied how they made choices between A1 and RCC in this market. As a consequence of these decisions, the waste stream towards the waste management system and the dynamics of the stock of materials were investigated. In this model, the real location of the market’s suppliers (quarries and recycling facilities) in the territory were found and used.

The environmental assessment results showed that the quarry process in the territory is the main contributor to the environmental impacts of the system we studied. The recycling process of CCDW had much lower environmental impacts compared to the quarry process. Transport was found to be negligible for all environmental impacts compared to other processes in the territory. The local market mechanism model revealed that the current mechanisms in the basic quality aggregate market were mainly structured based on the prices of the resources (A1 and RCC) and the buyers’ degree of confidence in the quality of RCC. Comparative environmental assessment results indicated that increasing the share of RCC in the market did not have substantial environmental benefits (except for the fossil cumulative energy demand, urban land occupation and depletion of the abiotic resource indicators). This was mainly due to the fact that, the lower environmental impacts of CCDW recycling were offset by the impacts of the stock of unused A1. Although replacing A1 with RCC in the foundations minimized the waste streams to landfills, it did not avoid A1 production in the quarry.

In order to decrease the dependence on primary materials in the construction sector, the quality of RCC needs to be improved to replace high quality natural aggregates (the determining co-product of the quarry process) in high-grade applications. In addition, it is required to work on the

buyers' confidence in the quality of RCC. However, an environmental analysis is required to determine whether using RCC as high-quality aggregates would significantly improve the environmental performance in the territory, especially if some modifications are required to obtain a better quality of RCC.
Key words: Construction and Demolition Waste (CDW) management, system expansion, Consequential Life Cycle Assessment (LCA), Material Flow Analysis (MFA), local market mechanism, modeling market mechanism, territorial impacts.

Acknowledgement

Funds for the research and education in chair of civil engineering and eco-construction were provided by the Chamber of Trade and Industry of Nantes and Saint-Nazaire cities, the CARENE (urban agglomeration of Saint-Nazaire), Charier, Architectes Ingénieurs Associés, Vinci construction, the Regional Federation of Buildings, and the Regional Federation of Public Works. I would like to thank them all for their financial support.

I would like to express my sincere gratitude to my director, **Prof. Anne Ventura** head of Chair-Civil Engineering and Eco-Construction at University of Nantes, and my co-director, **Prof. Nicolas Antheaume** director of the Institute of Economics and Management at University of Nantes, who gave me this opportunity to work on this interesting subject. I am sure this dissertation would not have been possible without their truly helpful support. Thank you, **Anne Ventura**, for all your scientific supports during my PhD concerning conceptual modeling and LCA. **Nicolas Antheaume**, thank you for your scientific support concerning market mechanism modelling. I was not so familiar with economic and market issues, but I have learnt a lot from you. Thanks for your good pieces of advice and your patience.

I would like to thank **Valéry Ferber** from Charier Company and **François Boisson** from CERC who patiently provided us with data required for my PhD thesis. Especial thanks to **Pierre Thiriet** from IRSTEA who helped me with GIS model and drawing a nice map.

I owe sincere thanks to **Dr. Naeem Adibi**, managing director at We-Loop, whose feedbacks enabled me to considerably improve my works.

I would like to thank **Prof. Bernard Christophe**, **Prof. Nicolas Perry**, **Adélaïde Feraille, Nordine Leklou**, **Valéry Ferber** and **Stéphane Lepochat** for accepting to take part in evaluation of my thesis and participate as jury members of my PhD.

To IEG team at institute of Research in Civil Engineering and Mechanics (GeM), IUT in Saint-Nazaire, France: Dear **Prof. Abdelhafid Khelidj**, thank you for so kindly welcoming me into your team, IEG. Thanks for all your supports during these three years, you always gave me energy. Dear **Prof. Didier Marot**, whenever I had any questions, you tried to help me kindly, thank you. Dear **Karine frocq**, I would never forget all your helps and supports when I arrived in France. You are missed at IEG. Especial thanks to **Abdo Yammine** who helped with the French summary. Finally, all PhD students, my colleagues and officemates at IEG, we shared a lot of good memories and laughter together. Thank you!

Dear **Luc** and **Marie Chereau**, thank you both for your great support and friendship during these three years. You were and still are like my family I have never had in France. I never felt like I was a foreigner, or I was from another culture. You, like parents, came with me step by step during these three years and were with me in any moments, happiness, success, sadness, disappointment. You were trying to teach me French and correct me patiently. I owe learning my new language to you! Thank you for letting me to be one of your family members. You cannot imagine how much I felt relaxed whenever I was with you. You could cheer me up easily. Again, thanks to **Anne Ventura** who introduced one of the most wonderful people in the world to me.

Dear **Line** and **Bernard Ventura**, I would never forget all your helps and supports especially in the beginning. You know how difficult it is to live in France without knowing the language, but you made things very easy for me. **Bernard** you were the only person whom I could communicate and speak in English with in the beginning. Once you told me that kindness is like a loop that would come back to yourself at the end. I wish all your kindness comes back to you lovely creatures.

Dear **Bob, Malika, Simeon** and **Augustin**, thanks for all your kindness and hospitality. **Augustin** and **Simeon**, you cannot imagine how you were able to drag me out of the PhD bubble and make me forget about all the challenges of PhD for a few hours I was spending with you.

Dear **Mireille Winka**, I would never forget that whenever I was tired of struggling with French and trying to speak French, you invited me over to discuss in English to rest my mind. Thank you!

The last but not least, I would like to express my deepest gratitude to my **father (baba), my mother (maman), my sister (Maryam)** and **my brother (Mohammad)** that without their help and support I would not have been here today. To my father, **baba** thank you for teaching me to be strong in the ups and downs of life and supporting me to pursue my goals. You have sacrificed your life for me to stand where I am now. I would never forget how much you insisted that I had to learn English. You have been supporting me since my first grade, and here I am in the last grade that you always wished for me. To my mother, **maman** thank you for your unconditional love and teaching me to be patient in the difficulties of life. During my disappointment moments, your sentence "don't worry! Everything will be OK!" was like a cure-all to any problems. I believe in your positive energy and it makes me calm down. To my sister, my best friend, **Maryam** thank you for your kindness and true friendship. You have been always beside me in any moments of my life and I have never felt this physical distance between us. You have always cheered me up in difficulties. To my brother, **Mohammad** thank you for being a great support for your little sister. You have been always there for me and ready to help me in any situation. Love you all!

At the end, I would like to cite a poem from one of the most famous poets and philosophers from my home country, Iran, Naser Khosrow:

درخت تو گر بار دانش بگیرد   به زیر آوری چرخ نیلوفری را

If the tree of human being gets the fruit of knowledge, you can bring the whole universe down.

Saint-Nazaire, France, 2018

Marjan Mousavi

Table of contents

List of Figures

List of Tables

Résumé étendu

La valorisation des déchets de construction et de démolition (DCD) et la préservation des ressources naturelles est devenue une préoccupation fondamentale en Europe, en raison des énormes quantités générées chaque année. En général, les déchets sont classifiées en trois catégories basées sur les réglementations, les déchets inertes, déchets dangereux et déchets non dangereux (European Commission, 2016). Les DCD incluent plusieurs matériaux dont parmi eux on trouve le béton, les céramiques, le bois, les métaux, les plastiques et d'autres mélanges de matériaux qui peuvent être majoritairement recyclés (Sonawane and Pimplikar, 2013). Le béton est classé comme un déchet inerte et représente un tiers des déchets de construction et de démolition (Pepe, 2015).

On estime à 1 milliard de tonne la production mondiale annuelle de DCD (Yazdanbakhsh et al., 2017). En Europe 450 à 970 millions de tonnes de DCD sont produits annuellement, avec une disparité selon les pays européens par rapport à la production par habitant. En France 5,9 de tonnes de DCD sont produits annuellement par habitant contre 15 tonnes pour le Luxembourg et 0,2 pour la Norvège (Pacheco-Torgal et al., 2013). Les déchets inertes représentent deux tiers des déchets totaux produit en France dont 95% proviennent du secteur du BTP (DREAL, 2014). En conséquence, des espaces sont occupées chaque année pour stocker les déchets inertes. Ainsi, le recyclage des DCD pourrait être une solution intéressante pour préserver les ressources naturelles, diminuer le débit de déchets dans les décharges et baisser l'impact environnemental.

Plusieurs études ont été menées dans l'optique d'évaluer la performance environnementale du recyclage des déchets de construction (principalement des déchets de démolition de béton) comme agrégats dans des applications de faible qualité ou de haute qualité (par exemple dans les éléments des structures en béton).

Cependant, malgré les études précédentes, il subsiste des incertitudes quant aux bénéfices environnementaux obtenus par le recyclage des DCD, en particulier les déchets inertes. Ce qui a abouti à poser les questions suivantes dans cette thèse :

- La promotion du recyclage dans le secteur de la construction conduirait-elle à minimiser la dépendance vis-à-vis des matières premières ?
- Le remplacement des ressources naturelles par des matériaux recyclés améliorerait-il les performances environnementales ?
- Des matériaux recyclés, tels que les granulats de béton recyclé (GBR), pourraient-ils être considérés comme une alternative appropriée aux matériaux naturels ?

En conséquence, l'objectif principal dans cette thèse sera d'évaluer la performance environnementale de la gestion des déchets de béton de démolition (DBD) dans un territoire donné pour sa situation actuelle et pour différents scénarios.

On suppose dans cette thèse que les granulats de béton recyclés (GBR) qui proviennent des déchets de béton de démolition (DBD), remplacent les granulats naturels de qualité basique selon les pratiques actuelles. Dans cette thèse ces granulats sont dénommés sous le terme

« A1 ». Les granulats naturels de qualités basiques sont utilisés dans les fondations, ainsi que dans les couches ou les sous-couches routières (Thorn and Brown, 1989).

Etude bibliographique

Selon l'étude de Marinkovic (2010), actuellement le béton de démolition est essentiellement recyclé dans des applications granulaires ou des couches de fondation des chaussées plutôt que des granulats utilisés pour produire du béton structurel de haute qualité (Marinković et al., 2010). Ceci est principalement dû aux propriétés inférieures des granulats de béton recyclés par rapport aux agrégats naturels, tels qu'une densité moindre, une porosité plus élevée et une absorption d'eau plus élevée (Etxeberria et al., 2007b). Les propriétés inférieures des granulats de béton recyclés sont dues au fait que le mortier et la pâte de ciment restent attachées aux GBR (par exemple Etxeberria et al., 2007b; Shayan and Xu, 2003). Cependant, la qualité des GBR est directement liée à la qualité du béton à la base dont provenaient les agrégats. Ainsi, le tri des déchets démolis est un facteur influent sur la qualité des granulats de béton recyclé.

Selon la littérature, les pratiques actuelles sont censées remplacer les granulats naturels de qualité basique (A1) par les GBR.

Afin d'évaluer la performance environnementale des GBR utilisés dans différents projets de construction, il est nécessaire de spécifier les circonstances dans lesquelles le béton démoli est traité et utilisé. Les conditions locales auront une influence sur les impacts environnementaux. Par exemple, on pourrait mettre l'accent sur les différentes technologies de traitement, les types de transport et les distances, les sources d'énergies, les applications d'agrégats et de béton recyclé, etc. (Marinković et al., 2010).

La plupart des études qui ont évalué la performance environnementale du recyclage des DCD ont utilisé l'analyse de cycle de vie (ACV) comme outil principal d'évaluation. En ACV, les possibles avantages de la valorisation des déchets pose un problème méthodologique, notamment lorsqu'un système produit un déchet valorisable dans un autre système. Ce problème est connu sous le nom du problème de multifonctionnalité du recyclage dans les ACV (van der Harst et al., 2016). Les résultats de l'ACV dépendent fortement des méthodologies choisies et des hypothèses formulées. Les méthodes de multifonctionnalité qui sont couramment utilisées pour modéliser recyclage dans l'ACV sont la méthode de l' « expansion de système » qui élargit le système en incluant le cycle de vie du déchet valorisé, la méthode des « impacts évités » qui est inclue une expansion de sytème mais soustrait ensuite les impacts du produit substitué par le déchet valorisé, la méthode « cut-off » et la méthode de l'affectation par partitionnement physique ou économique (e.g. Heijungs and Guinée, 2007b; van der Harst et al., 2016).

La plupart des méthodes utilisées par les études précédentes, pour effectuer une évaluation environnementale comparative entre les granulats naturels et recyclés, sont la méthode « cut-off » et la méthode « impacts évités ». (e.g. Knoeri et al., 2013; De Schepper et al., 2014; Dahlbo et al., 2015; Marinković et al., 2010; Wijayasundara et al., 2017; Yazdanbakhsh et al., 2017). Les résultats d'ACV de la plupart de ces études montrent que l'impact environnemental du béton à base de GBR est similaire ou légèrement inférieure à celle du béton fabriqué avec des granulats naturels (e.g. Marinković et al., 2010; Wijayasundara et al., 2017; Yazdanbakhsh et al., 2017). D'autres études ont montrés que l'utilisation des GBR dans les applications de faible qualité, telles que les fondations, les sous-couches routières ou les bétons maigres, présenterait des avantages environnementaux, principalement dans la prévention de l'enfouissement des DCD (Braunschweig et al., 2011; Woodward and Duffy, 2011). D'un autre côté, certaines études ont montré que les bénéfices environnementaux obtenus en utilisant des agrégats recyclés étaient significativement élevés, avec la méthode des « impacts évités » incluant une « expansion de système » (e.g. Knoeri et al., 2013; Yazdanbakhsh et al., 2017).

Dans le cas présent, il s'agit de modéliser le recyclage des DBD en GBR qui seront utilisées comme remplacement du granulat A1 dans les couches de fondation des chaussées (voir Figure II. 23). La méthode d'« expansion de systèm » couplée à celle des « imapcts évités » (comme le montre la Figure II. 23), devrait être appliquée, selon la littérature, pour modéliser le recyclage dans l'ACV. Cette méthode correspond au cas de la règle N°3 proposée par Weidema (2001). Dans les conditions de la règle N°3, lorsque les GBR remplacent le granulat A1 dans les fondations, le processus remplacé (processus de carrière) est considéré comment n'ayant aucun impact, les impacts du recyclage sont affectés au processus d'élaboration des fondations des chaussées et l'empêchement de la mise en décharge des DBD qui est l'avantage du recyclage des DBD. Par conséquent, les « impact évités » de la carrière et de la mise en décharge sont soustraits des impacts environnementaux totaux du système élargi.

Cependant, la méthode citée ci-dessus a des limites. Lorsque le processus remplacé d'un système étendu produit non seulement le produit remplacé, mais aussi d'autres coproduits, un nouveau problème de multifonctionnalité peut survenir. Dans notre étude de cas, le processus de carrière est un processus de co-production, qui produit trois catégories d'agrégats avec des qualités et des applications différentes, y compris A1, A2 et A3 (comme le montre Figure 1). A1 est principalement utilisé dans les fondations, A2 dans la base de la route et A3 dans les productions de béton de ciment et d'enrobé bitumineux.

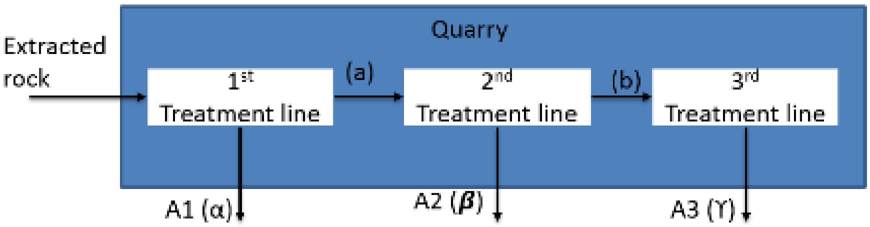


Figure 1 Processus de carrière de coproduction avec trois coproduits

En conséquence, l'étude de cas montre une complexité en ce qui concerne non seulement la modélisation du recyclage dans l'ACV, mais également les problèmes de multifonctionnalité en général pour le processus de recyclage et le processus de carrière. Comment les charges environnementales associées au processus de carrière devraient-elles être attribuées aux différents coproduits du processus de carrière ?

On peut utiliser le partitionnement pour séparer les charges environnementales allouées à la production du granulat A1 au sein du processus carrière. Cependant, cela pourrait montrer les conséquences environnementales de l'utilisation des matériaux recyclés du point de vue d'un utilisateur des matériaux recyclés, mais non du territoire. De plus le partitionnement ignore la relation physique entre le granulat A1 et les autres coproduits A2 et A3. Or, le granulat A3 est le coproduit déterminant du processus de carrière, qui détermine la production de la carrière et donc des autres coproduits A2 et A1. Par conséquent, les impacts environnementaux du processus carrière ne sont pas évités. Afin de donner un meilleur aperçu du territoire d'un point de vue environnemental, le modèle conceptuel de la Figure II. 28 est élargi pour inclure la demande du granulat A3 sur les marchés connexes (marchés du béton de ciment et d'enrobé bitumineux). Il est également nécessaire de considérer dans notre modèle que la production des autres coproduits (A1 et A2) est déterminée par la demande du granulat A3. Cela signifie que l'augmentation de la demande pour A3 augmentera l'accumulation de A1 et de A2 dans la carrière. Les variations de ces stocks sont affectées non seulement par les changements dans la demande de A3, mais aussi par la demande de A1 et de A2 sur le marché concerné. En conséquence, le système élargi présenté à la Figure II. 28 devrait inclure les stocks de A1 et A2 et les marchés connexes. Les modifications sont illustrées dans la Figure II. 32.

Comme montre la Figure II.32, le marché des granulats de qualité basique (marché 3 de la Figure II.32) a deux fournisseurs : le granulat A1 et les GBR. Par conséquent, il devrait y avoir une concurrence entre les deux ressources sur la base de laquelle l'accumulation de A1 dans le stock et le flux de déchets vers le processus de recyclage seront déterminés. Ainsi, il est nécessaire d'identifier les paramètres qui affectent la demande des granulats A1 et des GBR dans le marché 3.

Selon la littérature, le prix de vente est le principal paramètre qui affecte le choix des consommateurs sur le marché, par conséquent, nous supposons qu'il existe une concurrence entre les granulats A1 et les GBR sur la base du prix de vente sur le marché. Le prix total qu'un acheteur devrait payer sur le marché comprend également les prix de transport. Les distances de transport jouent ainsi un rôle important dans le choix des acheteurs sur le marché, étant donné que cela affecte le prix total.

Pour représenter la situation de façon plus fidèle à la réalité, il est nécessaire de développer un modèle d'un mécanisme de marché basé sur les prix du marché pour estimer les parts de A1 et des GBR dans le marché et les distances entre les distributeurs de granulats (carrières et plateformes de recyclage) et les acheteurs. En effet, selon la littérature, il existe une barrière culturelle à la promotion du recyclage des DCD qui se traduit par une méfiance des clients à l'égard de la qualité des granulats recyclés. Cette question est considérée comme un paramètre dans le modèle de mécanisme de marché à tester.

La fourniture des DBD est déterminée par les activités de démolition de bâtiments qui ont lieu dans un territoire donné au cours d'une année donnée. Il n'est pas nécessaire d'inclure le processus de démolition dans le système élargi de la Figure II. 32, puisque les activités de démolition ont lieu indépendamment de la demande des GBR. Par contre la décharge des DBD devrait être ajoutée au système étendu dans la Figure II. 32, puisque la quantité de DBD mise en décharge est supposée varier en fonction des changements dans la quantité de DBD recyclée. Si la quantité de DBD recyclée est inférieure à la quantité de DBD totale produite dans un territoire donné, le reste de DBD est supposé être déposé dans les décharges. En conséquence, la Figure II. 32 montre le modèle conceptuel final pour la gestion des DBD au niveau territorial. Les limites du système en cours d'étude seront restreintes comme la Figure II. 32 le montre en excluant les processus de fondation, l'enrobé bitumineux et le béton de ciment et le marché 4 du champ de l'étude. En résumé, la gestion territoriale des DBD et un modèle ACV basé dur la qualité des matériaux, l'analyse des flux de matériaux (AFM) et le modèle du mécanisme de marché. La gestion territoriale des DBD pourrait être appliquée pour n'importe quelle zone choisie en utilisant les données locales.

Méthodologie : Combinaison d'ACV, d'AFM et de modèle de mécanisme de marché :

Une combinaison de différentes méthodes est proposée pour évaluer la performance environnementale de la gestion territoriale des DBD : l'ACV, l'AFM et le modèle de mécanisme de marché. L'ACV est utilisée pour estimer les impacts environnementaux potentiels des processus physiques qui sont les éléments au sein desquels les impacts environnementaux ont lieu. Les flux et les processus dans le modèle de l'ACV sont adaptés au cas de la France en utilisant le logiciel UMBERTO. L'analyse des flux de matériaux est utilisée pour analyser les entrées et les sorties de matériaux du système en considérant l'interaction entre les éléments dans le système. Un système d'information géographique a été utilisé pour positionner les différents sites (carrières, plateformes de recyclage, et installations de stockage de déchets inertes) et calculer les distances de transports entre ces différents sites. La modélisation du mécanisme du marché est utilisée pour identifier la part du marché du granulat de qualité basique entre A1 et GBR. La part de marché obtenue pour GBR détermine le flux de déchets DBD vers la mise en décharge, tandis que la part de marché obtenue pour A1 détermine le flux de sortie du stock des A1 de la carrière.

Le modèle de mécanisme de marché est basé sur la comparaison des prix totaux des granulats A1 et des GBR, et en intégrant différents paramètres (notamment un facteur de confiance et un facteur de méfiance pour les GBR) (représenté sur la Figure III. 7). Sur la base de ces paramètres, nous définissons trois scénarios.

- Le scénario 1, qui reflète un modèle de mécanisme de marché basé sur les prix, et ne considère aucune préférence entre A1 et GBR pour les acheteurs de granulats de qualité basique sur le marché 3. Les choix des acheteurs sont donc exclusivement basés sur les prix totaux des produits.
- Le scénario 2 reflète un modèle de mécanisme de marché basé sur les prix avec un facteur de méfiance pour les GBR. Dans ce scénario, nous supposons qu'il faut une différence de prix de 15% pour que les acheteurs acceptent de choisir GBR. Le coefficient de 15% est nommé coefficient de méfiance.
- Au contraire, le scénario 3 reflète un modèle de mécanisme de marché basé sur le prix avec un facteur de confiance pour les GBR. Nous supposons que les acheteurs préfèrent acheter des GBR même s'ils étaient 15% plus chers que le granulat A1 en raison de leurs préoccupations environnementales.

Les résultats des scénarios : 1, 2 et 3 sont comparés à un scénario de référence reflétant la situation actuelle sur le territoire, en termes de parts A1/GBR sur le marché 3 pour valider la modélisation du mécanisme du marché (Figure III. 7).

En outre, nous considérons une application de la loi dans le marché 3 pour définir le scénario 4 et le scénario 5. Dans le scénario 4, nous supposons une utilisation obligatoire des GBR au lieu du granulat A1. Au contraire, dans le scénario 5, nous supposons une utilisation obligatoire de A1 au lieu des GBR.

Enfin, nous visons à comparer les résultats des cinq scénarios avec ceux du scénario de référence en termes de 12 impacts environnementaux enfin d'identifier si ces scénarios affectent significativement la performance environnementale de la gestion territoriale des DBD.

Résultats

Le territoire étudié dans cette thèse est le département de la *Loire-Atlantique* situé sur la côte ouest de la France. Les données concernant la consommation et la production de matériaux associés à la gestion territoriale des DBD ont été collectées ou estimées en utilisant différentes sources, telles que les données statistiques, la base de données des plateformes et la littérature.

Les données statistiques révèlent les parts de A1 et des GBR dans le marché 3 pour le scénario de référence, respectivement 94% et 6%. Les résultats de l'évaluation environnementale montrent que le principal facteur contribuant aux impacts environnementaux est le processus de carrière, car d'énormes quantités d'agrégats naturels ont été produites sur le territoire. Les impacts du processus de recyclage par rapport au processus de la carrière ne sont pas considérables. Le transport a été jugé négligeable pour tous les impacts environnementaux par rapport aux autres processus de la gestion territoriale des DBD.

Les parts de A1 et des GBR sur le marché 3 résultant du modèle du mécanisme du marché fondé sur les prix (scénario 1) sont respectivement 62% et 38%. Les parts de A1 et des GBR dans le marché 3 sont largement éloignés de celles du scénario de référence ce qui est plus ou moins évident (94% pour A1 contre 6% pour les GBR dans le marché 3). Cela signifie que, si le mécanisme du marché était basé sur les prix, il était possible d'augmenter la part des GBR à 38% dans le marché 3. En revanche, les parts de A1 et des GBR sur marché 3 issues du scénario 2 incluant un facteur de méfiance pour les GBR sont proches de celles du scénario de référence. Les valeurs sont respectivement de 90% et 10% pour le granulat A1 et les GBR. Les parts de A1 et des GBR sont obtenues à partie du scénario 3 sont similaires à celles du scénario 1.

D'un point de vue environnemental aucune différence substantielle n'existe entre les scénarios de référence, et les scénarios : 1,2 et 3 (comme le montre la Figure 2). Les performances environnementales de la gestion territoriale des DBD sont légèrement améliorées dans le scénario 1 et le scénario 3 par rapport au scénario de référence. Les plus grandes différences dans la Figure 2 sont pour la demande cumulée d'énergie fossile, l'occupation des terres urbaines et l'épuisement des indicateurs de ressources abiotiques.

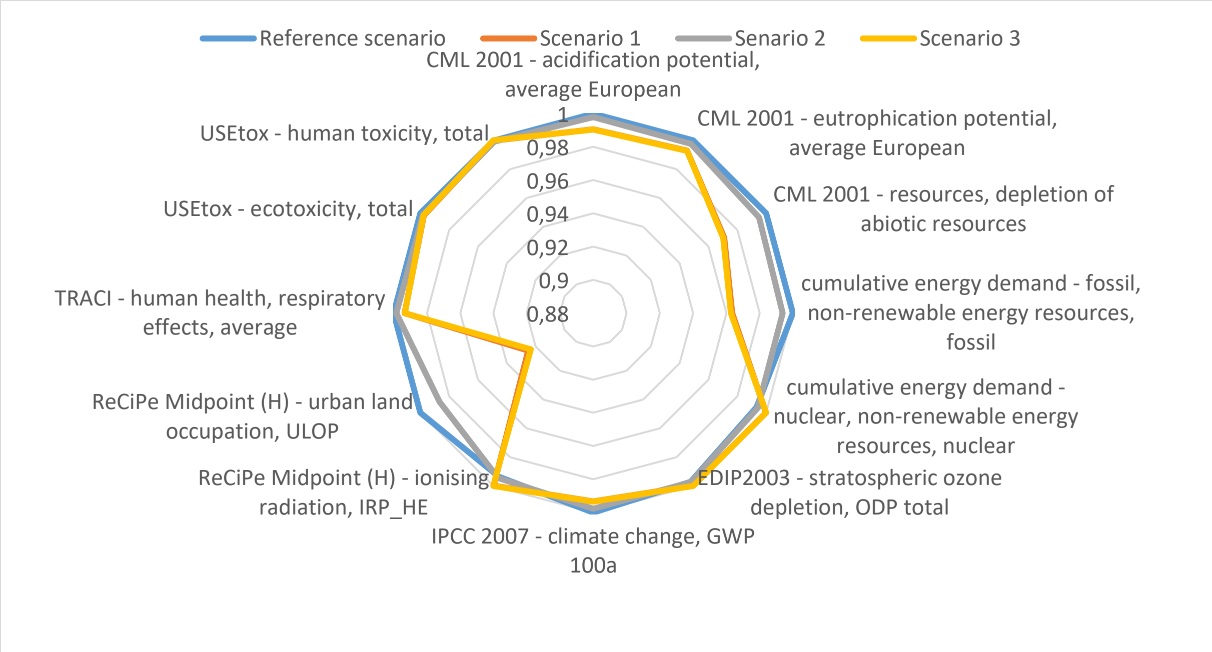


Figure 2 Comparaison des indicateurs d'impact environnemental mesurés pour le modèle environnemental territorial de la gestion des DBD en Loire-Atlantique avec quatre conditions différentes sur le marché 3. Les 4 différentes conditions : « scénario de référence : 94% A1 contre 6% GBR ; scénario 1 : 62% A1 contre 38% GBR, scénario 2 : 90% A1 contre 10% GBR et scénario 3 : 61% A1 contre 39% GBR, tous dans le marché 3.

La comparaison des résultats de l'évaluation environnementale entre les scénarios de référence, le scénario 4 et le scénario 5, montrent une légère amélioration de la performance environnementale du scénario 4 par rapport au scénario de référence, comme le montre la Figure 3.

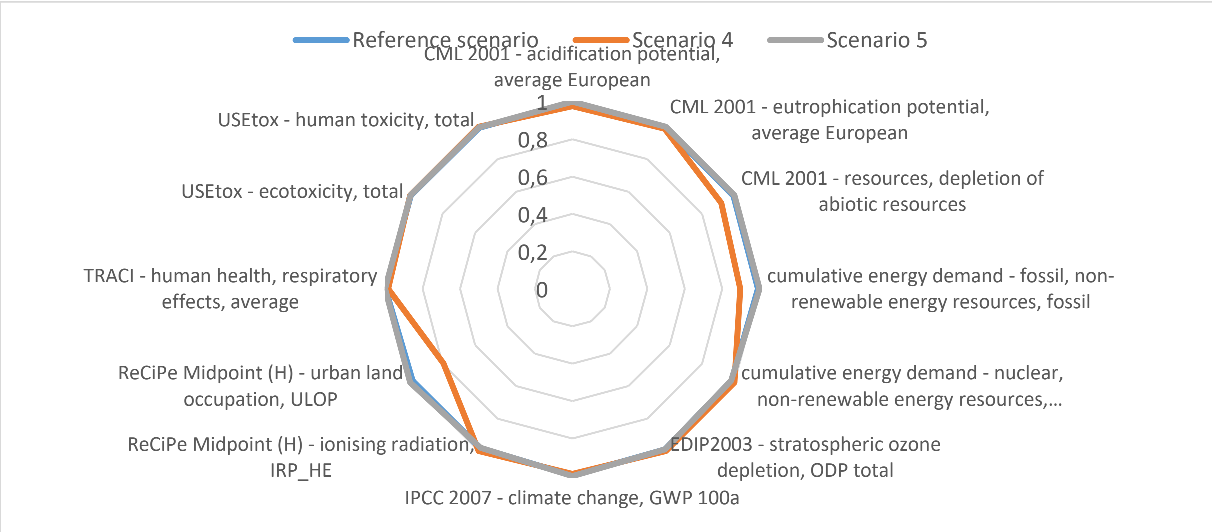


Figure 3 Comparaison des indicateurs d'impact environnemental mesurés pour le modèle environnemental territorial de la gestion des DBD en Loire-Atlantique avec quatre conditions différentes sur le marché 3. Les 4 différentes conditions : « scénario de référence : 94% A1 contre 6% GBR ; scénario 4 : 0% A1 contre 100% GBR, scénario 5 : 100% A1 contre 0% GBR, tous dans le marché 3.

Conclusions

La méthodologie proposée dans cette thèse nous a permis d'évaluer la performance environnementale de la gestion des DBD en *Loire-Atlantique* pour la situation actuelle du territoire et pour différents scénarios. Ainsi on a pu répondre aux différentes questions demandées.

Par conséquent, l'utilisation des GBR au lieu de granulats naturels dans les applications de qualités basiques (fondations des chaussées) ne réduirait pas la dépendance aux matériaux primaires, car peu importe le fait qu'une demande existe ou pas au granulat A1, une production locale de ce granulat existe même si elle n'est pas utilisée. En effet, des carrières sont toujours nécessaires pour produire les granulats A2 et A3 pour des applications de qualité supérieure (pour l'enrobé bitumineux et le béton de ciment). Seule une légère amélioration de la performance environnementale de la gestion territoriale des DBD est obtenue par le remplacement de A1 par les GBR, sur certains indicateurs seulement. Ceci est principalement dû au stock d'A1 non utilisé dans les carrières. Les GBR pourraient être considérés comme une alternative appropriée aux agrégats naturels. Les raisons pour lesquelles cette alternative est intéressante sont, l'équivalence techniques entre A1 et GBR, les bénéfices économiques plus intéressants des GBR et l'impact environnemental de production plus faible des GBR en comparaison avec les granulats naturels A1 des carrières.

Afin de bénéficier des avantages environnementaux plus élevés, les politiques du marché devraient se concentrer sur le développement de projet d'économie circulaire lorsqu'il existe une solution de recyclage techniquement faisable pour les coproduits principaux (par exemple A3) ou qu'il existe une demande de coproduit (exemple A1) qui est plus élevée que la production de ce coproduit. En effet, mettre l'accent sur le recyclage d'un produit qui remplace en coproduit dépendant ne conduirait pas à une diminution de la production de ce coproduit.

Cependant, d'autres études sont nécessaires pour pouvoir améliorer la qualité des GBR pour qu'ils puissent devenir techniquement équivalent au granulat A3. De plus, il serait nécessaire de mener de compléter notre modèle notamment si l'augmentation de la qualité des GBR nécessite des processus supplémentaires (meilleur tri, plusieurs étapes de concassage) afin de déterminer si la modification du type d'agrégats dans les applications de haute qualité (béton de ciment structurel) du granulat A3 aux GBR entraine des avantages environnementaux significatifs.

The list bellow can be used as an easy accessible reference for definitions or interpretations of some terms and vocabulary that have been used in this thesis.

Glossary

A1- Primary category of natural aggregates	Natural aggregates goes through the first crusher (treatment process) in the quarry. It is one of the dependent co-products of the quarry process that has lower quality compared to tertiary category of natural aggregates (A3). A1 is also called basic quality natural aggregates in this PhD thesis.
A2- Secondary category of natural aggregates	Natural aggregates goes through the first and second crushers (treatment process) in the quarry. It is one of the dependent co-products of the quarry process that has lower quality compared to tertiary category of natural aggregates (A3). A2 is also called intermediate quality natural aggregates in this PhD thesis.
A3- Tertiary category of natural aggregates	Natural aggregates goes through the first, second and third crushers (treatment process) in the quarry. It is determining co-product of the quarry process that has higher quality compared to primary category of natural aggregates (A1) and secondary category of natural aggregates (A2). Therefore, it is mostly used in the concrete mixes. A3 is also called high quality natural aggregates in this PhD thesis.
Aggregate	Mineral materials such as gravel and crushed stones
Bituminous concrete	Contains mainly bitumen and aggregates (crushed gravels) that aggregate constitutes the largest proportion, about 92-96% of the total concrete volume.
Cement concrete	Contains mainly cement, water, sand and aggregates (crushed gravels) that aggregate constitutes the largest proportion, about 70-80% of the total concrete volume.
Cement Concrete Demolition Waste- CCDW	It is produced from demolition of building, tunnels and bridges.
Construction and Demolition Waste- CDW	Including mainly concrete, wood, asphalt, metals and plastics, which many of them could be recycled.
Co-producing/ co-production process	A process which yields more than one product (co-product) or functional outflow. It is considered as joint production.

Co-product	Any of two or more products coming from the same unit process or system.
Dependent co-product	One of the co-products of the joint production (or co-producing process) that does not identify the production volume of co-producing process.
Determining co-product	One of the co-products of the joint production (or co-producing process) for which a change in demand will affect the production volume of the co-producing process. It usually provides the highest revenue to the process.
Functional flow	A product produced from a process, or a waste treated by a process.
Hazardous waste	The waste that is dangerous or potentially harmful to our health or the environment. Hazardous wastes can be liquids, solids, gases, or sludge. They can be discarded commercial products, like cleaning fluids or pesticides, or the by-products of manufacturing processes (EPA, 2016).
Impact value- SZ	It gives a measure of the resistance of aggregates to dynamic crushing, and is equal to one fifth of the sum of the mass percentages of the tested sample passing through five specified test sieves (NF EN 1097-2, 2010).
Inert waste	The waste that does not undergo any significant physical, chemical or biological transformations. Inert waste will not dissolve, burn or otherwise physically or chemically react, biodegrade or adversely affect other matter with which it comes into contact in a way likely to give rise to environmental pollution or harm human health. The total leachability and pollutant content of the waste and the ecotoxicity of the leachate must be insignificant, and in particular not endanger the quality of surface water and/or groundwater (Directive 2006/21/EC, 2006).
Joint production	Refers to a production process that produces different co-products with fixed relative output volume. In other words, it produces different co-products whose production volumes cannot be independently changed. In this PhD thesis co-producing process refers to joint production.
Los Angeles coefficient- LA	Percentage of the test portion passing a pre-determined sieve after completion of the test (NF EN 1097-2, 2010).

Multi-functional process	A process yields more than one functional flow, such as recycling or co-production process.
Multi-functionality/ allocation problems	A situation in which the functional flows of a multi-functional process is not used by just one product system. Therefore, the environmental burdens should be shared between different product systems. This situation may happen due to recycling or co-production process.
Natural aggregate concrete- NAC	Concrete made from natural aggregate.
Non-hazardous waste	Waste which is not classified as hazardous waste (EEA, 2016).
Product system	"Collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product." (ISO, 2006a)
Recycled aggregate- RA	It is produced from treatment of waste generated from demolition of concrete structures and other construction wastes such as concrete waste, rejected precast concrete members, broken masonry, concrete road beds and asphalt pavements.
Recycled aggregate concrete- RAC	Concrete made with RCA.
[1]Recycled concrete aggregate- RCA	It is produced from crushing of demolished concrete, and screening and removal of contaminants such as reinforcement, paper, wood, plastic and gypsum. In this thesis project by mentioning Recycled Cement Concrete (RCC), RCA is implied.
Recycled Cement Concrete- RCC	It is produced from crushing of demolished concrete. In this thesis project by mentioning RCA, RCC is implied. RCC is considered as basic quality aggregates.
Test portion	Sample used as a whole in a single test (NF EN 1097-2, 2010).

[1] In this thesis "recycled aggregate" and "recycled concrete aggregate" are used interchangeably as general terms for recycled materials. But the terms "RA" and "RCA" refer to the specific types of recycled aggregates as defined above. Likewise, "recycled aggregate concrete" can represent concrete made from recycled aggregate, but "RAC" does not.

Test specimen	Sample used in a single determination when a test method requires more than one determination of a property (NF EN 1097-2, 2010)
Basic quality aggregates	Refer to primary category of natural aggregates (A1) and Recycled Cement Concrete (RCC) together.
Unit process	Processes included in the product system or product's life cycle, for which input and output flows are identified.

List of symbols

A1	Basic quality natural aggregates (primary category of natural aggregates)
A2	Intermediate quality natural aggregates (secondary category of natural aggregates)
A3	High quality natural aggregates (tertiary category of natural aggregates)
A3BC	High quality natural aggregates (A3) for the bituminous concrete market
A3CC	High quality natural aggregates (A3) for the cement concrete market
BC	Bituminous concrete
BQA	Basic quality aggregates
CC	Cement concrete
CCDW	Cement Concrete Demolition Wastes
D_{A1}	Demand for basic quality natural aggregates (A1) in the basic quality aggregate market
D_{A2}	Demand for intermediate quality natural aggregates (A2)
D_{A3}	Demand for high quality natural aggregates (A3)
D_{A3BC}	Demand for high quality natural aggregates (A3) in the bituminous concrete market
D_{A3CC}	Demand for high quality natural aggregates (A3) in the cement concrete market
D_{BQA}	Demand for basic quality aggregates in the basic quality aggregate market
D_{RCC}	Demand for Recycled Cement Concrete in the basic quality aggregate market
LCCDW	Fraction (L) of Cement Concrete Demolition Wastes sent to the landfill
Market 1	Bituminous concrete market
Market 2	Cement concrete market
Market 3	Basic quality aggregate market
Market 4	Road base market
P_{A1}	Production of basic quality natural aggregates (A1) in the quarry
P_{A2}	Production of intermediate quality natural aggregates (A2) in the quarry
P_{A3}	Production of high quality natural aggregates (A3) in the quarry
RCC	Recycled Cement Concrete
RCCDW	Fraction (R) of Cement Concrete Demolition Wastes sent to the recycling facilities

INTRODUCTION

1.1 General context

A constant and rapid increase in the generation of Construction and Demolition Waste (CDW) and the consumption of natural resources have become some of the biggest environmental problems in the construction sector. CDW consists of numerous materials_40% concrete, 30% ceramics, 10% wood, 5% metals, 5% plastics and 10% other mixtures_ which mostly could be recycled (Sonawane and Pimplikar, 2013). According to Pepe (2015), materials included in CDW have different qualities and demolished concrete represents about one third of total CDW. This is mainly due to the high compressive strength of concrete, its high durability, low maintenance cost and resistance to different weather conditions as well as its low purchase price compared to other construction materials (Behera et al., 2014). Therefore, it is one of the most widely used construction materials (Behera et al., 2014).

CDW annual production in the world is about 1 billion tons (Yazdanbakhsh et al., 2017). About 450-970 million tons of CDW are produced yearly in Europe, with differences in the amount of CDW generated per capita for different countries in Europe, e.g. about 5.9 tons per capita in France (Pacheco-Torgal et al., 2013). Inert waste materials (such as non-polluted soil and loose materials, gravels and rock materials and concrete demolition wastes) represent two third of the total waste generated in France 95% of which is produced by the building and public work sectors (DREAL, 2014). In 2012, about 8.2 million tons of inert waste was generated in the *Pays de la Loire* region in France (DREAL, 2014). And about 3.8 million tons of inert waste were generated from public works and buildings in *Loire-Atlantique* in France the same year(CERC, 2013).

About 20 billion tons of aggregate are consumed every year on a global scale and an annual growth rate of 4.7% is expected (Pacheco-Torgal et al., 2013). This leads to the consumption of non-renewable raw materials, energy consumption and to a reduction of biodiversity at extraction sites (Pacheco-Torgal et al., 2013). Hence, special care regarding its utilization is required and they must be produced and used according to sustainable development principles (Blengini and Garbarino, 2010) to be able to minimize economic, energy and environmental burdens caused by the construction industry.

Accordingly, it is required to focus more on recycling CDW. According to common belief, recycling in general improves environmental performance, since it is expected to decrease the demand for landfilling, the extraction of natural resources and the generation of air, water and soil pollution. Our society seems to be favorable to recycling because it is viewed as a way to conserve natural resources which in turn is expected to decrease environmental impacts. The European Commission (2008) stated that, compared to other waste management options, the benefits from recycling outweigh energy recovery or landfilling. In general, waste recycling is expected to return a discarded material to the original system, which in turn might result in minimizing energy consumption and environmental impacts due to the substitution of virgin materials with recycled materials (Damanhur, 2012).

Three factors need to be taken into consideration for recycling: its technical viability, its environmental benefits and its economic feasibility (Elshkaki and van der Voet, 2004). The environmental benefits from recycling in general depend on the recycling process and the avoided processes (such as extraction of raw materials and landfilling) (van der Harst et al., 2016). In other words, the recycling process can be environmentally beneficial, if the environmental burdens of the recycling process are less than those of the avoided processes, such as extraction of raw materials and production of materials (van der Harst et al., 2016). Besides considering the environmental benefits from recycling, it is required to investigate if there is an actual market for recycled materials, otherwise environmental improvements from recycling, if any, would not be practically viable.

Recycling CDW could be a potential solution to conserve natural resources and minimize environmental impacts. Sustainable development through climate actions and resource efficiency is one of the main targets of the EU framework program for research and Innovation-Horizon 2020, which would affect the future of the European construction industries. The influence of resource efficiency on the construction sector has been mentioned in COM 571 as follows (Pacheco-Torgal, 2014):

"By 2020 the renovation and construction of buildings and infrastructure will be made to high resource efficiency levels. The Lifecycle approach will be widely applied; all new buildings will be nearly zero-energy and highly material efficient and policies for renovating the existing building stock will be in place so that it is cost-efficiently refurbished at a rate of 2% per year. 70% of nonhazardous construction and demolition waste will be recycled."

Different studies have been carried out to evaluate the environmental performance of recycling CDW (mostly concrete demolition waste) to be used as aggregates in different applications (e.g. concrete or foundations) by using Life Cycle Assessment (LCA) as the main methodology. Most of these studies have used avoided processes (e.g. avoided landfilling or avoided quarry due to recycling) as the environmental benefits of recycling CDW.

Despite the previous studies on environmental assessment of CDW recycling, there are still uncertainties about environmental benefits gained from recycling CDW, especially with inert waste materials (such as concrete demolition waste). It is required to consider local conditions related to a specific case study for managing the construction materials. Replacing natural resources by recycled materials may cause some indirect environmental consequences (either positive or negative) on other processes through economic market mechanisms. As a matter of fact, decreasing the demand for a product in the market does not necessarily decrease the production of that product. Therefore, the environmental assessment of recycling CDW through life cycle assessment has given rise to further research questions. The main questions to be answered are:

- Would promoting recycling in the construction sector lead to minimizing the dependence on primary materials?
- Would replacing natural resources by recycled material improve environmental performances?
- Could recycled materials, such as Recycled Cement Concrete (RCC), be considered as a proper alternative to natural materials?

In this thesis, it is assumed that RCC, which is recycled from Cement Concrete Demolition Waste (CCDW), replaces basic quality natural aggregates based on actual practices. Basic quality natural aggregates have the lowest quality of natural aggregates processed in the quarries. In this thesis, they are denominated as A1. Basic quality aggregates are not usually bounded by cementitious materials or bituminous binders, rather they are mostly used in the foundations of constructions or as sub-base for roads (Thorn and Brown, 1989).

1.2 **Objective and sub-objectives**

The main objective of this PhD is to assess the environmental performance of Cement Concrete Demolition Waste (CCDW) management for current situation and prospective scenarios, in a given territory, in order to provide answers to the main research questions listed at the end of section 1.1.

The following sub-objectives serve to achieve the main objective of the PhD thesis:

- Studying the technical replacement feasibility of natural aggregates by RCC;
- Comparing physical and mechanical properties of RCC with that of natural aggregates;
- Identifying the main applications of RCC, based on its quality;
- Providing information about the characteristics of recycling in Life Cycle Assessment (LCA);
- Providing an overview of the state of the art on modeling of recycling in LCA and on allocation problems of recycling;
- Developing a territorial environmental model of CCDW management using an LCA approach, at local scale, based on a review of literature;

The territorial environmental model of CCDW management is used as the basis for comparing different scenarios in terms of environmental performance that may help decision makers involved in the waste management.

The territory understudy in this PhD is *Loire-Atlantique*, one of the departments of the *Pays de la Loire* region, on the west coast of France.

1.3 **Outline of the thesis**

This thesis comprises 6 chapters:

Chapter I: describes the general context of the thesis, as well as its general aims and objectives.

Chapter II: describes the quality assessment of materials (natural aggregates and recycled concrete aggregates), the recycling process of CDW, the applications of recycled concrete aggregate based on its quality, introduction to LCA and MFA and different types of stocks. It also reviews the environmental assessment studies on recycling concrete demolition waste and different methods used in these studies to model recycling in LCA to account for credits and burdens from recycling. Finally, this chapter proposes and justifies a new conceptual model for the territorial environmental model of CCDW management.

Chapter III: presents how different elements included in the conceptual model of the territorial CCDW management are interacting, interrelating and interdependent. It proposes a methodology by combing different methods: LCA, MFA and a local market mechanism by considering the quality of materials. Different scenarios regarding CCDW management are discussed and defined in this chapter.

Chapter IV: introduces the territory understudy in this PhD and data related to the current situation in this territory, including real locations of quarries and recycling facilities (sellers of basic quality aggregates), the current structure of the basic quality aggregate market, production and consumption of materials in the territory. It presents the results of different scenarios defined in Chapter III. Finally, this chapter compares different scenarios with the current situation in the territory from an environmental point of view to identify whether increasing the share of RCC in the market significantly affects the environmental performance of CCDW management in the territory or not.

Chapter V: discusses whether the methodology proposed in this PhD could reach the main aim of this PhD and provide answers to the main research questions. It also discusses the limits of this PhD thesis.

Chapter VI: presents a general conclusion and discusses avenues for future research.

CHAPTER II Literature review

2.1 Introduction

This chapter presents the general context of natural and recycled aggregates in the construction sector, their amounts and existing regulations in the context of recycling. Materials' quality and their applications based on their quality are then discussed.

In addition, the main aspects of Life Cycle Assessment (LCA) methodology with regard to ISO standards and procedures to model recycling in LCA and overcome the multi-functionality problems of recycling are introduced. Besides, basics of material flow analysis (MFA) are presented.

Different studies on comparative environmental assessment of natural aggregates and recycled concrete aggregates are reviewed to discover the methodologies used and assumptions made for environmental assessment of recycling.

Accordingly, an environmental modeling approach for our case study of Cement Concrete Demolition Waste (CCDW) management in the territory understudy, *Loire-Atlantique* in France, is introduced based on coupling LCA, MFA and market economy to provide a general conceptual model.

2.2 General context

2.2.1 Consumption of aggregates and concrete

Aggregates, which represent mineral materials such as sand, gravel and crushed stone, are used with binders such as Portland cement, bitumen, lime etc. to form construction materials such as bituminous concrete and Portland cement concrete. Aggregates constitute the largest proportion in concrete volume (about 70-80% of the total volume of Portland cement concrete and 92-96% of the total volume of bituminous concrete).

Natural aggregates are valuable resources for the social and economic development of human beings (Blengini and Garbarino, 2010). Therefore, special care regarding their utilization is required (Mathew and Krishna Rao, 2007). They must be produced and used according to sustainable development principles (Blengini and Garbarino, 2010) to be able to minimize economic, energy and environmental burdens caused by the construction industry. Every year about 20,000 million tons of aggregate is consumed at a global scale and an annual growth rate of 4.7% is expected (Pacheco-Torgal et al., 2013). This leads to the consumption of non-renewable raw materials, energy consumption and to the reduction of biodiversity at extraction sites (Pacheco-Torgal et al., 2013). Recycled aggregate, which could be produced from crushing of the demolished buildings, bridge supports, airport runways and concrete roadbeds (Rao et al., 2007), can be an alternative to natural aggregates.

Concrete is the second most consumed material in the world after water (Woodward and Duffy, 2011). Because, concrete has high compressive strength, high durability, low maintenance cost and resistance to different weather conditions as well as having low purchase price compared to other construction materials (Behera et al., 2014).

2.2.2 **Construction and Demolition Waste (CDW)**

Construction and Demolition Waste (CDW) consists of numerous materials, including mainly 40% concrete, 30% ceramics, 10% wood, 5% metals, 5% plastics and 10% other mixtures, most of which could be recycled (Sonawane and Pimplikar, 2013). CDW could also be broken concrete, broken pavement or bricks from buildings, bridges etc. (Rao et al., 2007).

Annual production of CDW in the world is estimated about 1 billion tons (Yazdanbakhsh et al., 2017). In European Union, there is no consensus about total CDW generation, but it is about 22-49% of the total waste generated in Europe, which is about 450-970 million tons of CDW per year (Cabral et al., 2012). CDW generated per capita varies for different countries in Europe (Cabral et al., 2012), e.g. about 0.2 tons for Norway (Cabral et al., 2012), 5.9 tons for France (Pacheco-Torgal et al., 2013) and 15 tons for Luxembourg (Cabral et al., 2012). According to a survey, waste generated from the construction sector in France in 2008 was 38 million tons of which 65% was from demolition sites (Ablouh et al., 2015).

The first research studies on using CDW as raw materials were conducted in 1928 (Mymrin and Correa, 2007). But in practice, these materials were used widely in Europe after the end of World War II to rebuild the cities destroyed during the war (Mymrin and Correa, 2007). In the 1970s, the United States began to promote recycling CDW, such as recycling of concrete waste, to be used in non-structural applications such as fill material, foundations and base course material (Buck, 1977).

2.2.3 **Different categories of CDW based on regulations**

In Europe, CDW in general is sorted into three categories based on regulation: inert, hazardous and non-hazardous wastes (European Commission, 2016) and these categories are managed and treated differently.

- Inert waste refers to waste that does not undergo any significant physical, chemical or biological transformations. Inert waste will not dissolve, burn or otherwise physically or chemically react, biodegrade or adversely affect other matter with which it comes into contact in a way it is likely to give rise to environmental pollution or harm human health. The total leachability and pollutant content of the waste and the ecotoxicity of the leachate must be insignificant, and in particular not endanger the quality of surface water and/or groundwater (Directive 2006/21/EC, 2006).
- Hazardous waste refers to waste that is dangerous or potentially harmful to our health or the environment. Hazardous wastes can be liquids, solids, gases, or sludge. They can be discarded commercial products, like cleaning fluids or pesticides, or the by-products of manufacturing processes (Directive 2006/21/EC, 2006; EPA, 2016).

- Non-hazardous waste refers to waste which is not classified as hazardous waste mentioned above (Directive 2006/21/EC, 2006; EEA, 2016).

A considerable part of the total amount of CDW accounts for inert wastes, such as non-polluted soil and loose materials, gravels and rock materials as well as concrete wastes (CERC, 2013). Inert waste represents two third of the total waste generated in France (DREAL, 2014). 95% of this waste is produced by the building and public works sector (DREAL, 2014).

2.2.4 Benefits gained from using recycled aggregates

Recycling CDW, like demolished concrete, is expected to bring different advantages, mainly reducing the required space for landfilling and keeping landfills for non-recyclable materials (Ismail et al., 2013; CCANZ, 2011). According to Hill et al. (2001), using recycled aggregates instead of natural aggregates could cause different environmental benefits such as minimizing extraction activities in the quarries (reduced noise, dust and land consumption), decreasing waste disposal sites, reducing waste stockpile sites and increasing reuse of waste materials. Using recycled aggregates conserve ecosystems from destruction and water resources from pollution, provided that it leads to a reduction of natural aggregates production (Ismail et al., 2013). Besides, recycling could create new jobs in the industry for people (Ismail et al., 2013).

2.3 Aggregate production, quality assessment and related applications

As applications of natural and recycled aggregates are mainly identified by their mechanical properties, they are discussed in detail in this section. In addition, the production process of natural and recycled aggregates are discussed, since the environmental impacts of aggregates are related to their production process.

2.3.1 Natural aggregate

2.3.1.1 Natural aggregate production process

In this section and the following one, 2.3.1.2, information was gathered based on a literature review and site visit to the quarry of Clarté in Herbignac, France.

Production of natural aggregates consists of two main operations: extraction and processing (Martaud, 2008). Figure II. 1 shows a schematic example of rock extraction and aggregate processing in a small quarry, which has been inspired from (Martaud, 2008).

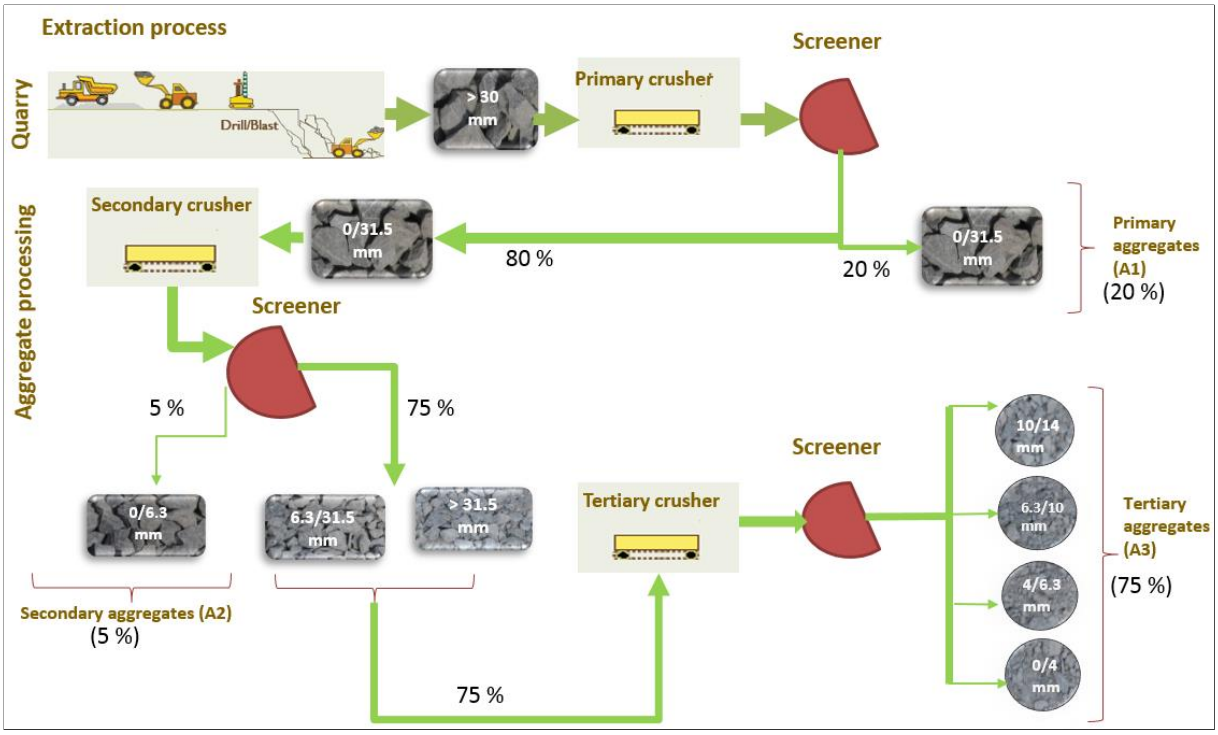


Figure II. 1 Schematic example of extraction of rocks and processing of aggregates in the quarry (Martaud, 2008; Jullien et al., 2012)

In general, a quarry process contains three main treatment lines from which three categories of aggregates are produced. Each treatment line contains crushing and screening processes. As seen in Figure II. 1, rocks extracted from the ground in the quarry have 0/600 mm size.

- In the first treatment line, they will be crushed to 0/31.5 mm size. Some parts of the crushed gravels due to their quality (more friable) cannot pass through the secondary treatment. They are kept as primary category (basic quality) of natural aggregates.
- The rest is sent to the second treatment line containing a crusher and a screener. Aggregates with sizes of 0/6.3 mm, 6.3/31.5 mm and > 31.5 mm are produced. The most friable part of the aggregates with 0/6.3 mm size are kept as secondary category (intermediate quality) of natural aggregates. They cannot pass through the third treatment.
- The rest with sizes of 6.3/31.5 mm and > 31.5 mm are sent to the third treatment line and crushed into different sizes to produce tertiary category (high quality) of natural aggregates, including 0/4 mm, 4.63 mm, 6.3/10 and 10/14. They are considered as concrete aggregates.

As it is observed, the quarry process is a multi-output process where different products with different qualities are produced simultaneously from the same process. In this thesis, primary, secondary and tertiary category of natural aggregates are shown by A1, A2 and A3 respectively. A1, A2 and A3 are classified as basic, intermediate and high quality natural aggregates respectively. Accordingly, A3 produces the highest revenue for the quarries owing to its higher quality compared to A1 and A2. Therefore, it is considered as the determining co-product of the quarry process, which drives the total production of the quarry. As a result, to produce A3, A1 and A2 are inevitably produced. Therefore, A1 and A2 are the dependent co-products of the quarry process.

The proportion of A1, A2 and A3 production can vary in different quarries based on geological issues as well as nature and quality of the rocks. Figure II. 1 is an example of a quarry that produces mainly A3, about 75%. Table II. 1 represents an example of a bigger quarry, La Clarté in *Loire-Atlantique* in France. As can be seen from Table II. 1, production proportion of products in this quarry is the same. Based on Table II. 1, total sold of each product category in the market and its stocks in the quarry can be seen as well.

Table II. 1 Different categories of aggregates produced in the quarry of La Clarté and their amounts of production and selling

Product category	**Production % (total ≈ 100%)**	**[a]sold %**	**Stockpile (%)**
Primary (A1)	33	45	55
Secondary (A2)	33	30	70
Tertiary (A3)	33	75-90	10-25

[a]sold per produced of each category.

2.3.1.2 **Usage of the natural aggregates based on their quality**

In road construction different layers of a road are filled with different qualities of aggregates; upper layers with aggregates of higher quality and lower layers with lower quality.

Aggregates obtained from primary and secondary treatment processes (A1 and A2) are mostly adequate for the lower layers of the roads, such as sub-base (or foundations) and road bases. Upper layers of the road (inside pavement) are filled with binded materials (either bituminous or cement concretes) and with smaller sizes and better quality of aggregates, which are gained from tertiary treatment line. The shape and solidarity of the gravels play an important role for the upper layers of the pavements. Size 6.3/10 mm from tertiary treatment process is the most popular aggregate fraction for most customers. Tertiary category of natural aggregates (A3) are also used for the production of structural cement concrete mainly for building applications.

2.3.1.3 **Quality assessment of natural aggregates**

Aggregates undergo substantial wear and tear throughout their life. Therefore they should be hard and tough enough to resist crushing and degradation from different activities such as manufacturing, stockpiling, production etc. (Roberts et al., 1996). Aggregates suitability should be tested in different ways to determine their hardness, wear and fragmentation based on different applications or end use and origin of the aggregate. Then the relevant physical properties would be determined. There are different tests carried out to evaluate the hardness of the gravels. Three main tests explained in detail as follows are Los Angeles (LA) abrasion test, Micro-Deval test and crushing test.

2.3.1.3.1 Resistance to fragmentation

- Resistance to fragmentation based on standards

Resistance to fragmentation can be determined by the Los Angeles (LA) test method as specified in EN 1097-2. This European standard applies to natural, manufactured or recycled aggregates used in building and civil engineering. The LA coefficient should be identified in accordance with the relevant category which is based on particular application and end use of the aggregates (NF EN 1097-2, 2010).

- Principles of LA test method

According to EN 1097-2, the principle of LA test method for determining the resistance to fragmentation is to identify the quantity of materials remaining on a 1.6 mm sieve after rolling the sample of aggregate with steel balls in a rotating drum.

The mass of the sample sent to the laboratory should have at least 15kg of particle sizes in the range of 10 mm to 14 mm.

The test should be carried out on aggregates passing through 14 mm test sieve and retained on 10 mm test sieve. Moreover, the grading of the test portion should comply with one of the following requirements:

a) Between 60% and 70% passing a 12.5 mm test sieve, or
b) Between 30% and 40% passing a 11.2 mm test sieve.

- Calculation of Los Angeles coefficient LA

Equation (II. 1) is used to calculate Los Angeles coefficient LA:

$$\mathrm{LA} = \frac{5000 - \mathrm{m}}{50} \qquad \textit{II. 1}$$

Where *LA* is Los Angeles coefficient and *m* is the mass remained on the 1.6 mm sieve in grams.

It should be mentioned that the lower the value of LA coefficient, the more resistance the aggregates are towards crushing.

- LA (Los Angeles) Abrasion Test based on personal visits

This part explains the Los Angeles (LA) abrasion test based on a personal visit from a quarry in Charier Company located in *Loire-Atlantique* department in France (Personal communication, Charier Company, 2015). LA test is a common test method to indicate coarse aggregates toughness. Aggregates are sent to a rotating drums, as shown in Figure II. 2, containing a specified number of steel spheres in order to test their resistance towards grinding. The machine turns 500 times and aggregates should not be broken apart to smaller sizes than 1.6 mm during the process. The test is performed on aggregates with 31/80 mm size.

Figure II. 2 Major equipment used in the Los Angeles (LA) abrasion test

2.3.1.3.2 Resistance to wear

- Resistance to wear based on standards

Resistance to wear (Micro-Deval coefficient - MDE) of an aggregates' sample could be determined according to EN 1097-1 and the results should be declared based on particular applications and end use of the aggregates. In general, the sample is tested in the presence of water but the test can also be performed in dry conditions. This European standard applies to natural, manufactured or recycled aggregates used in building or civil engineering work (NF EN 1097-1, 2011). Some terms and conditions which have been applied in EN 1097-1 are the same as those in EN 1097-2.

- Principle of Micro-Deval test method

The Micro-Deval coefficient, which is the percentage of the original sample reduced to a size smaller than 1.6 mm during rolling is determined by the test.
The test includes measuring the wear caused by friction between the aggregates and an abrasive charge in a rotating drum. The Micro-Deval coefficient can be calculated from the percentage of the aggregates remaining on a 1.6 mm sieve after rolling.
It should be noted that a lower value of the micro-Deval coefficient indicates a better resistance to wear.
Test sieves that are used in this test are 1.6 mm, 8 mm, 10 mm, 11.2 mm (or 12.5 mm) and 14 mm.
The sample, which is sent to the laboratory, should have at least a mass of 2 kg of aggregates with 10 mm to 14 mm fraction size. The test should be carried out on aggregates passing 14 mm sieve and remained on 10 mm sieve. The grading of the test portion should fulfill one of these requirements:

a) Between 30% and 40% passing a 11.2 mm sieve, or
b) Between 60% and 70% passing a 12.5 mm sieve.

- Calculation of Micro-Deval coefficient MDE

Micro-Deval coefficient could be calculated for each test specimen from the following equation:

$$\mathrm{MDE} = \frac{500 - \mathrm{m}}{5} \qquad \textit{II. 2}$$

Where *MDE* is Micro-Deval coefficient in wet condition and *m* is the mass of oversize fraction remained on 1.6 mm in grams. From the values obtained for the two specimens, the mean value of micro-Deval coefficient could be calculated.

- Micro-Deval test

This part explains the Micro-Deval test based on a personal visit to quarry of Charier Company located in *Loire-Atlantique* department in France (Personal communication, Charier Company, 2015). Micro-Deval test is the same as LA test but the rotating drum contains water in addition to metal spheres and it turns 1200 times (see Figure II. 3 and Figure II. 4). The Micro-Deval test tends to polish (smoothen) aggregate particles (see Figure II. 5) while the LA abrasion test tends to break them. The Micro-Deval test is performed on aggregates with 31/80 mm size as well.

Figure II. 3 Drums used in Micro-Deval apparatus

Figure II. 4 Steel spheres used in Micro-Deval test

Figure II. 5 Aggregate particles before and after Micro-Deval

2.3.1.3.3 Crushing test

The crushing test is standardized by IS: 2386 part-IV and used to identify the crushing strength of aggregate. Aggregate crushing value (ACV) shows relative resistance of aggregates to crushing under a gradually applied crushing load. The aggregate sample in the standard mold undergoes a compression test under standard conditions, see Figure II. 6 (Mathew and Krishna Rao, 2007).

- Principle of crushing test

Aggregates passing through a 14 mm test sieve and retained on a 10 mm test sieve are filled in a cylinder with a 115 mm diameter and 18 cm of height in three layers. Each layer should be tamped 25 times with a standard tamping rod. Weight (*W1*) of the test sample should be measured and placed into the three layers of the cylinder; each layer should be tamped again. The sample is exposed to a compressive load of 40 tons gradually applied at the rate of 4 tons per minute. Afterwards, crushed aggregates are sieved through 2.36 mm sieve and passing materials are weighted (*W2*). *ACV* is expressed as the weight of passing materials to weight of total sample, see equation (II. 3) (IS: 2386, 1963, p. 2386).

$$\mathrm{ACV} = \frac{\mathrm{W2}}{\mathrm{W1}} * 100 \qquad \textit{II. 3}$$

Where *ACV* is the aggregate crushing value, *W1* is the total weight of the sample and *W2* is the weight of the portion of crushed materials passing 2.36 mm IS sieve.

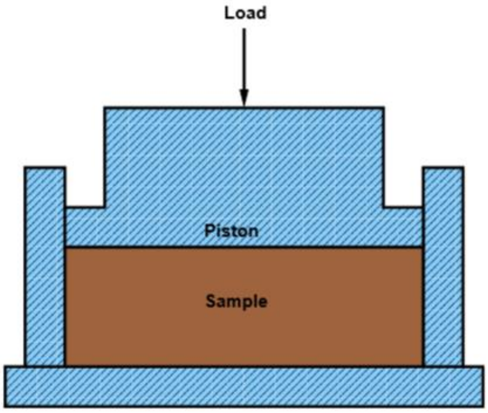


Figure II. 6 Crushing test setup (Mathew and Krishna Rao, 2007)

2.3.2 **Recycled aggregates**

There are different types of recycled aggregates: recycled aggregates (RA) and recycled aggregate concrete (RCA) [2]. RA is usually produced from the treatment of waste generated from demolition of concrete structures and other construction wastes such as concrete waste, rejected precast concrete members, broken masonry, concrete road beds and asphalt pavements etc. Aggregates recycled from the crushing of demolished concrete are defined as RCA. RCA is generally mixed with bricks, tiles, metals and other miscellaneous such as glass, wood, paper, plastic and other wastes (Behera et al., 2014). In a study by McNeil and Kang (2013), RCA is defined as concrete removal from road and building demolition wastes that is collected and crushed. RCA are primarily concrete rubbles, which are mainly produced from plain or steel reinforced concrete constructions (Schiller et al., 2017). In this thesis project, by mentioning Recycled Cement Concrete (RCC), RCA is implied, which is pure concrete rubble.

2.3.2.1 **Recycled aggregate production process**

Recycling process of concrete waste materials to produce recycled concrete aggregates includes crushing demolished concrete to smaller sizes, removal of steel reinforcement, wood, plastics etc., and finally screening and sorting (Behera et al., 2014). Recycling of demolition concrete waste in contrast with other types of waste, such as municipal waste, does not require special treatment technologies, because concrete waste is inert (Woodward and Duffy, 2011). There are several methods of contaminant removal from demolition wastes. They can be divided into two groups, pre-crushing separation and post-crushing separation (O'Mahony, 1990). Recycled aggregate production process is explained in detail as follows:

2.3.2.1.1 Pre-crushing treatment

Waste can be sorted while a structure is demolished. But this method could be time consuming and expensive for demolition companies. However, it is more common to sort waste when it reaches a recycling plant rather than sorting on demolition site. At the recycling

[2] Different studies use "recycled aggregate" and "recycled concrete aggregate" interchangeably, so does this thesis. But if "RA" and "RCA" are used, they refer to the specific types of recycled materials as explained above.

plant waste will be stored according to its major constituent or its amount of contaminants. This initial sorting will help to improve crushing time because a large quantity of the clean stored rubble can be crushed in a single and continuous crusher run. At recycling facilities prior to entering the primary crusher, the rubble is usually passed over a sieve to separate materials that already have the desired size and do not need further crushing. Afterwards, these fractions will be screened to remove soil and other fine contaminants and the remainder will be sent to the next stage of the recycling process.

2.3.2.1.2 Crushing treatment

There are different crushers for crushing demolished concrete, including the jaw crusher, the hammer mill, the impact crusher and the cone crusher or manually using hammer. Each type has a different influence on the mechanical and physical properties of recycled aggregates which in turn will affect the performance of the new concrete produced with them (Behera et al., 2014). According to Matias et al. (2013), the best size distribution and shape are gained when first a jaw crusher (primary crusher) and then a rotary crusher (jaw and impact crusher or secondary crusher) to crush the demolished concrete are used, since some parts of the weaker mortar attached to the demolished concrete will be separated in the process. Meanwhile, they stated that an impact crusher would improve the concrete quality by making aggregates rounder (Matias et al., 2013). Indeed, angular particles require more cement paste due to the higher voids content as well as higher water demand to provide workability to concrete. Also angular particles might cause a decrease in the strength and durability of the concrete, while the rounder aggregates cause less such problems. As a result, the crushing process can affect the aggregates' shapes and texture, which will affect the performance of the concrete. A jaw crusher crushes demolished concrete into smaller sizes, 60-80 mm and then it feeds particles into an impact crusher which reduces them to smaller sizes. Afterwards materials will pass through two screens to become separated based on different sizes, particles greater than 19 mm, between 7 mm and 19 mm and smaller than 7 mm. Particles bigger than 19 mm will be sent back to impact crusher and particles smaller than 7 mm will be removed and used as road metal (CCANZ, 2011).

2.3.2.1.3 Post-crushing treatment

After crushing the demolished concrete, there are different methods for the removal of contaminants. The simplest method is manual sorting. The main advantage of this method is that human eyes can recognize some contaminants like glass that would be difficult to remove by mechanical equipment (O'Mahony, 1990). Right now in *Pays de La Loire* region, 81% of waste is sorted manually on the ground or with grapnel, and the rest is sorted mechanically and manually (CERC, 2013).

The following methods are considered as automatic methods for contaminant removal (O'Mahony, 1990):

- Electromagnetic removal of steel- it is used for removal of steel from demolished concrete at recycling plants. The magnet is usually located across the conveyor belt between primary and secondary crushers.

- Dry sieving- it is usually used to separate the materials into fractions, which can be recombined later to produce well graded aggregates. In this step a large quantity of dust is produced.

Wet separation- it could be used to separate low density contaminants from crushed concrete by using aquamator. Materials with particle size greater than 10 mm are sent to a tank full of water. Wood and other lightweight contaminants would be collected by combs, which move from one end of the tank to the other.

2.3.2.2 **Properties of recycled aggregates**

RCA is usually of lower physical quality than natural aggregates. The main reason is that recycled concrete aggregates mostly contain original aggregates and adhered mortar (Etxeberria et al., 2007b). Therefore, the amounts of adhered mortar affects physical properties of recycled aggregates like density, porosity and water absorption are influenced by the amount and quality of adhered mortar (Etxeberria et al., 2007b). Likewise, De Juan and Gutiérrez (2009) found that lower quality of the recycled concrete aggregate is mainly due to some amounts of mortar and cement paste from the original concrete that remains attached to the aggregates after crushing old concrete. Therefore, recycled concrete aggregate is generally weaker, more porous and less dense and also has more water absorption and less abrasion resistance, compared to natural aggregate (de Juan and Gutiérrez, 2009). As Limbachiya et al. (2000) showed, the relative density of RCA in the saturated surface dry state is approximately 7-9% lower than that of natural aggregates (NA). Sagoe-Crentsil et al. (2001) found density of RCA 17% lower than that of NA. Adhered mortar on RCA has high porosity that causes aggregate to absorb more water than NA (de Juan and Gutiérrez, 2009; Shayan and Xu, 2003). Water absorption for NA in saturated surface dry condition is about 0.5-1% while it is about 4-4.7% for RCA (Shayan and Xu, 2003). Other studies show 5.6% and 4.9-5.2% water absorption for RCA compared to 1% and 2.5% water absorption for NA (Limbachiya et al., 2000; Sagoe-Crentsil et al., 2001).

The recycling process has, however, an influence on the quality of RCA. Marie and Quiasrawi (2012) showed that continuous crushing of the concrete leads to less amount of cement mortar attached to the aggregates. Etxeberria et al. (2007b) also stated that the amount of adhered mortar attached to the recycled aggregate is affected by the crushing process and dimension of recycled aggregates.

The amount of adhered mortar must be identified to control the physical properties of recycled aggregates before using them. Since, the amount of adhered mortar may limit the use of recycled aggregates in some applications, such as concrete mixes (Etxeberria et al., 2007b). This is mainly due to the adverse effects of mortars on the physical properties of recycled aggregates.

Accordingly, some studies have been conducted to investigate new techniques on how to decrease the amount of mortar attached to the recycled concrete to improve its quality. Some of these techniques are the nitric acid dissolution method, the thermal expansion method microwave heating method, freeze-thaw method, pre-soaking treatment method etc. (Behera et al., 2014). For that reason Tam et al. (2007) investigated three pre-soaking treatment approaches in Hong Kong to reduce the amount of mortar attached to RA. Each approach respectively attributes to one acidic solvent, including Hydrochloric acid (HCl), Sulfuric acid (H2SO4) and phosphoric acid (H3PO4) with a concentration of 0.1 mole.

The procedure proposed by Tam et al. (2007), is to soak the RA in an acidic environment at around 20 ◦C for 24 hours and watering it with distillate water to remove the acidic solvents afterwards. An acidic environment with 0.1 mole concentration would cause aggregates to be removed from the old cement mortar and increase the aggregate quality. In general water absorption of RA was found to be between 3% and 10% compared to that of natural aggregate, which is less than 1% to 5%. Results indicate that, water absorption rates for RA after treatment decrease considerably with an improvement between 7.27% and 12.17%. This shows that this method can effectively remove a great amount of old cement mortar from RA(Tam et al., 2007).

According to Tam et al. (2007), the pre-soaking treatment method is a useful method to improve the quality of the RA in order to be used more largely in construction activities.

The results of different studies show that crushing and LA abrasion values for RCA are higher compared to that of NA. This means that when RCA is gone through crushing and abrasion test, more fine particles will remain inside the drums. According to the studies by Sagoe-Crentsil et al. (2001) and Shayan and Xu (2003) , crushing test values for RCA were 23.1% vs. 15.7% for NA and 24% vs. 13% for NA. LA abrasion values for RCA were found 32% vs. 11% for NA and 26.4-42.7% vs. 22.9% for NA (Shayan and Xu, 2003; Tavakoli and Soroushian, 1996). The results of crushing and LA abrasion test on RCA resulted mainly from residual mortars attached to RCA. Because they can break off easily at the interfacial transition zone, which is typically the weak area of concrete. Therefore, when they are loaded, the residual mortar will break off, while NA does not have similar coating to lose (Sagoe-Crentsil et al., 2001; Shayan and Xu, 2003). Accordingly, the adhered mortar attached to RCA might create a weak connection within concrete (Etxeberria et al., 2007a).

2.3.2.3 **Usage of recycled aggregates**

2.3.2.3.1 Unbound gravel for road construction

Recycled concrete aggregates (RCA) are mostly used as sub-base course, construction fill and in drainage system in many places in the world (Yazdanbakhsh et al., 2017). This is mainly because of inferior physical properties of recycled aggregates compared to those of natural aggregates, as discussed in section 2.3.2.2. Therefore, recycled aggregates produced from demolition are mostly down-cycled as aggregates in granular base or sub-base applications as well as in embankment and earth construction works (Marinković et al., 2010; Thorn and Brown, 1989). The sub-base layers lie between the base-course and the subgrade (see Figure II. 7). It has three main functions (O'Mahony, 1990):

- It acts as a structural component of the pavement.

- It is not frost susceptible and it insulates the sub-grade.
- It provides a working platform for construction traffic.

The stresses caused by traffic in a road pavement decreases with depth, which means that the sub-base is exposed to the stresses more than the sub-grade layer. Figure II. 7 indicates road pavement structure.

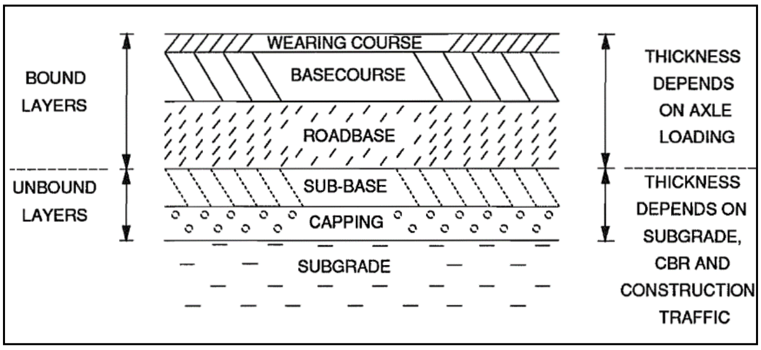


Figure II. 7 - Road pavement structure (O'Mahony, 1990)

However, recycled aggregate could partly or fully replace natural coarse aggregate in concrete mixes, but some considerations and modifications in the mixes are required, as will be discussed in section 2.3.2.3.2. In this regard, technical approval and standards for higher grade applications exist (Knoeri et al., 2014).

According to Corinaldesi (2010), 30% replacement of natural aggregate with recycled concrete aggregate is allowed to produce concrete with quite accepted quality. 100% replacement usually would adversely affect concrete properties such as compressive strength, shrinkage and creep (CCANZ, 2011). Therefore, many researchers limited the replacement rate of natural coarse aggregate with crushed concrete in producing recycled aggregate concrete.

Different studies show that concrete made with recycled coarse aggregates could meet the demand for having concrete with low to middle compressive strength (30-35 MPa), regardless of the quality of the recycled aggregates (Marinković et al., 2010). But it is not recommended to use recycled concrete aggregate (RAC) in conditions with high risk of corrosion, freezing or chemical attack.

Right now in France, demolished concrete is not sorted based on different qualities, demolished concrete with different qualities are mixed together and they are recycled and usually used as one type of natural aggregates in the quarry, which is primary category of natural aggregate (A1), see section 2.3.1. A1 is also known as basic quality natural aggregates in this PhD thesis. This type is proper for the foundation of roads, railways, etc. and earthworks. However, it should be mentioned that it is technically possible to replace 10-20% of the natural aggregates used in concrete production with these recycled aggregates generated at inert waste storage facilities and recycling platforms in Charier Company in France (Personal communication, Charier Company, 2015_ see Appendix A). However, this is based on experts' opinion but has not yet been carried out in France yet.

2.3.2.3.2 Cement Concrete

One of the applications of recycled aggregates is in cement concrete as course aggregates. In this section the effect of recycled aggregates on different mechanical properties of concrete made with recycled aggregates are studied.

- Allowable crushing and LA values for using RCA in cement concrete

In this section required and permissible crushing and LA abrasion values for aggregates used in structural concrete, are discussed, based on a Serbian standard in order to identify whether RCA meets the requirements or not. It should be taken into account that all these values might be varied for different conditions.

An experiment was carried out by Malešev et al. (2010) compares some properties of RCA, such as crushing strength and LA abrasion values, with those of natural aggregates based on a Serbian standard for natural aggregates. These values identified the feasibility of using RCA in structural concrete.

To perform the experiment, natural fine and coarse aggregates were derived from River Sava and they dominantly consist of quartz grains. RCA was produced from crushing of old concrete cubes, which were used for compressive strength testing, with strength class of C30/37, and from one precast reinforced concrete column, which had inappropriate dimensions, with strength class of C40/50. Crushed concrete particles were separated into standard fractions of coarse aggregate, 4/8 mm, 8/16 mm and 16/32 mm (Malešev et al., 2010).

Table II. 2 and Table II. 3 show the results of this experiment for crushing resistance of natural aggregates and RCA respectively. Quality requirements given in these tables are according to Serbian standard for natural aggregates (Malešev et al., 2010).

Table II. 2 Results of crushing resistance test for natural aggregates and required value for being used in structural concrete (Malešev et al., 2010)

Tested property	**Measured value**	**Grain size**				**Quality requirement**
		0/4	**4/8**	**8/16**	**16/32**	
Crushing test (in cylinder)	Mass loss (%)	-	14	18.6	23.8	<30
Content of weak grains	(%)	-	0	0	0	<3
Crushing resistance (LA test)	Mass loss (%)	-	26.3	29	29.2	<30

Table II. 3 Results of crushing resistance test for RCA and required value for being used in structural concrete (Malešev et al., 2010)

Tested property	**Measured value**	**Grain size**			**Quality requirement**
		4/8	**8/16**	**16/32**	
Crushing test (in cylinder)	Mass loss (%)	18.3	26.4	30.7	<30
Content of weak grains	(%)	0	3.7	7.1	<3
Crushing resistance (LA test)	Mass loss (%)	29.6	33.7	34	<30

As can be seen from Table II. 3, recycled aggregates with grain sizes of 8/16 and 16/32 don't meet the crushing resistance quality requirements for being used in structural concrete. This is due to the mortar and cement paste attached to the stone particles in the recycled aggregates (Malešev et al., 2010).

- Comparison of cement concrete made with NA and RCA

Marie and Quiasrawi (2012) made three concrete mixes as samples to compare some mechanical properties associated to each of these samples. They use the same w/c ratio and mixing water content for the samples. They made a sample concrete containing 100% natural aggregates and considered as conventional concrete mix, then recovered recycled concrete aggregates from crushing the concrete sample to produce first generation concrete, which contained up to 20% of recycled concrete aggregates instead of natural coarse aggregates. Afterwards, recycled concrete aggregates, obtained from recycling of the first-generation concrete, were used to produce second generation concrete, which contained up to 20% of recycled concrete aggregates instead of natural coarse aggregates.

Results (Marie and Quiasrawi, 2012) indicate that, workability (slump) of the first generation concrete decreases compared to that of conventional concrete mix and second generation concrete. Compressive strength of second-generation concrete is higher than that of first generation concrete but it is still lower than that of conventional concrete mix. In addition, they quantified the amount of residual mortar that remains attached to the recycled concrete aggregates. They found that during crushing the first-generation concrete, less mortar remains attached to the aggregate surface and mortar is getting crushed to the finer particles which get removed during sieving. Therefore, the amount of mortar attached to the recovered concrete from first generation concrete is less than the amount attached to the recycled concrete from crushing conventional concrete mix. Accordingly, the first-generation concrete shows higher water absorption than the other two concrete types due to the higher amount of mortar attached to the recycled concrete from conventional concrete mix. Therefore, higher absorption capacity requires more water for producing new concrete to maintain the workability property (Matias et al., 2013). Comparing two methods of water compensation and pre-saturation of the aggregate by de Brito et al. (2011) indicates that to produce concrete by using recycled concrete aggregate similar to conventional concrete, the potential absorption and the absorption over time of the recycled aggregate must be known to predict the progress of the effective w/c ratio during the mix and afterwards. Results show that pre-saturation of the recycled aggregate has impacts on mechanical performance and durability of the concrete.

Overall, Marie and Quiasrawi (2012) concluded that continuous crushing of the concrete leads to less amount of cement mortar attached to the aggregates which in turn results in higher quality recycled concrete aggregates.

Likewise, Table II. 4, which was compiled by Marinković et al. (2010), shows general conclusion regarding the comparison of the properties of two types of ready-mixed concrete with the same water-cement ratio. One type of concrete is assumed to be made with natural fine and coarse aggregates named as natural aggregate concrete (NAC) and the other type is made with natural fine aggregate and 100% replacement of natural coarse aggregates with recycled coarse aggregates named as recycled aggregate concrete (RAC). Recycled fine aggregate cannot replace natural fine aggregates in producing RAC for structural uses, regarding its high water absorption and high cohesion.

As can be seen from Table II. 4, mechanical properties of RAC are lower than properties of NAC with the same water-cement ratio. As suggested by Marinković et al. (2010) and (Etxeberria et al., 2007b) adding more amount of cement to the mixture of concrete production made with recycled coarse aggregate could bring about the same compressive strength and workability as NAC. Marinković et al. (2010) suggested adding about 5% more cement. While Hansen (1990) demonstrated the feasibility of producing new concrete made from recycled concrete aggregate by adding fly ash without requiring adding new cement to the mix.

Table II. 4 Properties of RAC compared to NAC (Marinković et al., 2010)

Properties	**RAC compared to NAC**
Compressive strength	Decreased up to 25%
Splitting and flexural tensile strength	Decreased up to 10%
Modulus of elasticity	Decreased up to 45%
Drying shrinkage	Increased up to 50%
Creep	Increased up to 50%
Water absorption	Increased up to 50%
Freezing and thawing resistance	Decreased
Carbonation depth	Similar
Chloride penetration	Similar or slightly increased

- Compressive strength

"Compressive strength is a major and important mechanical property, which is generally obtained by measuring concrete specimen after a standard curing of 28 days. Compressive strength is the maximum compressive stress that, under a gradually applied load, a given solid material can sustain without fracture." (Ni and Wang, 2000).

Behera et al. (2014) defined recycled aggregate concrete (RAC) as concrete which is made from recycled aggregate recycled from CDW instead of natural aggregate. The quality of concrete is identified by its compressive strength (Woodward and Duffy, 2011). The compressive strength of new concrete could be influenced by the properties and the amount of recycled aggregate (McNeil and Kang, 2013). While Malešev et al. (2010) showed that the compressive and tensile strength of new concrete are only affected by the quality of the recycled aggregates. This means that if recycled aggregate obtained from crushing high strength class concrete (using this crushed concrete as an aggregate for producing new concrete) will not affect the compressive strength, regardless of the replacement ratio of natural coarse aggregate with recycled aggregate (Malešev et al., 2010). This implies that the original concrete properties that are used to produce crushed concrete, significantly influence the quality of the obtained concrete (Malešev et al., 2010). In this study recycled aggregate obtained from crushing good quality concrete i.e. concrete with strength class of C30/37 and C40/50.

Behera et al. (2014) stated that the compressive strength of RAC depends on different parameters, such as the replacement rate of RA, w/c ratio, moisture condition of RA etc. The level of change in compressive strength when natural aggregate is fully replaced by RA have been investigated by several researchers (Behera et al., 2014). A number of them observed 12-30% reduction in compressive strength while a few of them reported 60-76% reduction (Behera et al., 2014). But many publications have shown that compressive strength of RAC will remain almost unchanged if just 30% of natural aggregate is replaced by RA (Behera et al., 2014). It can be observed in Figure II. 8 that the compressive strength of concrete made with 30% RCA is almost the same as the concrete made with 100% NA for different w/c ratios. But, the compressive strength values of concrete made with 100% RCA are lower than compressive strength values of concrete, in the same w/c ratios, made with 0% and 30% RCA respectively (McNeil and Kang, 2013).

Hansen (1986) stated that the compressive strength of recycled aggregate concrete was affected by both water-cement (w/c) ratio of the original concrete and w/c ratio of RAC, if other factors kept constant. Etxeberria et al. (2007a) stated that, the higher w/c ratio, the lower the compressive strength. Concrete with 100% recycled coarse aggregate and lower w/c ratio than conventional concrete might have higher compressive strength (Etxeberria et al., 2007b). But if the w/c ratio is the same then it is expected that the compressive strength of the recycled aggregate concrete will be lower than that of the conventional concrete (Etxeberria et al., 2007b). A study by McNeil and Kang (2013) showed that the w/c ratio, the proportion of RCA used in concrete and the amount of adhered mortar on RCA could be influential factors on compressive strength.

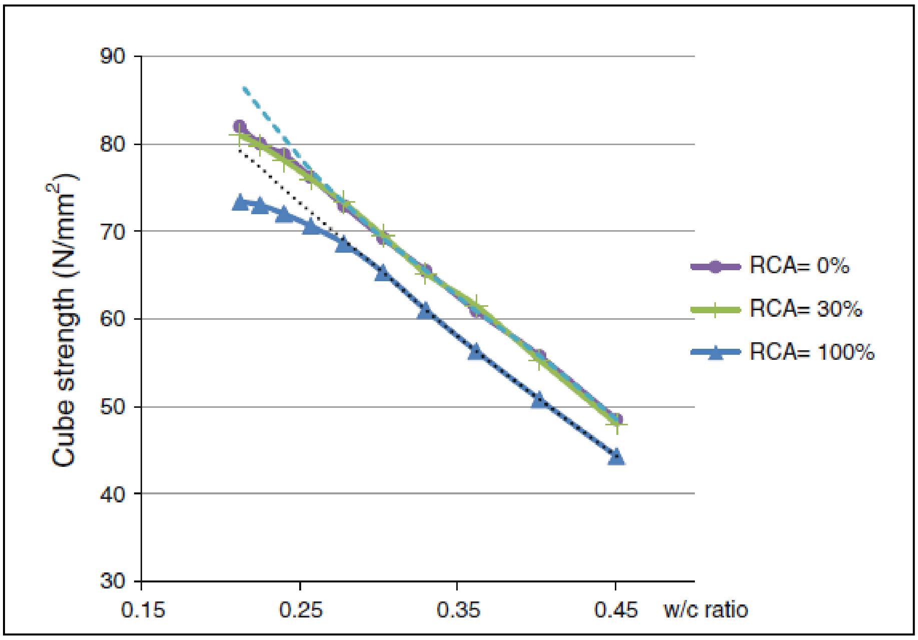


Figure II. 8 Concrete compressive strength versus water to cement ratio for RCA contents of 0–100 % (McNeil and Kang, 2013)

Many research studies show that, desired compressive strength will be achieved in RAC by adding more cement content (5-10%) or by adjusting lower (4-10%) w/c ratio than conventional concrete (Etxeberria et al., 2007b). As reported by Behera et al. (2014) based on different publications, the problem of lower compressive strength can be solved by modified mixing approach, by combing alternative cementitious materials such as silica fume, fly ash and GGBS (ground granulated blast furnace slag).

Wagih et al. (2013) indicated that by replacing 25% of natural aggregates with RCA, compressive strength was decreased insignificantly, by 2-4%. By increasing the replacement ratio to 50% the compressive strength was reduced by 6-13%. In case of a replacement ratio of more than 50%, compressive strength declined non-linearly by 15-23%. Therefore according to the authors, a 25-50% replacement ratio would be acceptable to produce good quality concrete by considering the properties of recycled aggregate and concrete mix (Wagih et al., 2013).

However, since there are different qualities of recycled aggregates, different w/c ratios applied and different cement types used, the results of most publications are not comparable.

- Workability

"Workability is a property that determines the effort required to manipulate a freshly mixed quantity of concrete with a minimum loss of homogeneity. The term "manipulate" includes the early-age operations of placing, compacting, and finishing." (ASTM C 125, 2015).

According to Behera et al. (2014), some properties of the concrete such as workability and wet density are mostly affected by the w/c ratio, types of aggregate, water absorption of aggregate etc. In addition, workability of the concrete is greatly influenced by some properties of the aggregate including surface texture, aggregate size and shape. RAC requires more water compared to the conventional concrete to reach the same workability (Behera et al., 2014). The higher the replacement ratio of natural aggregate with recycled aggregate is, the higher water demand will be (Behera et al., 2014). According to CCANZ (2011), the increase in water demand depends on the recycled aggregate properties and source

According to Malešev et al. (2010), due to the mortar content of RCA, recycled aggregate has higher water absorption than natural aggregates. Therefore, the procedure for producing RAC is different from natural aggregate concrete (NAC). In order to reach the required workability, it is needed to add a certain amount of water to saturate recycled aggregates before or during mixing, otherwise water-reducing admixture is applied. It is possible either to saturate recycled aggregate to the condition first _water saturated surface dry_ or to use dried recycled aggregate and to add the additional water quantity during mixing. The additional water quantity is calculated on the basis of recycled aggregate water absorption in prescribed time.

- Durability

Durability is the concrete ability to resist weathering action, chemical attack, and abrasion while maintaining its desired engineering properties.

The permeation characteristic of concrete is one of the factors that affect the durability performance of the concrete (Behera et al., 2014). Besides, residence of concrete towards some particles in the environment such as sulphate, chlorides, acids, carbon dioxide etc., would determine the durability performance of the concrete (Behera et al., 2014). Different studies show that the durability of the RAC is shorter than that of conventional concrete, mostly due to the quality and properties of recycled aggregates. Because there are many pores and cracks inside recycled aggregates that increase penetration. Therefore the porosity of recycled aggregates is an influential factor for durability performance of RAC (Behera et al., 2014). Recycled aggregates must be characterized based on their qualities, as it could affect the mechanical and durability performance of RAC considerably (Behera et al., 2014).

2.4 Economic performance from recycling CDW

Besides possible environmental advantages, significant economic advantages could be gained when the disposal of waste materials into landfills is avoided. This is due to conserving raw materials, avoiding disposal costs and benefiting from secondary uses of waste materials (Batayneh et al., 2007). Recycling is a process that transforms wastes into resources and prevents their economic value from being buried (Ferreira et al., 2012). In general, the economic benefits gained from recycling can be affected by the recycling process itself, the avoided material production process and the market for recycled materials. Recycling is economically profitable if gains from the recycled material are higher than costs of the recycling process (van der Harst et al., 2016).

A strategic Analysis of the European Materials and Chemicals Market in the construction Industry reported that in 2010 the market for recycled construction materials generated revenues of 744.1 million euros and it was predicted to reach 1.3 billion euros in 2016 (Pacheco-Torgal et al., 2013).

One of the main factors that determines if the recycled material is economically viable, is market demand and subsequently price of the recycled material (which also depends on the offer available). Costs of recycling process and prices of recycled materials are affected by geographical location, since prices of machinery, materials, production and labor costs depend on the location (Ferreira et al., 2012).

According to the case study carried out by Coelho and de Brito (2011), the economic performance of conventional demolition vs. selective demolition (sending less waste to the landfills) highly depends on local conditions. Conventional demolition costs depend on the final disposal cost of the mixed CDW, but selective demolition costs mostly depend on the costs of labor, equipment, transportation and final disposal costs.

In addition, the European Commission (DG ENV, 2011) stated that economic benefits from recycling concrete would depend on local conditions, such as availability of natural aggregates, availability of CDW materials and recycling facilities, landfilling fees, taxes on natural aggregates and standards and regulations regarding treatment process and recycled materials. The prices for recycled concrete aggregates in Europe ranges between 3 and 12 € per ton and the cost of its production process is between 2.5 and 10 € per ton (DG ENV, 2011).

The results of a study carried out by Dahlbo et al. (2015), for assessing the economic performance of common Finish CDW management, shows that recycling of CDW in total was economically profitable but the recycling of concrete and mineral materials had low economic profits.

Appendix B presents the economic data in Charier Company that we have managed to collect for two recycling platforms (Theix and La Vraie Croix, as already discussed in Appendix A).

2.5 Barriers towards recycling CDW and how to overcome them

In general, recycling needs to overcome natural product availability, price and quality (Wilburn and Goonan, 1998).The main barriers on the way of promoting recycling CDW are the lack of knowledge regarding the use of recycled materials and a low level of confidence towards them (Knoeri et al., 2014; Silva et al., 2014).

According to Knoeri et al. (2014), increasing awareness of construction actors towards recycling combined with price incentives were the most effective factors for enhancing the use of recycled materials. Recycling could be promoted by increasing the price of virgin materials and disposal fees and setting some obligatory regulations for the end of life treatment of construction materials. This would increase the probability that recycled materials would find the market (Dahlbo et al., 2015; Wilburn and Goonan, 1998).

According to the European Commission, there are mainly three barriers towards recycling CDW, Economic, cultural and technical (DG ENV, 2011).

The main economic obstacle to recycling CDW is the low cost and local availability of virgin materials. Accordingly, recycling and reusing CDW is more costly than using virgin materials. Recycling the mineral fraction of CDW is more feasible in densely populated (urban) areas where raw materials extracted from local quarries are less available. Transporting natural aggregates to these areas, from distant quarries, makes these materials more expensive. To overcome the economic obstacle, DG ENV (2011) suggests:

- Increasing the cost of disposal
- Developing bans on disposing CDW into the landfills
- Putting taxes on raw material extraction.

Our interview with professionals, throughout the thesis, showed us that, there are often misunderstandings and a lack of confidence in the quality of the recycled materials to be used in structural applications, such as the use of recycled aggregates in the production of structural concrete. In order to overcome the cultural barriers it is needed to (DG ENV, 2011) :

- Turn waste into valuable raw materials. This can be achieved through quality certification of secondary raw material from CDW.
- Communicate on the advantage of secondary raw materials; it has been proved that using 20% of recycled aggregate for making concrete is feasible even without changing the quality of the concrete.
- Conduct further research on the applications of recycled materials from CDW and mainly on their long-term behavior.

Finally, a bad sorting and presence of contaminants in CDW are some of the technical barriers towards recycling CDW. Dealing with this problem could be carried out as follows(DG ENV, 2011):

- Encouraging sorting of CDW “at the source”, which means that sorting out different CDW materials and identifying their potential contaminants to avoid contaminating the inert fraction and ensure high quality of recycled materials, which in turn causes collection of some small valuable materials such as glasses, plastics, metals, gypsums etc. as well as a better handling and managing of hazardous materials.
- Selective demolition and controlled deconstruction including systematic removal of contaminants prior to demolition and sorting different building materials could be promoted.

In Appendix C, obstacles that recycling facility owners in *Loire-Atlantique* in France face concerning recycling or recovering CDW are presented according to CERC (2013).

2.6 Introduction to Life Cycle Assessment (LCA) and recycling in LCA

2.6.1 Life Cycle Assessment (LCA) method

The importance of environmental protection and specifying the environmental impacts related to produced and also consumed [3]products have drawn attention to the development of methods that can make these impacts more understandable. One of these methods is Life Cycle Assessment (LCA) (ISO, 2006b).

LCA can help in (ISO, 2006b):

- identifying the possible areas of improvements in a product's life cycle from environmental points of view;
- decision support to have more informed decisions;
- selection of appropriate environmental performance indicators, including measurement techniques;
- marketing, such as producing an environmental product declaration.

LCA is a technique to assess the [4]potential environmental impacts and to quantify material and energy consumptions associated with a product's life cycle, e.g. from cradle to grave (from extraction of raw materials, materials preparation, manufacturing, distribution, use, end of life treatment, recycling and disposal) (ISO, 2006b).

A product's life cycle is considered as a product system in ISO 14040 standard (ISO, 2006b). Processes included in the product system are called [5]unit processes. Unit processes are connected to one another with the flow of intermediate products and to the environment with elementary flows. Input elementary flows to the product system refer to the flows of unprocessed substances and materials withdrawn from the environment, such as water from oceans and rivers, extracted primary materials from the earth etc. Output elementary flows from the product system refer to flows of substances or materials released to the environment without going through further processes or human transformation. Examples of output elementary flows are emissions to air, soil and water. Wastes or man-made products that are released in nature such as plastic bags left in the forests are also referred to output elementary flows. Because they will not undergo further processes.

LCA studies include four phases, goal and scope definition, life cycle inventory, impact assessment and interpretation of the results (ISO, 2006b). Figure II. 9 shows the interactions between four phases of the LCA. They are discussed in sections 2.6.1.1-2.6.1.4.

---

[3] In ISO 14040 Standard, "the term "product" includes services" (ISO, 2006b).
[4] It will be discussed in section 2.6.1.3 why it is potential.
[5] A unit process could be considered as a product system.

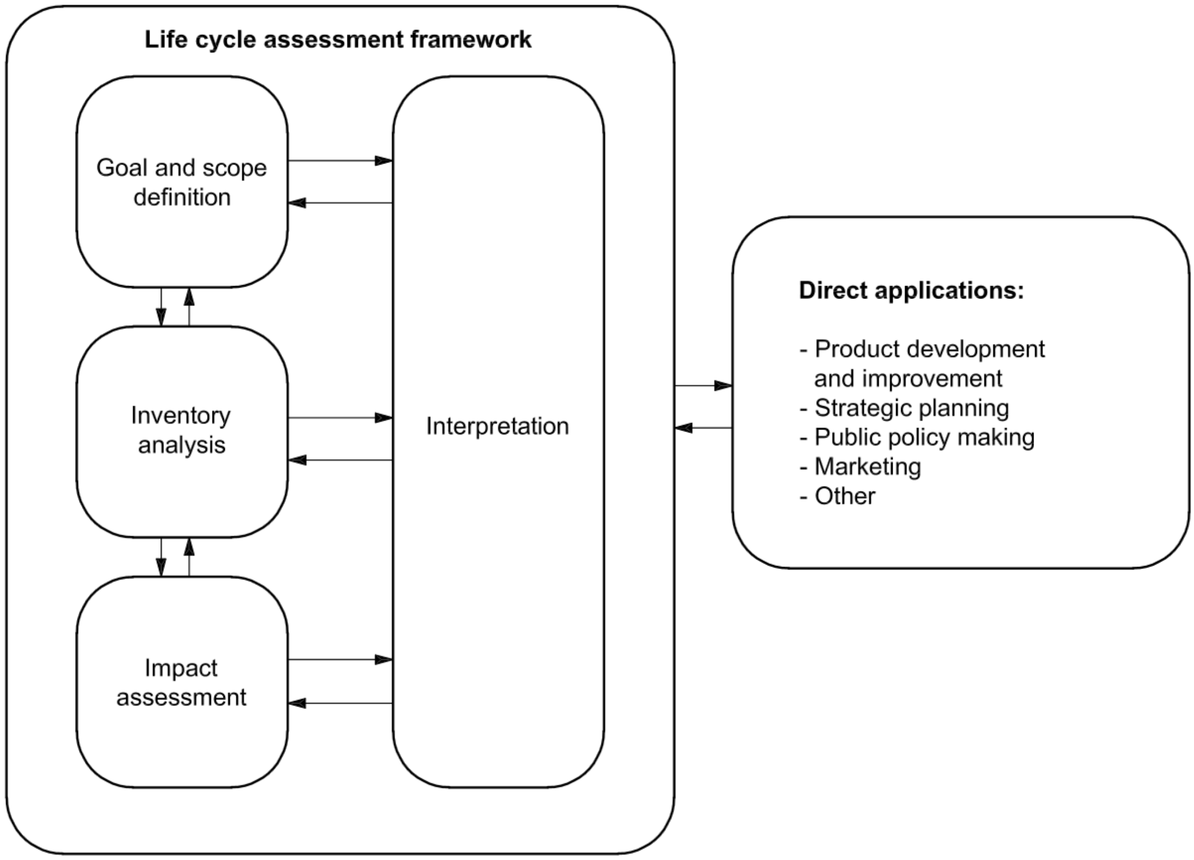


Figure II. 9 Phases of LCA (ISO, 2006b)

2.6.1.1 **Goal and scope of the LCA**

The goal of LCA mainly describes the reasons for performing LCA, the applications of the LCA results (for whom the results are intended to be used). Scope includes the functional unit, system boundary and assumptions.

Unit processes included in the product system understudy in LCA focus on fulfillment of one of the functions of the system based on the goals of the study, which is called a functional unit. The functional unit determines what is being studied. It also defines the quantified performance of the product system to provide a reference to which the inputs and outputs of the system are related. (ISO, 2006b). Functional unit is mainly useful to compare several product systems that provide the same function. For instance, comparing the LCA results of a wooden bridge and that of a concrete bridge whose function is providing a service for pedestrians and the reference flow to be compared is a specific volume (e.g. m^3) of the bridges. The functional unit should be differentiated from the reference flow. The reference flow is an intermediate flow reflecting the amount and unit of product under study.

If the product system provides additional functions besides the functional unit, the product system is considered as a multi-functional product system. Therefore, various procedures can be applied to handle multi-functionality problems and conduct LCA of the functional unit (by isolating the functional unit) (ISO, 2006a). Multi-functionality is further discussed in section 2.6.4.

System boundary identifies which stages of the product's life cycle (e.g. production, use and disposal) and unit processes, based on the goals and scope of the study, are included in the product system (ISO, 2006b).

2.6.1.2 **Life Cycle Inventory (LCI)**

During Life Cycle Inventory (LCI) analysis, data collection is carried out to identify and quantify all intermediate and elementary input and output flows to and from the product system related to the required functional unit (ISO, 2006b).

Data for each unit process in the product system should be collected, including: elementary flows, such as raw material inputs, emissions to air and discharges to water and soil, and intermediate flows, such as inputs (or outputs) from (or to) another unit process in the product system (ISO, 2006b). Handling the multi-functional process is also carried out in this step. It is of the most importance to be as accurate as possible in data collection. Because, it will affect the accuracy of the LCA results significantly.

2.6.1.3 **Life Cycle Impact Assessment (LCIA)**

In this phase elementary flows gained from the LCI phase are converted to environmental impacts (ISO, 2006a). It should be noted that, processes included in the product system can happen at different places and in different periods of time. Accordingly, results from an LCIA cannot refer to real environmental impacts due to a lack of specific locations and periods, they refer to potential environmental impacts (T. N. Ligthart and Ansems, 2012).

According to ISO 14044, LCIA contains mandatory and optional elements. They are listed as follows (ISO, 2006a):

- mandatory elements:
    - selection of impact categories, category indicators and characterization models
    - assignment of LCI results to the selected impact categories (classification)
    - calculation of category indicator results (characterization)
- optional elements:
    - normalization
    - grouping
    - weighting
    - data quality analysis

The optional elements are not the concerns of this PhD thesis, but mandatory elements are discussed in Appendix D.

2.6.1.4 **Interpretation**

The interpretation phase contains the following elements (ISO, 2006a):

- identification of the significant issues based on the results of the LCI and LCIA phases of LCA;
- an evaluation that considers completeness, sensitivity and consistency checks;
- conclusions, limitations, and recommendations.

The goal and scope and interpretation phases frame the study, while LCI and LCIA produce information on the product system. The interpretation of the results gained from LCI or LCIA should be carried out based on the goal and scope of the study (ISO, 2006a).

2.6.2 LCA modeling approaches

Different goals of the LCA studies, require different types of LCA modeling procedures, such as attributional LCA (ALCA), consequential LCA (CLCA) and IO (Input/Output) LCAs (Tillman, 2000). The results of LCA would be influenced by the type of method chosen, because each method may require different procedures to handle allocation problems (Tillman, 2000).

ALCA refers to retrospective and cause-oriented LCAs, while CLCA refers to prospective and effect oriented LCAs and studies the effects of changes (Tillman, 2000). IO LCAs are based on IO economic matrixes, but they are not considered in this work. Only ALCA and CLCA are discussed in the following sections (2.6.2.1-2.6.2.2).

2.6.2.1 Attributional LCA (ALCA)

Attributional LCA (ALCA) is considered as a traditional approach for LCA. ALCA can respond to different questions. Finnveden et al. (2009) stated that “ALCA is defined by its aim to describe the environmentally relevant physical flows to and from a life cycle and its subsystems”. According to Sonnemann and Vigon (2011) “ALCA is System modeling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule.” (Ekvall et al., 2016). Level of knowledge required for ALCA is physical mechanism level (Thomassen et al., 2008). In addition, to handle multi-functionality problem in ALCA, physical or economic portioning is usually applied (Thomassen et al., 2008).

2.6.2.2 Consequential LCA (CLCA)

“Consequential LCA (CLCA) reflects the possible future environmental impacts from a change in demand of a product understudy.” (Thomassen et al., 2008). Therefore, in order to show the environmental consequences of a change in a system, e.g. changes in demand or supply of recycled materials, it is required to apply consequential approach (Sandén and Karlström, 2007). The main concept in CLCA is to understand the market quantitatively and determine how changes in supply or demand of the analyzed materials would affect the supply and demand of other materials (European Commission, 2010a). The principle of modeling CLCA is to consider processes that are affected by a change in supply or demand of a co-product in the system understudy (Zamagni et al., 2012). These processes are called “marginal technologies” as well.

CLCA was initially introduced in the 1990s through primary allocation problems when waste management questions and allocation were considered (Ventura, 2013). There are different definitions for CLCA that have been improved over the years. Initially CLCA was defined as “aiming at describing the effect of changes within the life cycle.” The earlier definition was improved as “ attempting to estimate how flows to and from the environment will change as the result of different potential decisions” or “describing how the environmental relevant physical flows to and from the technology system will change in response to possible changes in life cycle." (Zamagni et al., 2012).

According to Ventura (2013), CLCA is mainly based on social and economic mechanisms concerning the consequences of alternative products and how they will drive the substitution. Sandén and Karlström (2007) stated that CLCA is a method that quantifies environmental consequences from changes in a system by taking the status of the market before and after applying the changes, this refers to being dynamic. Zamagni et al. (2012) concluded that CLCA is more a modeling approach that takes (some) market mechanisms into account. However, according to Zamagni et al. (2012) there are many uncertainties regarding CLCA mainly due to the ambiguity about what CLCA is, for what it is useful and what it involves from a methodological point of view. So they suggested using scenario modeling for improving the structure of CLCA. It would increase the validity of studies to provide an approach to think about probable future developments in a structured manner (Zamagni et al., 2012).

In CLCA studies, it is required to consider market aspects for anticipating the consequences of a change in supply/demand of the co-product, otherwise the study carried out is more ALCA (Ekvall, 2000). These market mechanisms should be based on price elasticity related to supply and demand economic models (Weidema, 2003a). In this regard, ILCD mentions that showing the real consequence of a decision in consequential modeling requires taking the market and economic implications of the decision into account. In other words, the central concept in consequential modeling is to identify the effects of changes in supply and demand of a product through the market of supply and demand of other products (European Commission, 2010a).

All these definitions imply the "market-oriented" nature of the CLCA model. Therefore, according to Thomassen et al. (2008), it is required to have a knowledge of physical and market mechanisms in CLCA. In addition, they mentioned that to handle multi-functionality problems in CLCA, system expansion must be applied.

2.6.3 **Recycling in LCA**

A product' life cycle consists of different stages. The end of life stage can be performed in different ways, such as reuse, recycling, incineration with and without energy recovery and landfilling. The priority order for waste management according to European Commission is: prevention, reuse, recycling, recovery and disposal (the least preferred option which includes landfilling and incineration without energy recovery) (European Commission, 2008).

2.6.3.1 **Types of recycling**

Depending on where and how a recycled material is used, there are three different approaches to model recycling in LCA: closed loop recycling, open loop recycling and semi-closed loop recycling (T. N. Ligthart and Ansems, 2012).

Closed loop recycling corresponds to the case when materials related to a product life cycle are recycled and reused in the same product system (T. N. Ligthart and Ansems, 2012). In this case the material properties will not change compared to the primary materials, see Figure II.

10. Bottle-to-bottle recycling is an example of closed loop recycling (T. N. Ligthart and Ansems, 2012).

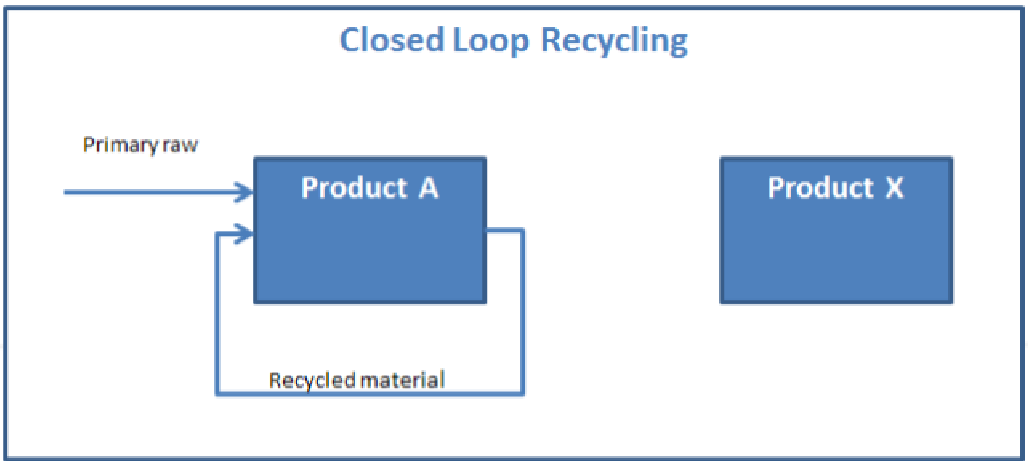


Figure II. 10 Closed loop recycling in LCA *(T. N. Ligthart and Ansems, 2012)*

Semi-closed loop recycling happens when recycled materials are used in another product system without any changes in the inherent properties of the materials, see Figure II. 11 (T. N. Ligthart and Ansems, 2012).

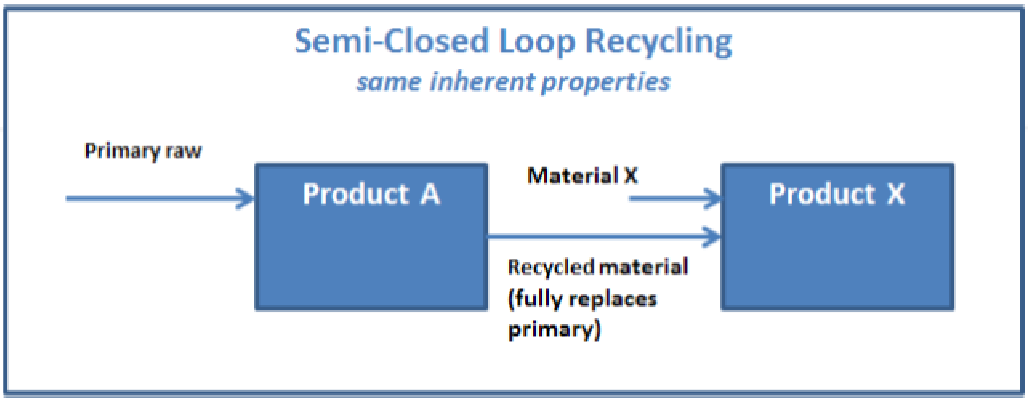


Figure II. 11 Semi-closed loop recycling (T. N. Ligthart and Ansems, 2012)

Open loop recycling happens when the materials in a product life cycle are recycled and used in another product life cycle (T. N. Ligthart and Ansems, 2012). The inherent properties of materials will change in this type of recycling. Because of that they cannot be used again in the original product life cycle. This type is also known as down cycling due to the losses in material qualities, see Figure II. 12 (T. N. Ligthart and Ansems, 2012).

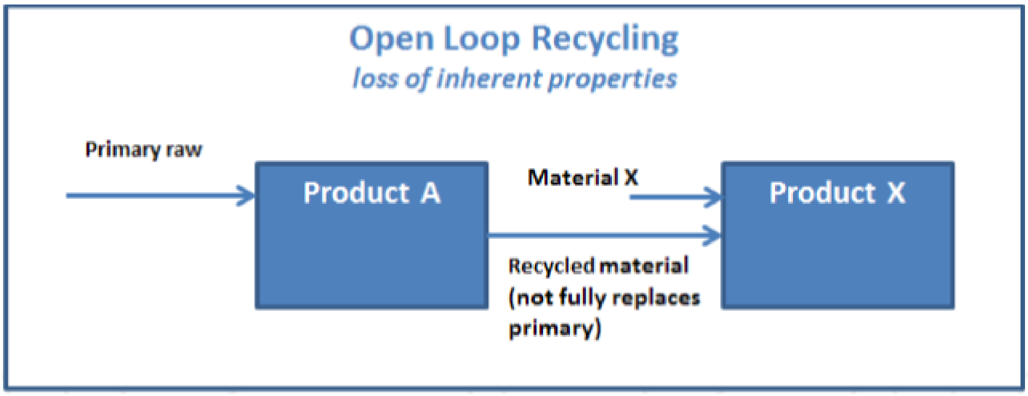


Figure II. 12 Open loop recycling in LCA (T. N. Ligthart and Ansems, 2012)

For ILCD (European Commission, 2010a), open-loop recycling includes two sub-types: "open loop – same primary route" recycling and "open loop – different primary route" recycling. The first sub-type could be referred to the semi-closed loop recycling that has been mentioned above and subsequently the second one to open-loop recycling.

Figure II. 13 and Figure II. 14 show two types of open-loop recycling mentioned in ILCD, "open loop- same primary route" and "open loop - different primary route" recycling respectively (European Commission, 2010a). Figure II. 13 shows that in "open loop – same primary route" recycling, waste from first life cycle (blue) is recycled in the green process and then recycled material is used in other life cycle (yellow). However, it will replace the same primary route (Material production1) of its first life cycle.

Figure II. 14 shows that in "open loop – different primary route" recycling, the waste from the first product system (blue) is recycled (green) and then it will be used in other product system (yellow) and replace a different primary production route.

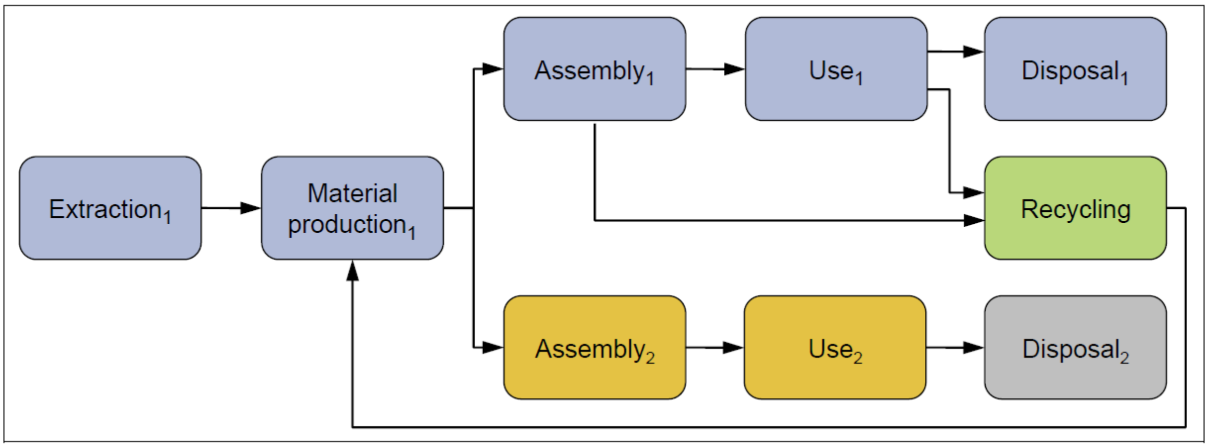


Figure II. 13 "Open loop – same primary route" recycling (European Commission, 2010a)

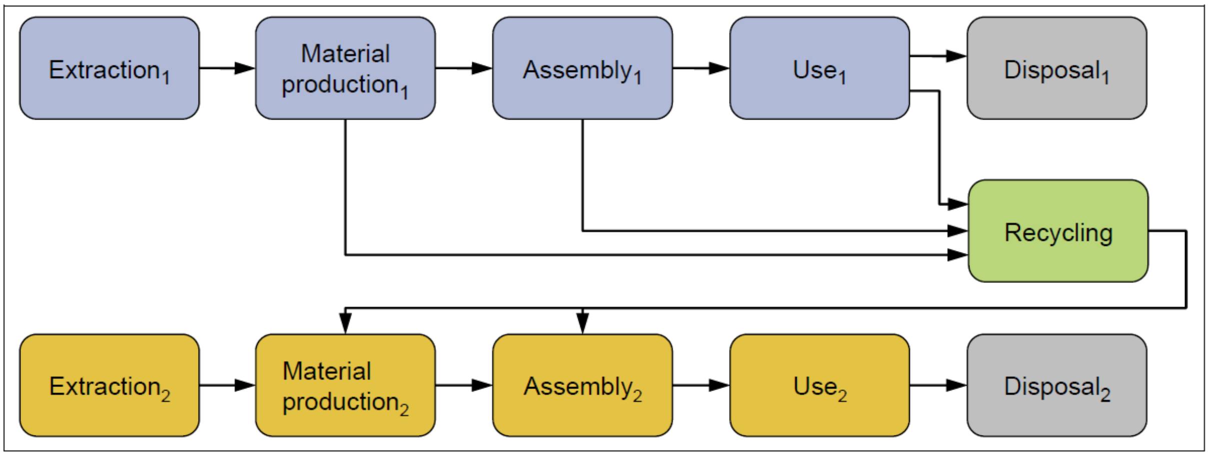


Figure II. 14 "Open loop – different primary route" recycling (European Commission, 2010a)

2.6.4 Multi-functionality and methods to overcome the multi-functionality problems

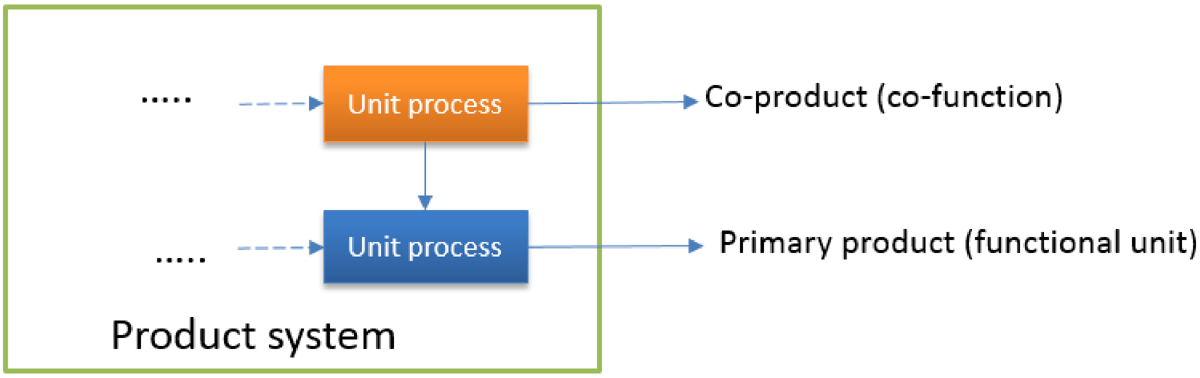
When a product system provides one function, which is defined as functional unit, all inventory flows of the product system are allocated to this functional unit, as mentioned in section 2.6.1.2.

However, some product systems provide more than one function, which makes the product system multi-functional.

In order to identify the multi-functional product system, functional flows of the product system should be identified (Guinée et al., 2004). According to Guinée et al. (2004), a [6]functional flow is either a product produced from a process, or a waste treated by a process. If a process yields more than one functional flow, the process is a multi-functional process (Guinée et al., 2004). Two typical multi-functional processes are co-production process and recycling process (Guinée et al., 2004). As, a co-production process has more than one functional outflow and no functional inflow; and recycling has at least one functional inflow (e.g. waste) and at least one functional outflow (e.g. recycled product).

When a product system contains a co-production process, and not all the co-products of the co-production process are used in the product system, the product system is considered [7]multi-functional, see Figure II. 15. Because, it provides additional functions besides the functional unit and the product system can be connected to other product systems due to the co-products, see Figure II. 15.

[6] Functional flow is also defined as: "One of the (co-) product flow(s) in the inventory of a process or system that fulfils the process'/ system's function." (European Commission, 2010a).
[7] Multi-functionality is also defined as: "Process or system that performs more than one function." (European Commission, 2010a).



[8]Figure II. 15 Example of a product system containing a multi-functional process (co-production process). The orange box represents a multi-functional process due to the production of two co-products, and green cadre represents a multifunctional product system due to the production of a primary product and a co-product.

A product system is also multi-functional, if at its end of life stage valorization (such as recycling, reusing or energy recovery) takes place. In the case of open-loop recycling, the product system is connected to a subsequent product system, since the recycled product will be used as an input product in the subsequent product system. Therefore, the product system will provide two functions; one is related to the use of the primary product during its service life and the other to the use of the recycled product, see Figure II. 16.

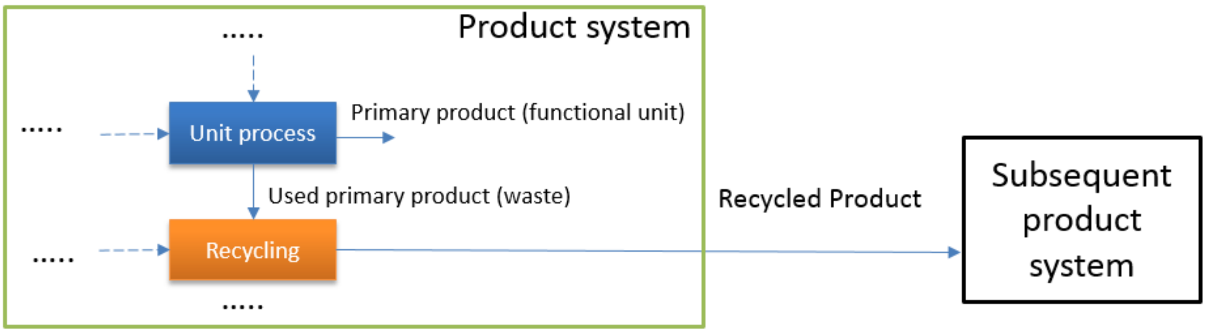


Figure II. 16 Example of a multi-functional product system due to its end of life treatment, which is recycling. The orange box represents a recycling process as a multi-functional process, and green cadre represents a multifunctional product system due to the production of a primary product and a recycled product.

In the case of having a multifunctional product system due to either recycling or co-production process, different questions may arise. How can one allocate materials consumed in the co-production process, or emissions released from that process to different co-products of the process, when an LCA practitioner focuses on LCA of one of the co-products (see Figure II. 15)? How does one determine which impacts and benefits are related to which co-functions of the product system, if an LCA study aims to focus on environmental assessment of one of the

[8] Co-product: "Any of two or more products coming from the same unit process or system. [Source: ISO 14044:2006]." (European Commission, 2010a).
Co-function: "Any of two or more functions provided by the same unit process or system." (European Commission, 2010a).

functions of the product system to compare it with different product systems that provide the same function (Weidema, 2001)? How can one share impacts of the investigated product system between primary product and recycled product of the system? How does one share impacts or benefits of recycling between different product systems, the one that produces recycled material and the one that uses recycled material (van der Harst et al., 2016)? All these issues refer to multi-functionality problems or allocation problems in LCA (Heijungs and Guinée, 2007b; Pradel et al., 2016; van der Harst et al., 2016). That is why a method is required to overcome multi-functionality problems of recycling or co-production process and subsequently multi-functionality problem of a multi-functional product system. Allocation is one of the most controversial issues in LCA as it might affect the results of an LCA (Weidema, 2001).

2.6.4.1 **Combined and joint productions**

In the topic of multi-functionality situations, the difference between joint production and combined production are usually mentioned (Weidema, 2001). The combined production refers to a production process that produces different co-products whose production volumes can be independently changed (Weidema, 2001). While joint production refers to a production process that produces different co-products with fixed relative output volume (Weidema, 2001). In the latter case an allocation procedure must be applied to account for the environmental impacts related to the LCA of each co-product (Weidema, 2001). Recycling is an example of joint production. Because the amount of recycled materials depends on the amount of primary materials that is produced (Weidema, 2001).

Therefore, it could be seen that joint production (co-production process) and recycling are quite similar in terms of allocation problem. Accordingly, Guinée (2002) and Weidema (2001) mentioned that multi-functionality problem of recycling is not different from that of co-production. Therefore, similar methods could be considered to solve the multi-functionality problems for both co-production and recycling, as proposed by ISO 14044. This aspect is also consistent with European regulation that defines the necessary conditions under which a waste can become a co-product when it is valorized (European parliament, 2008).

2.6.4.2 **Methods to solve multi-functionality problems in LCA according to ISO 14044 standard**

ISO standard has proposed a hierarchy to solve multi-functionality problems of co-production: subdivision, system expansion, physical or economic [partitioning] allocation (ISO, 2006a). In ISO standard, “allocation” refers to “partitioning”, that could be physical partitioning or economic partitioning or both. In this thesis, this method is shown by partitioning.

There is the same hierarchy to overcome multi-functionality problem of recycling according to ISO 14044. However, ISO standards do not prescribe a specific method for handling multi-functionality of recycling. Because, ISO 14044 suggests a sensitivity analysis, if several methods are feasible (ISO, 2006a). These methods are presented in Appendix E. In the following section, some of these methods for handling recycling in LCA are discussed in detail according to some authors.

2.6.4.3 **Methods to solve multi-functionality problems of recycling in LCA**

Modeling recycling in LCA has been a controversial issue in the past two decades. To assess recycling in LCA, the main question that has to be answered is how to assign the environmental impacts and benefits of recycling to different product systems (the one that produces recycled materials and the others that use recycled materials) (van der Harst et al., 2016). Identifying the right boundaries for different flows ending in different product systems is one of the difficult issues in recycling: which observed material flows belong to the first product system and which ones belong to the second or other systems; which rules exist to allocate environmental impacts of recycling to each system (T. N. Ligthart and Ansems, 2012). The mentioned issues refer to allocation problems or multi-functionality problems of recycling (Heijungs and Guinée, 2007b; van der Harst et al., 2016).

LCA results depend on the methodologies chosen and the assumptions made in accounting for recycling (Bauman and Tillman, 2004; Heijungs and Guinée, 2007a). Therefore, it is necessary to choose a proper method to account for the environmental performance of recycling and overcome the multi-functionality problems.

The following methods are the most common ones according to different articles (T. N. Ligthart and Ansems, 2012; Heijungs and Guinée, 2007 ; van der Harst et al., 2016):

- System expansion and Substitution (or avoided burden method) methods
- Recycled- content or cut-off
- Economic partitioning

They are further clarified in the following sections (2.6.4.3.1-2.6.4.3.5).

2.6.4.3.1 System expansion method

According to Weidema (2001), system expansion is preferable procedure for overcoming the multi-functionality problems, since it got noticed in the procedure of ISO 14041. Weidema (2001) proposed 4 rules to solve multi-functionality problems of a multi-functional product system due to a joint production (such as process A in Figure II. 17) by means of system expansion. He mentioned, system expansion is performed by expanding the boundary of product system under study to include all the material production processes that are affected by a change in a system, such as changing in demand for the co-product of the interest to the life cycle.

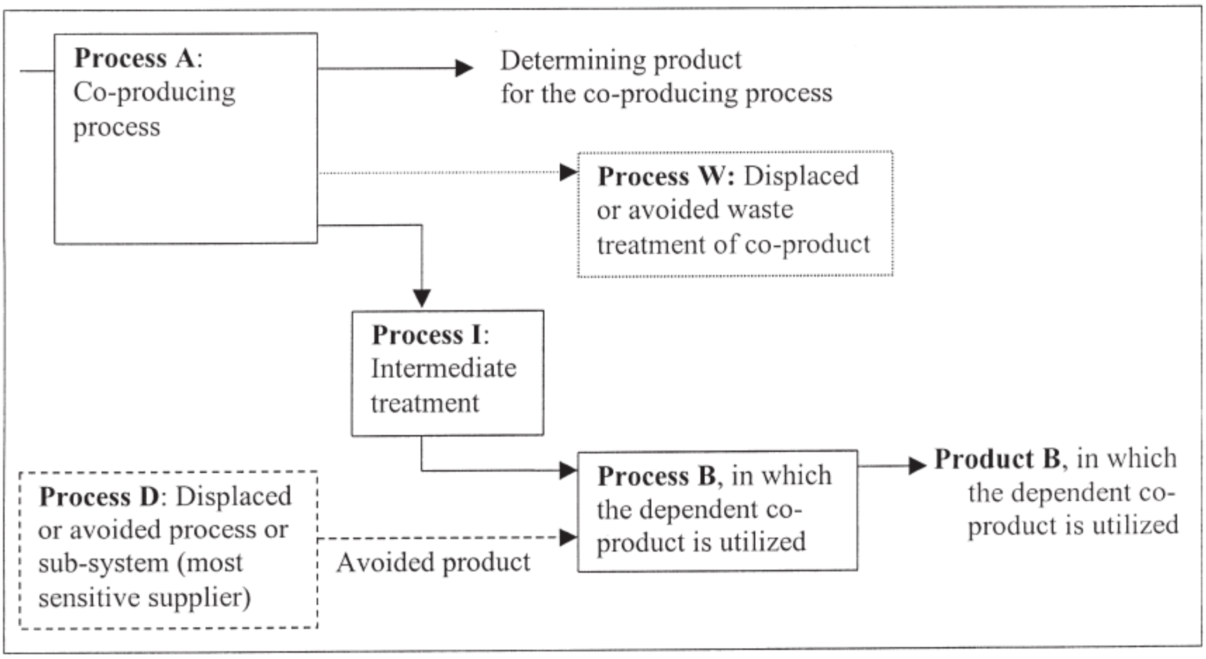


Figure II. 17 system expansion methodology (Weidema, 2001)

In Figure II. 17 process A is a co-producing process. Product A is the determining co-product of process A. Therefore, it identifies the production volume of process A. Knowing this, four rules are explained as follows:

Rule N°1: the co-producing process (Process A) and its exchanges should be fully ascribed to the determining co-product (product A).

Rule N°2: if the [9]dependent co-product of process A is fully utilized in other processes (Process B), where it displaces other products (Product D), product A should be credited for the processes that are displaced. On the other hand, the intermediate process (Process I) should be ascribed to product A. Because, product A is the determining co-product of the process and supply of the dependent co-product depends on the change in production volume of process A, which this in turn depends on the demand for product A.

Under this condition, process B and process D should be ascribed to product B.

Rule N°3: if the dependent co-product of process A is not fully utilized in other processes (Process B), but partly displaces another product, and some parts of it is regarded as waste, intermediate process should be ascribed to product B and at the same time product B should be credited for the avoided landfilling (Process W). Because, the volume of the intermediate process is determined by the demand of process B for the product of the intermediate process. This will also determine the extent to which waste is avoided in the landfill. Therefore,

[9] A dependent co-product is one of the co-products of the joint production that does not identify the production volume of co-producing process (Weidema, 2001). In other words, changes in demand for this co-product will not affect the production volume of the co-producing process.

the avoided landfilling of this amount of waste should be credited to product B. The intermediate process in this case could be a recycling process.

Product A should be ascribed for the landfilling of the dependent co-product that is co-produced with product A.

Rule N°4: if the dependent co-product does not replace other products, all processes in the entire life cycle of the co-product shall be fully ascribed to product A. This is due to the fact that, the volume of these processes is determined by the production of the co-producing process. However, according to the author, this situation would rarely happen.

Therefore, these rules will identify, under different conditions, how system expansion should be performed and which processes in Figure II. 17 should be ascribed to the product of interest in LCA studies.

Accordingly:

- if the dependent co-product displaces other products in other product systems and is fully utilized:

  Processes ascribed to product A are: Rules N°1+2 → A+I-D

  Processes ascribed to product B are: Rules N°1+2 → B+D
- if the dependent co-product displaces other products in other product systems but is not fully utilized:

  Processes ascribed to product A are: Rules N°1+3 → A+W'

  Processes ascribed to product B are: Rules N°1+3 → B+I-W''

  (W' is quantity of the dependent co-product that is not utilized because of lack of demand and W'' is quantity of the dependent co-product that is utilized in product B and which is thus not landfilled)

- if the dependent co-product does not displace other products in other product systems:

  Processes ascribed to product A are: Rules N°1+4 → A+I+B

It should be noted that ascribing implies to ascribe the environmental burdens of a given process to a given product.

2.6.4.3.2 Substitution (avoided burden) method

Substitution step is usually preceded by the system expansion method: the environmental load of a so-called 'avoided product' is subtracted from the total environmental loads of the expanded system. In other words, they implement system expansion with the aim of an avoided burden method (Thomassen et al., 2008), as Weidema (2001) did in rule N°2 and N°3.

The main concept of the substitution approach is to avoid the production process of a product by replacing it with an alternative production route that produces the same function. This avoidance implies to subtract the displaced process from the product system that provides the alternative production route.

According to van der Harst et al. (2016) there are three different substitution methods: 1) substitution-with-equal-quality, 2) substitution with-correction-factor, 3) substitution-with-alternative-material.

Van der Harst et al. (2016) explained how substitution method could be performed to solve multi-functionality problem of recycling in LCA.

The application of the recycled material, which is regained (via recycling) at the end of life of the first product, depends on the quality of the recycled material. The recycled material which leaves this recycling process can be used in the production of a next product. Therefore, recycled material can be considered as: 1) similar to virgin material (substitution-with-equal-quality), 2) partly comparable to virgin material (substitution-with-correction-factor), or 3) similar to a different material (substitution-with-alternative-material).

The use of the recycled material in a next product avoids the production of a certain material, which can be virgin material, reduced quality material, or an alternative material. This means that the analyzed (first) product system receives credits for the avoided production of a certain material (van der Harst et al., 2016). These credits are applied by subtracting the environmental burdens of the production of the avoided material from the environmental burdens of the analyzed product system. Environmental burdens of the first product system are calculated up to the recycling process. Then after, the environmental burdens for the recycling process itself (grinding, melting, washing, etc.) are added to the environmental burdens of the first product system (van der Harst et al., 2016).

The first substitution method can be applied for closed loop recycling, where recycled material could substitute virgin material on a 1:1 ratio. In this case the life cycle under study will receive both environmental burdens from recycling of the product and environmental credits from avoided production. For the case that there are some losses in inherent properties of recycled materials, substitution should be applied on open loop recycling either with the same or different primary route that refer to two other substitution methods respectively, either applying a correction factor and replacing some limited parts of virgin materials by recycled material or using recycled material instead of an alternative material respectively (van der Harst et al., 2016). As can be seen the substitution method promotes recycling.

In Heijungs and Guinée (2007b) the substitution method is applied to a multi-output process, where process 1 is a waste treatment process that treats wastes A and B and produces marketable products C and D, as shown in Figure II. 18. This process uses product E and produces waste F and it is connected to the environment through the two environmental flows, use of resource G and discharges of emission H. 'a, b, c, d, e, f, g and h' are the magnitudes of each mentioned flow respectively. In order to calculate the total environmental burdens from the waste treatment process by using the substitution method (or avoided burden) method, it is needed to identify the proper avoided processes. For instance, if a product system needs one of the functional flows such as A, the other three flows B, C and D need to be subtracted by chosen processes. In that case, three mono-functional processes should be introduced, *1B'*, *1C'* and *1D'*, with the magnitudes of each flow included in each process shown in brackets in Figure II. 18. Therefore, total emissions from process 1 would be calculated as follow:

$$H = h - \frac{b}{b'} hB' - \frac{c}{c'} hC' - \frac{d}{d'} hD' \quad \text{II. 4}$$

Flows are distinguished by (') to show that flows are not exactly equal.

Therefore, Figure II. 18 shows that flow B' is a substitute for flow B. Thus, treatment of waste B' would be avoided by treatment of waste B as well as production of product C' and D' would be avoided by production of product C and D respectively.

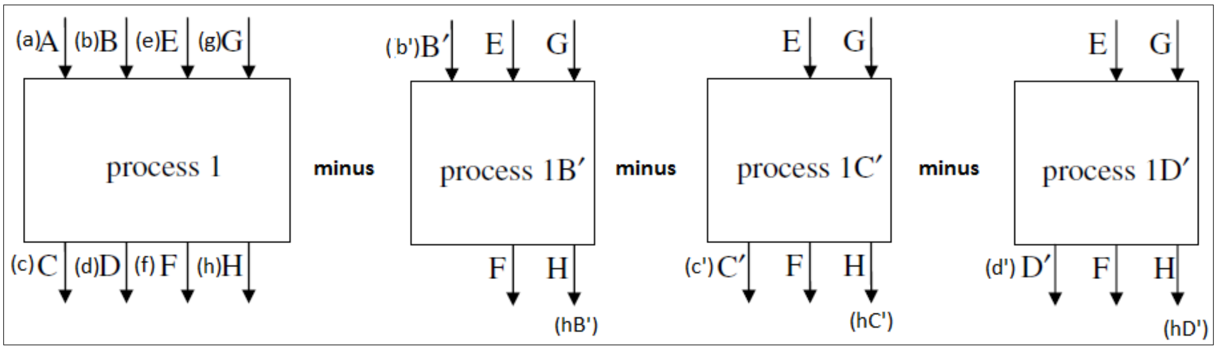


Figure II. 18 Substitution method applied on process 1 (waste treatment process) to account for allocation problem of multi-output process (the figure is inspired by Figure 3 shown by (Heijungs and Guinée, 2007a))

2.6.4.3.3 Relationships between system expansion and substitution methods

According to the European Commission (European Commission, 2010a), substitution is mentioned as an alternative for system expansion, given the point of view that they are mathematically equivalent (see Figure II. 19). They provide parallel approaches for solving multi-functionality problems. Substitution can be performed by expanding the system boundaries and substituting not required co-products with an alternative way of producing it, e.g. a process or a product that the not required co-products supersedes. In fact, substitution implies to subtract the life cycle inventory of the superseded process or product from that of the analyzed system (European Commission, 2010a). This means that the system understudy is credited for the superseded process. While system expansion is applied by expanding the system boundaries and adding alternative production routes that provide the same functions as the co-products of the system understudy (European Commission, 2010a). In other words, substitution is a subtractive case of applying the system expansion principles (European Commission, 2010a).

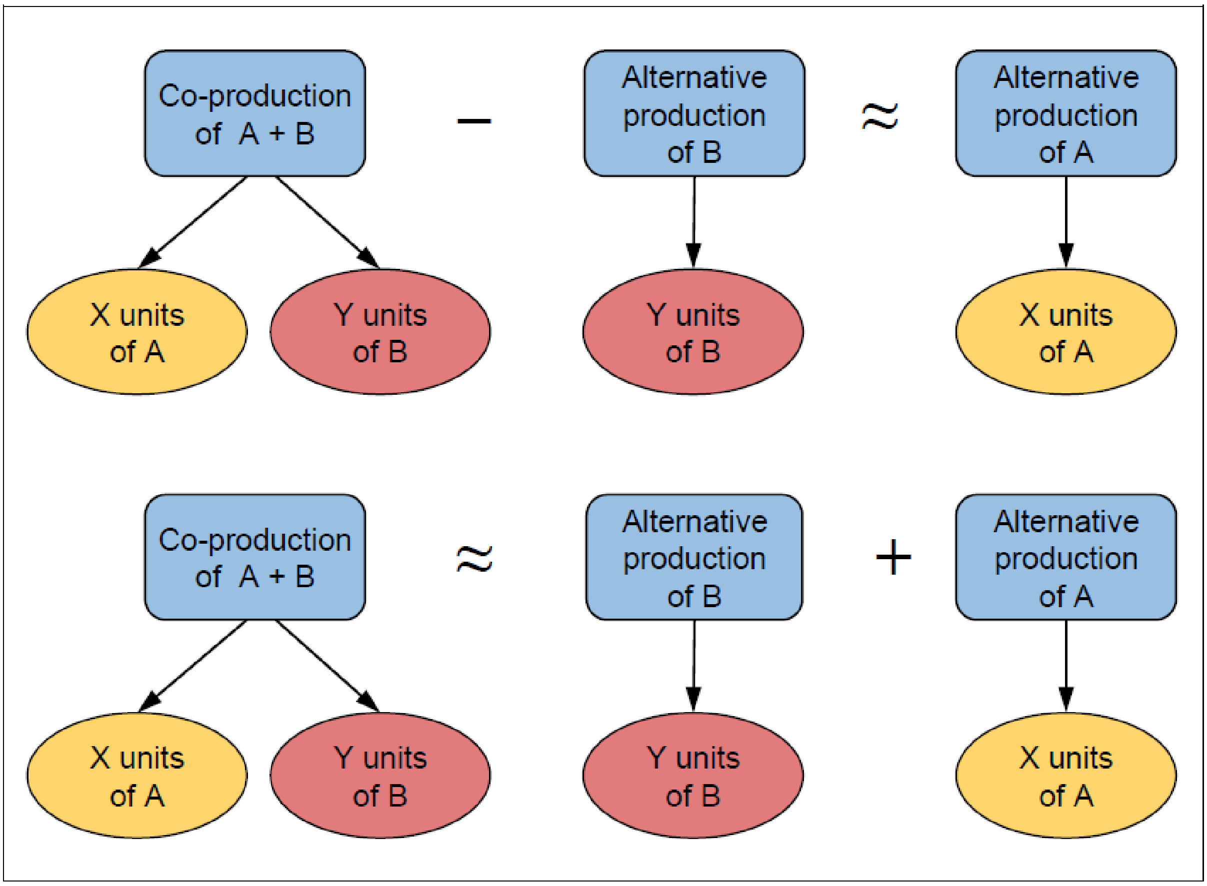


Figure II. 19 Solving multi-functionality problem by either adding (system expansion, bottom figure) or subtracting (substitution, top figure) functions (European Commission, 2010a).

System expansion has been supported by the ISO 14044 preference scheme for allocation procedure, where is defined as "expanding the product system to include the additional functions related to the co-products" (Heijungs and Guinée, 2007). Many authors have shown that system expansion that has been mentioned in ISO 14044 and the substitution method are conceptually equivalent (Heijungs and Guinée, 2007a), although the substitution method has not been mentioned clearly in ISO standards ((Chen et al., 2010a).

2.6.4.3.4 Recycled - content or cut-off method

When recycled-content or cut-off method is applied, the product system under study will receive credits for using recycled material, but will not gain burdens nor credits from the end of life recycling process of the analyzed product system (van der Harst et al., 2016). The total environmental impacts from the analyzed system in this method are calculated as follow.

Environmental burdens from the analyzed product system should be calculated including the burdens from production of required primary material entering the system as well as burdens from the disposal of waste generated by the system and not from recycling of the analyzed product. Afterward, environmental burdens from the amount of recycled material entering the analyzed system should be calculated by means of the burdens from the recycling process of waste which is needed to produce the desired amount of recycled material (van der Harst et al., 2016; T. N. Ligthart and Ansems, 2012). This method unlike the substitution method tries to stimulate the use of recycled material, see Figure II. 20. What is important in the recycled- content or cut-off method is to identify the amount of primary material and recycled material that enters the life cycle under study.

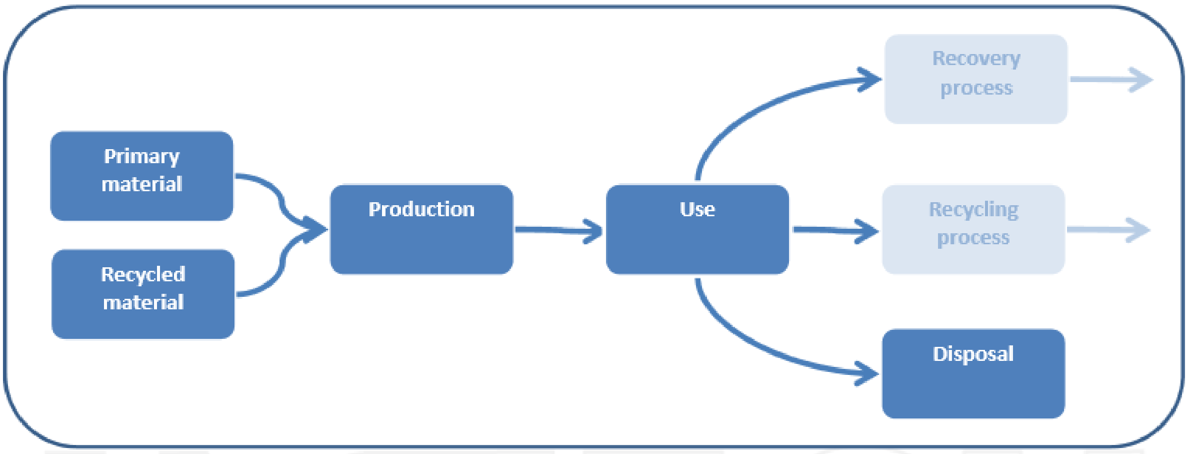


Figure II. 20 The product system for cut-off approach (T. N. Ligthart and Ansems, 2012)

2.6.4.3.5 Economic partitioning

In general, partitioning method is based on economic or physical values of inputs and outputs of the recycling system. Guinée et al. (2004) explained economic partitioning by an example of secondary aluminum from a used engine (T. N. Ligthart and Ansems, 2012).

In the product system shown in Figure II. 21, collection and dismantling process is a multi-functional process, since it has two functional flows: used engine (as an input) and secondary aluminum (as an output). In the study by Guinée et al. (2004), it is assumed that the value of the used engine is 100 € and the value of the secondary aluminum is 150 €. Therefore, the total yield of the process (collection and dismantling) is 250 €.

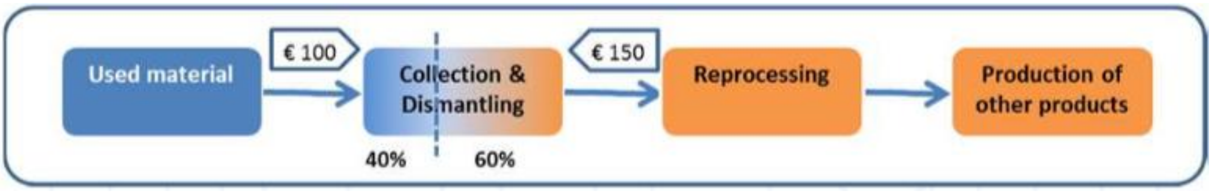


Figure II. 21 Example of economic partitioning of inputs and outputs of an open loop recycling system (T. N. Ligthart and Ansems, 2012).

In the case that the secondary aluminum is (partly) used in the original product system (first system), the recycling system could be considered as a (semi-)closed loop recycling process. In the study by Guinée et al. (2004), it is assumed that 1 kg out of 5 kg of the secondary aluminum is used back in the original product system. As a result, 12% (1/5*60%) of what is allocated to the secondary aluminum needs to be added to 40%. Therefore, 52% of the environmental burdens from collection and dismantling process is allocated to the original product system, see Figure II. 22.

Figure II. 22 Example of economic allocation of inputs and outputs of a semi-closed loop recycling system *(T. N. Ligthart and Ansems, 2012)*.

From the above examples, in the case of close-loop recycling that all functional flows remain within the same product system, no economic partitioning is required (Guinée et al., 2004). Therefore, the impacts of recycling is fully allocated to the first product system.

According to T. N. Ligthart and Ansems (2012), the economic partitioning implies that product systems are part of the economic system, as product systems are generally designed to generate economic value. Therefore using economic data for allocation seems to be an adequate method. The economic partitioning method could be considered as a modification of the cut-off method. Because, both have this in common that no avoided primary material production due to recycling is allocated to the product system that uses recycled material (T. N. Ligthart and Ansems, 2012).

2.6.4.3.6 General discussion

As already mentioned, there are different approaches suggested by authors to solve the multi-functionality problems of recycling. In this part, we present advantages and drawbacks of these different methods.

In system expansion, finding proper substitutes for the expanded process is not always that easy. If the expanded system is based on another multi-functional process, allocation problems by means of system expansion will be difficult to solve and new allocation problems may occur (van der Harst et al., 2016), yet Weidema (2003) has concluded that system expansion is always feasible. Another problematic issue with system expansion, as mentioned by Chen et al. (2010), is that it is highly dependent on how system boundaries are defined and there is no unique way of defining system boundaries among different studies. Thus, it depends on the point of view and objectives of LCA practitioners. The main advantage of system expansion is that it accounts for physical relationships between co-products and integrate them in a global expanded system. Although accounting for a multitude of functions in the expanded system makes the system multifunctional, the environmental impacts of the expanded system do have a meaning. Therefore, it has been proposed by Blanc and Ventura (2015) to rename the system expansion method as "functional expansion". As the system becomes multi-functional and does not attribute any part of the environmental impacts to a single function, system expansion usually precedes substitution. However, there are some limitations associated with the substitution method, yet the substitution method has been used by many researchers to deal with the multi-functionality problems (van der Harst et al., 2016; T. N. Ligthart and Ansems, 2012; Heijungs and Guinée, 2007).

In many cases losses in inherent properties of materials is not taken into account in this method. If this issue is not considered the substitution will not be accepted (Weidema, 2001). This means that there is not always 1:1 substitution ratio between the substitute flow and substituted flow. As suggested by van der Harst et al. (2016), there are two possibilities to overcome this problem, either using a correction factor, replacing limited part of primary materials by recycled material, or recycled material replaces alternative materials. Therefore, the main task is to choose a proper correction factor or alternative material, whose production is avoided, since either of these methods would affect the LCA results considerably. However, it is not that simple to decide on the equivalence of substitute flow and substituted flow (Heijungs and Guinée, 2007a).

Partitioning of processes between several functions is avoided by system expansion, and for this reason, substitution has been justified as a suitable method to avoid partitioning (Weidema, 2001). However, in some cases the avoided process is also a multi-output process. In that case the multi-functional problem would not be solved by means of the substitution method. Indeed, if the avoided product is a dependent co-product of a multi-output process, this is the production of the determining co-product of this multi-output process that will drive the production of the substituted co-products and not its replacement by an alternative (Ventura, 2013). Therefore, the avoided multi-output process, would need an avoided process itself or would have to be partitioned, which was supposed to be avoided.

In many studies using substitution, the actual replacement of a product by another is not checked or validated by existing data and that can cause very different results (Ventura, 2013). In fact, a new product rarely completely replaces another product, therefore, the current market situation should be accounted (Ventura, 2013). That is why substitution refers to "what if scenarios" (Heijungs and Guinée, 2007a). However, despite the fact that there are important limitations for the substitution method, it seems that it still remains the most commonly used method to solve the allocation problems in LCA.

The cut-off method is the easiest method that accounts for the amount of recycled materials and primary materials that enter the product system without accounting for the avoided burdens as the benefit of recycling. The main limits of the cut-off method is that it ignores recyclability of products at the end of life (van der Harst et al., 2016). Losses in inherent properties of materials is not incorporated in the cut-off method, the same as in the substitution-with – equal – quality method (van der Harst et al., 2016).

The main shortcoming of the economic partitioning method according to Chen et al. (2010), is that it is unstable, mainly due to the potential market prices that are not stable.

One of the main difference between all approaches is the way they credit recycling and where to assign the environmental burdens and credits, either on the input side (recycled - content method) or on the end of life side (substitution method). The cut-off approach is the easiest method and stimulates using of recycled material (T. N. Ligthart and Ansems, 2012). The economic partition method is based on cut-off approach and its results are often not very far from this approach (T. N. Ligthart and Ansems, 2012).

As can be seen, choosing a suitable method for assessing environmental performance of recycling in LCA is one of the most debated and controversial issues in LCA that performing a sensitivity analysis of different methods might be necessary, as suggested by ISO 14044 (ISO, 2006a). The choice of a method can significantly affect the LCA results (Bauman and Tillman, 2004). Therefore, LCA practitioners may choose the method that results in the most environmental benefits for the system understudy. There is no unique way to solve the multi-functionality problems, and every method is an artificial solution to an artificial problem, such as dividing a multi-functional process into several mono-functional processes (Heijungs and Guinée, 2007a). Indeed, the problems occur when one tries to reduce a multi-functional system into a single functional one and thus it is required defining rules about who (i.e. which part of the system) will get the benefits from recycling. Resolving multi-functionality problems is thus becoming more a political concern than a scientific question (Chen et al., 2010b). The system expansion method can be satisfying, if done properly, since total results have a physical meaning regardless of who will gain the benefits from recycling. When a multi-functional system is divided into mono-functional systems, results would lose their physical meaning, because they depend on the method applied to distribute the credits of recycling.

However, according to van der Harst et al. (2016), applying credits from recycling becomes applicable, if there is an actual market for the additional recycled materials. In addition, it is required to take into account the reactions of different markets, in terms of increased and decreased demand or supply for the recycled material (van der Harst et al., 2016). Credits should be also applied based on the quality of recycled materials. Consequently, in order to show the detailed consequences and affected processes by recycling beside conducting an LCA model, it is of great importance to have information regarding the market mechanisms and market forecast (European Commission, 2010a).

2.7 **Previous LCA studies on CDW recycling**

There is a common opinion among society that recycling of Construction and Demolition Wastes (CDW) improves environmental performances, since it would decrease the requirements for disposal sites, extraction of natural resources and emissions (CCANZ, 2011; Hill et al., 2001).

Therefore, this section aims at reviewing results of different studies on comparative environmental assessment between applications made from recycled aggregates recovered from CDW (mainly demolished concrete wastes) and those made from natural aggregates. In addition, it aims at extracting methods applied in these studies to handle multi-functionality problems of recycling CDW as well as identifying how environmental impacts or benefits from recycling CDW are assigned to the product system that uses recycled aggregates recovered from CDW.

Table II. 5 summarizes studies whose main objective was to compare the use of recycled and natural aggregates in different applications from an environmental point of view. In these studies LCA was used as a general methodology to evaluate potential environmental impacts of these applications. We have considered two different scales for these studies in Table II. 5. 'Product oriented' refers to the studies that performed a comparative LCA study regardless of considering the locations of recycling facilities, quarries, landfills and production sites. Therefore, they have either considered average transportation distances or excluded impacts of transport from their analysis. 'Territory' refers to studies that compared the results of different LCAs at the scale of cities or larger (e.g. at regional level) considering the locations of facilities such as quarries, recycling and landfilling and production sites. We have classified the applications of recycled aggregates produced from recycling of CDW in two groups in Table II. 5. According to these studies, CDW (mainly demolished concrete) has been either down-cycled as unbound materials in foundations, embankments and earth filling or in lean concrete (low-grade applications) or up-cycled as aggregates in structural concrete or cement production (high-grade applications). In most of these studies the final destination of concrete was not mentioned (e.g. building is the final destination for concrete). Therefore, concrete has been considered as an intermediate product, while building or foundation as a final product. Table II. 5 also presents methods applied in these studies for handling multi-functionality problems of recycling. The three methods presented in Table II. 5 as well as two exceptions mentioned below are shown schematically in Figure II. 23-Figure II. 27. They indicate the system boundaries and processes included in the system boundaries based on the method applied for handling the multi-functionality problems. As can be seen from Figure II. 23-Figure II. 27, in the studies presented in Table II. 5, the impacts of recycling CDW have been allocated to the product system that received the waste and used recycled aggregates in the investigated product.

In most studies presented in Table II. 5, the system understudy was expanded to include processes avoided through recycling of CDW. Indeed, they have used the system expansion method by considering the avoided burdens. Accordingly, the environmental impacts from recycling and benefits from the avoided processes were allocated to the product system that received waste and used recycled aggregates in the investigated product. Some of these studies have considered landfilling of CDW as the avoided process due to recycling CDW (e.g. (Knoeri et al., 2013)), as shown in Figure II. 23. The impacts from the avoided landfilling were subtracted from the total impacts of the system, as assumed by Weidema (2001) (discussed in section 2.6.4.3.1). Whereas, other studies considered virgin material production (such as extraction and production of natural aggregates) as the avoided process due to recycling and use of recycled aggregates (e.g. (Dahlbo et al., 2015)), as shown in Figure II. 24.

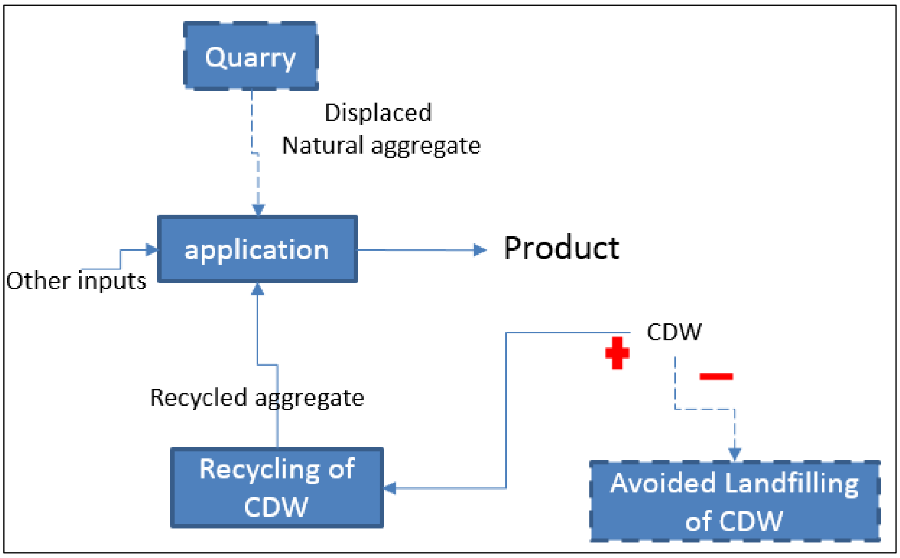


Figure II. 23 System boundary considered in Method 1 presented in Table II. 5 (displaced process or product has zero impact).

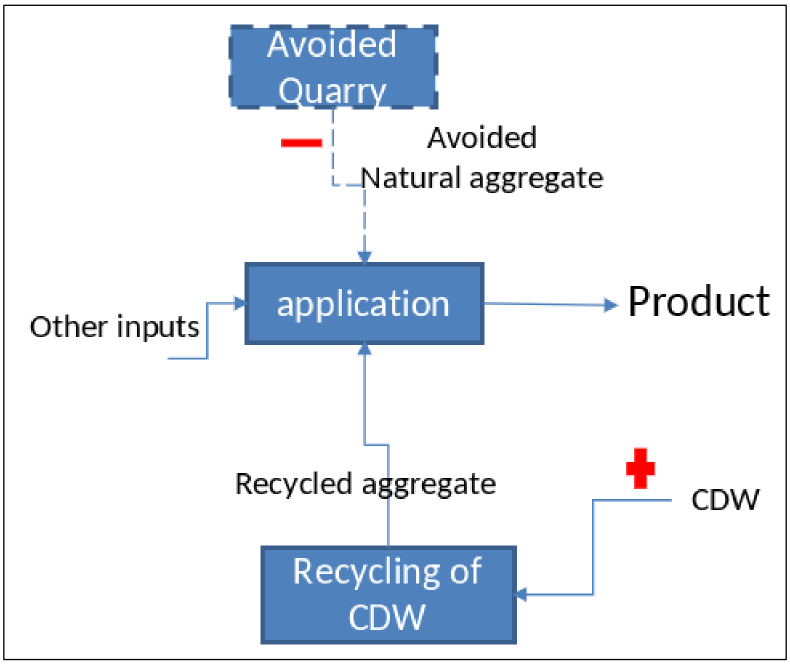


Figure II. 24 System boundary considered in Method 2 presented in Table II. 5.

Some other studies presented in Table II. 5 have not considered the avoided processes as benefits of CDW recycling. They allocated environmental impacts of CDW recycling process to the product system in which recycled aggregates were used and they considered zero impacts for the avoided processes through recycling (Figure II. 25). Therefore, it could be assumed that they used cut-off method.

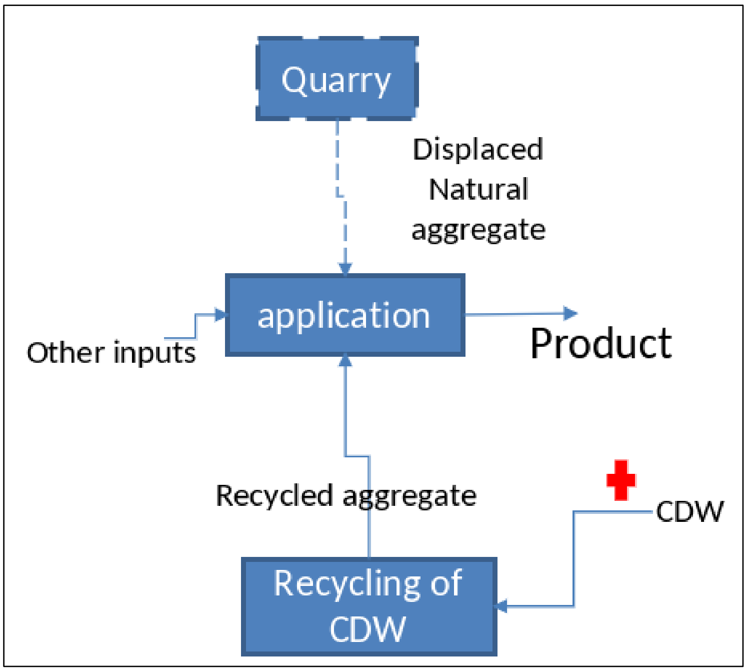


Figure II. 25 System boundary considered in Method 3 presented in Table II. 5 (displaced process or product has zero impact)

The studies presented in Table II. 5 have considered waste as burden free. This implies that impacts from dismantling (building demolition) and producing waste were not allocated to the product system that used recycled aggregates. This is mainly justified by the authors due to the fact that, old buildings would be demolished regardless of the destination of CDW. There are two exceptions. Knoeri et al. (2013) have included the dismantling process in the expanded system (Figure II. 26) and Napolano et al. (2016) have included the co-producing process that produced the waste in the expanded system Figure II. 27.

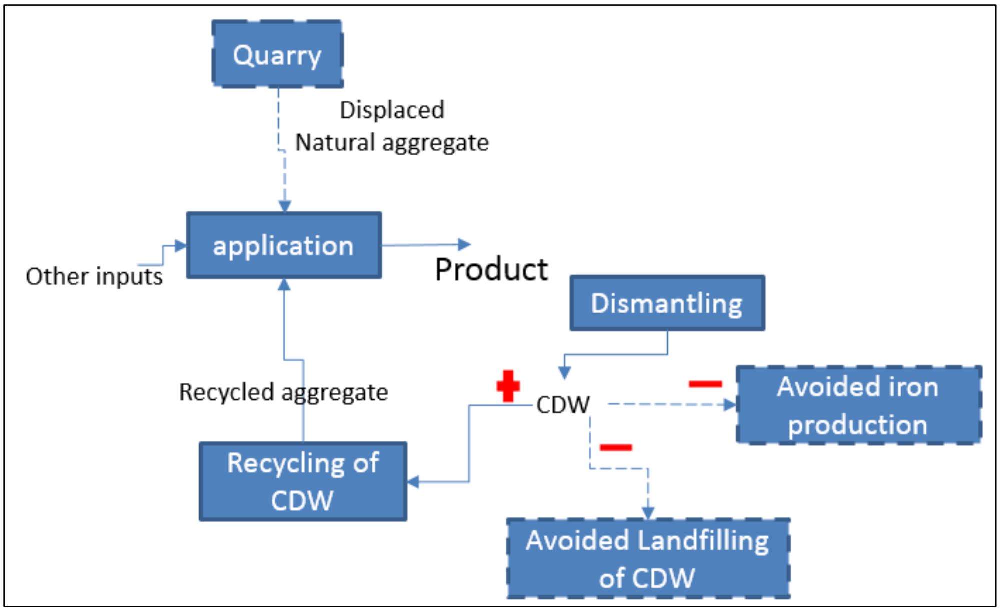


Figure II. 26 System boundary considered in (Knoeri et al., 2013) (displaced process or product has zero impact)

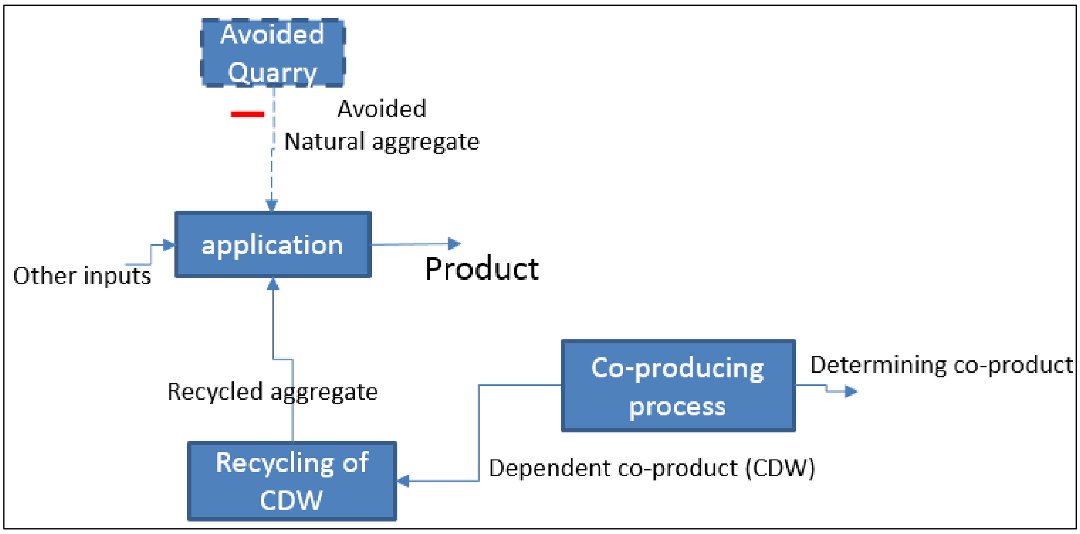


Figure II. 27 System boundary considered in (Napolano et al., 2016)

Table II. 5 summary of methods applied in different studies to model recycling of CDW in LCA and overcome the allocation problems of CDW recycling

		Scale of the study								Considering stocks in the analysis	Considering market mechanism in the analysis
		Product oriented				Territory					
		[a] High-grade application		[b] Low-grade application		High-grade application		Low-grade application			
		[c] Intermediate product	[d]Final product	Intermediate product	Final product	Intermediate product	Final product	Intermediate product	Final product		
Allocation of environmental burdens and benefits from recycling CDW to product system that uses recycled	**Method1:** system expansion + [e]benefits from avoided landfilling	(Knoeri et al., 2013)		(Knoeri et al., 2013)	(Rosado et al., 2017), (Hossain et al., 2016)					NO	NO
	Method2: system expansion + benefits from avoided virgin materials	(De Schepper et al., 2014), [f](Knoeri et al., 2013)		[f](Knoeri et al., 2013), (Napolano et al., 2016)					(Dahlbo et al., 2015),	NO	NO
	Method3: Cut-off	(Marinković et al., 2010), (Colangelo et al., 2018), (Serres et al., 2016), (Wijayasundara et al., 2017), (Braunschweig et al., 2011)			(Braunschweig et al., 2011)	(Yazdanbakhsh et al., 2017), (Fraj and Idir, 2017)				NO	[g] NO

[a] Using recycled aggregates as aggregates in structural concrete and cement.

[b] Using recycled aggregates as unbound aggregates in foundations, embankments and road sub-base and base, etc.

[c] Refers to the final product of a process, but it is used as an input in production process of some other products, e.g. concrete used in building construction is an intermediate product.

[d] Is the final product of a production process, but it is not used as an input in other processes, e.g. building, foundation etc.

[e] Benefits refer to subtracting the environmental impacts of the avoided process from the total environmental impacts.

[f] The authors considered the benefits from the avoided impacts related to the recovery of iron scrap from recycling reinforced concrete.

[g] (Wijayasundara et al., 2017) conducted a financial assessment on manufacturing recycled aggregate concrete in ready-mix plants to assess the economic benefits from recycling CDW.

The results of most studies in Table II. 5 using cut-off method showed that environmental benefits gained from replacement of natural aggregates with recycled aggregates in structural concrete were not significant (e.g. Fraj and Idir, 2017; Marinković et al., 2010; Wijayasundara et al., 2017; Yazdanbakhsh et al., 2017). It was mainly due to the similarities between recycling of concrete demolition waste into aggregates and processing natural aggregates in the quarries: crushing, sieving and transportation (DG ENV, 2011). Therefore, environmental impacts from producing recycled concrete aggregates were not significantly different from producing natural aggregates. According to these studies, the environmental benefits gained from recycling of concrete demolition waste into aggregates are not very considerable (Marinković et al., 2010), unless recycled aggregates are locally available (Fraj and Idir, 2017). In fact, If transportation distances decrease, fuel consumption and mainly greenhouse gas emissions may decrease (DG ENV, 2011). In this regard, Marinković et al. (2010) stated that, environmental performance of structural concrete made with recycled concrete aggregates significantly depends on transportation types and distances for aggregates (either natural or recycled). According to Marinković et al. (2010), geographical location would not affect data on cement, aggregate or concrete production considerably, but energy and transport data might be significantly different for each country. Therefore, it is necessary to take into account different circumstances which could affect the total environmental impacts.

A recent study by Yazdanbakhsh et al. (2017) showed that the environmental impacts of structural concrete with 40 MPa compressive strength made from recycled concrete aggregates were similar to those of concrete with the same compressive strength made from natural aggregates. It was mainly due to the reason that more cement was used in concrete made with recycled concrete aggregates, although transportation distance between recycled concrete aggregate source and concrete ready-mix plant was shorter. They concluded that the most influential factors on environmental impacts of concrete production were the amount of cement in concrete mix and aggregate transportation distances. Similarly, Woodward and Duffy (2011) stated that recycling demolished concrete into new concrete does not reduce the impacts significantly, especially greenhouse gas emissions. This is due to the reason that, emissions from concrete production mostly result from cement production (Woodward and Duffy, 2011). On the contrary, they mentioned that, recycling demolished concrete into road sub-base can have beneficial impacts, provided that a huge amounts of concrete waste is shifted from landfills (Woodward and Duffy, 2011). Study by Woodward and Duffy (2011) has not been shown in Table II. 5, since they did not mention clearly the case study and methods used.

In the study by Braunschweig et al. (2011), they compared environmental performance of two types of concrete, high strength concrete and low strength concrete, in terms of using natural aggregates and recycled concrete aggregates. Results showed that environmental impacts from producing high quality concrete by using either natural aggregates or recycled concrete aggregates were similar. But environmental benefits from using recycled concrete aggregates in low strength concrete compared to those from using natural aggregates in low strength concrete were superior. Moreover, Braunschweig et al. (2011) showed that the amount of cement used in concrete mix had a significant impact on the environmental impacts of concrete production.

On the contrary, studies accounting for the avoided burdens in their analysis (Methods 1 and 2) indicated that environmental benefits gained from using recycled aggregates in different applications were significant mainly due to the avoided burdens through recycling. For instance, Yazdanbakhsh et al. (2017) showed that, if the avoided CDW landfilling that was recycled into recycled concrete aggregates and used in concrete was accounted for, the environmental impacts of producing recycled aggregate concrete were much lower than those of natural aggregate concrete. Similarly, Knoeri et al. (2013) showed that, replacing natural aggregates with recycled aggregates led to 30% environmental improvements, mainly due to accounting for the avoided landfilling of CDW and virgin material production (steel reinforced recovered from demolished concrete).

Studies presented in Table II. 5 neither distinguished clearly between different qualities of natural aggregates nor mentioned clearly that recycled aggregates displace which type and category of natural aggregates. Except Yazdanbakhsh et al. (2017) that used some data from (Etxeberria et al., 2007a), where natural aggregates were classified based on fraction sizes and qualities. Similarly, Fraj and Idir (2017) used different fraction sizes for natural aggregates and recycled aggregates. Therefore, it could be assumed that they (Fraj and Idir, 2017; Yazdanbakhsh et al., 2017) distinguished different qualities and categories of natural aggregates. However, they provided no information about differences in production processes according to different qualities of natural aggregates. The studies in Table II. 5, which considered different applications for recycled aggregates (low- or high-grade applications), might indirectly mention different qualities of natural aggregates; nevertheless, they did not mention that quarry was a co-producing process with different processes for each quality of natural aggregates. Therefore, they considered the avoided burdens (negative impacts) or zero burden for the quarry process. But, if it is assumed that when recycled aggregate is used in low-grade applications, it replaces lower quality natural aggregates (dependent co-products of the quarry process, A1 and A2), the avoidance of natural aggregate production is arguable. This is due to the probable demand for the determining co-product of the quarry process in the market (that we defined as A3 in section 2.3.1.1). Accordingly, stock of the displaced natural aggregates in the low-grade applications needs to be included in the system boundary of the environmental analysis. In this regard, Knoeri et al. (2013) considered natural aggregate conservation just for the case that recycled aggregates displaced natural aggregates in high-grade applications. Therefore, it could be assumed that they (Knoeri et al., 2013) indirectly mentioned the co-producing quarry process.

As it is evident from Table II. 5, these studies did not also account for the market mechanisms to discover the potential shares of natural aggregates and recycled aggregates in the market as well as estimate transportation distances travelled between the consumers of aggregates and distributers (quarries and recycling facilities). There are some exceptions. Wijayasundara et al. (2017) conducted a financial assessment on manufacturing recycled aggregate concrete in ready-mix plants to assess the economic benefits from recycling CDW. Fraj and Idir (2017) and Yazdanbakhsh et al. (2017) considered different distributers and consumers of aggregates in New York City and Paris respectively, but the resulting transportation distances were not based on the market mechanisms, they were average values.

As can be seen from Table II. 5, some studies have not considered avoided landfilling as a benefit of using recycled aggregates. This is according to what has been proposed by EN 15804 (NF EN 15804, 2014). However, Yazdanbakhsh et al. (2017) mentioned that avoided landfilling could not be considered as a benefit of using recycled aggregates, if recycled aggregates were produced regardless of its applications. But, they mentioned that avoided landfilling could be considered as a benefit of using recycled aggregates, if recycled aggregates were produced to be used in high-grade applications such as structural concrete (Yazdanbakhsh et al., 2017).

Consequently, based on these studies, the environmental impacts or benefits of CDW recycling can vary for different conditions and applications of recycled aggregates. They highly depend on aggregate transportation distances, applications of recycled aggregates and quality of recycled aggregates as well as methods used to handle multi-functionality problems of recycling in LCA.

2.8 Material flow analysis (MFA)

2.8.1 Introduction to general principles of MFA and definitions

Material flow analysis (MFA) is a systemic method. The MFA system includes two subsystems, economic and environmental subsystems. In general, the system contains flows, stocks and processes. Flows represent materials transferring from one process to another, stocks refer to materials stored within the economic subsystem. Processes in the economic subsystem, where environmental impacts take place, usually transform materials. There are flows of materials from the economic to the environmental subsystem. In other words, emissions could be defined as a flow of substances from economic subsystem to the environmental subsystem. As a result, in order to control the emissions, some processes in the economic subsystem have to be changed (Elshkaki and van der Voet, 2004).

Materials in MFA can represent both goods and substances. A substance is defined as a single type of matter consisting of uniform units such as atoms (chemical element), e.g. carbon, or molecules (chemical compound), e.g. carbon dioxide. A good is an economic entity and comprises one or many substances. Goods have an economic value, either positive or negative. For instance, cars, fuel etc. have positive values, whereas wastes have negative values. Therefore, in some cases MFA is used interchangeably for both goods and substance flow analysis (SFA) (Brunner and Rechberger, 2004).

The basis of MFA is conservation of matter- in which the mass of inputs equals the mass of all outputs. To keep mass balance, it is required to consider net addition to the stocks. Through input and output balancing, waste flows and their source as well as the accumulation of material stocks need to be identified. Mass balance in the model can be indicated as follow:

$$extraction + imports = consumptions + export + accumulation + wastes \qquad II.\,5$$

2.8.2 Use of MFA

MFA is an analytical tool that helps specifying (un)sustainability indicators and contributes to defining public environmental policy (Barles, 2009) . It is also considered as a tool for Industrial Ecology to control the flow of substances and goods circulating into and out of the system (Elshkaki and van der Voet, 2004). Likewise, Brunner and Rechberger (2004) stated that, MFA could be used to assess and quantify material and energy flows through a system defined in a space and time as well as to quantify stocks of goods or substances.

Systems investigated by MFA can be a region (it has a geographical border), a municipal incinerator, a factory etc. MFA can be used to support decision making in resource management, waste management and environmental management (Brunner and Rechberger, 2004; Moriguchi and Hashimoto, 2016). Because, MFA connects the sources, the pathways, and the intermediate and final sinks of a material. Therefore, an MFA system may contain different reference flows. One of the main issues in MFA is to minimize material flows and subsequently minimize waste, while increasing the welfare of human beings (Brunner and Rechberger, 2004). In addition, an MFA can either analyze the past flows and stocks using historical data, which is called retrospective, or analyze the future flows and stocks using data extrapolation, which is called prospective or can be combination of both (Müller et al., 2014).

Different types of stocks are discussed in the next section.

2.8.3 Different types of stocks in MFA

According to Elshkaki and van der Voet, (2004), the accumulation of materials in one place for more than one year refers to stocks. According to (Brunner and Rechberger, 2004), stocks are defined as material reservoir within the analyzed system. Stocks can stay constant or increase, which is called accumulation, or decrease, which is called depletion. Nowadays, there are large numbers of stocks within a region (with a specific geographical border), mainly because material inputs are larger than material outputs. Some examples of material stocks are: stocks of materials from industry and agriculture, urban stocks etc.

There are different types of stocks:

- Stocks of materials that are produced but not used yet; they mostly refer to accumulation of dependent co-products produced from a co-producing process in the system. This is due to the reason that their demand is constrained, but their production depends on the demand for the determining co-product of the same process (Schrijvers, 2017).
- Stocks of discarded materials; they refer to stocks of materials (e.g. waste) for which there is no demand to be recycled or recovered. Therefore, they will be landfilled (Schneider et al., 2011).
- Stocks-in-use; they represents "monetary investments and determine the long-term dynamics of social metabolism." (Baynes and Müller, 2016). They are resources that are currently in use, such as building stocks-in-use.

2.8.4 Relationships between MFA and LCA

MFA is like an inventory for LCA (Woodward and Duffy, 2011). This is mainly true when LCA is applied to a system rather than to a single product (Brunner and Rechberger, 2004). Therefore, the impact assessment of the LCA can be applied to MFA results. According to Brunner and Rechberger (2004), MFA is the first step of any LCA studies. Woodward and Duffy (2011) mentioned that MFA is a method for environmental assessment and is a tool to identify environmental pressures from using the materials in an economy.

2.9 Basics of Territorial LCA

This section discusses shortly the introduction of territorial assessment in LCA and focuses just on the elements that are of use for this thesis.

Enlarging the scale of LCA from the environmental performance of products or services to more complex system such as a given geographical territory is known as territorial LCA (Nitschelm et al., 2016). Therefore, a territorial LCA is defined as assessment of the eco-efficiency of a territory (Nitschelm et al., 2016). It can be performed by assessing human activities that take place in the territory and related background processes.

There are different definitions for the territory. A territory according to Nitschelm et al. (2016) is: "a geographical contiguous area in which human activities occur that is managed by local stakeholders, whose representations (individual, ideological, and societal) of the territory influence their decisions." Therefore, a territory is a place which includes stakeholders with common questions, e.g. economic, environmental, social, and also is a place where decisions are made (Nitschelm et al., 2016). In territorial LCA, a territory is considered as a black box that interacts with other territories (other black boxes) through a variety of input-output data (Nitschelm et al., 2016).

The territorial LCA method includes 1) defining the functional unit, 2) selecting the boundaries of the territory, 3) collecting the regional data and 4) considering the local context when evaluating the impacts (Nitschelm et al., 2016). The territory's boundaries and functions depend on the goal of the LCA study, such as evaluating the current situation, comparing different scenarios or assessing a prospective situation. As a territory is a multifunctional system (Loiseau et al., 2014, 2013; Nitschelm et al., 2016), e.g. economic, environmental, societal land use functions (Massari et al., 2016), there is no main function assigned to the system understudy, there are multiple functions (Massari et al., 2016). In addition, the land use functions (e.g. services provided such as wealth generation, access to facilities, or hosting a population) are the outputs of a given land planning scenario implemented in a given territory (Massari et al., 2016). In defining the system boundary in territorial LCA, the responsibilities of the territory in terms of environmental impacts should be taken into account (Loiseau et al., 2014). They have suggested that the scope of the study to be from cradle to the territory gate, since it is difficult to identify the destination of the products produced in the territory but leave the territory. Therefore, it is required to consider upstream and downstream economic flows related to consumption activities as well as all upstream economic flows related to production activities located in the territory understudy (Massari et al., 2016). This is considered as the LCI phase in the territorial LCA method. Then the inventory of all production and consumption within the territory understudy will result into categories of indicators: environmental impacts and land use functions (Loiseau et al., 2014). Finally the eco-efficiency of the territory can be assessed in terms of these two outputs (Massari et al., 2016).

Results of assessment in territorial LCA will represent the activities that take place in the territory as well as determine the main environmental issues which occur within the territory (Massari et al., 2016).

2.10 How to model a territorial Cement Concrete Demolition Waste (CCDW) management?

The main objective of this PhD thesis is to assess the environmental performance of Cement Concrete Demolition Waste (CCDW) management in a given territory. This section aims at developing a conceptual model for the territorial environmental modeling of CCDW management.

According to the literature review carried out in this chapter, a classical LCA model is developed for our case, which is recycling of CCDW into the foundations as an alternative to A1 (basic quality natural aggregates produced in the quarry). In the successive steps, the evolution of this model is justified to obtain a new conceptual model.

2.10.1 Synthesis and outcomes from the literature review

Because of constant and rapid increase in Construction and Demolition Waste (CDW) generation and natural resource consumption, waste valorization has become an essential issue in the construction sector. As mentioned in section 2.2.2, Cement Concrete Demolition Waste (CCDW) represents a considerable part of the total CDW. CCDW is considered as inert wastes by European regulation and thus landfill should be avoided (European Commission, 2008).

The literature review indicates that, nowadays demolished concrete is mostly down cycled in granular or sub-base applications rather than as aggregates used for producing high quality structural concrete (Marinković et al., 2010). This is mainly due to the inferior properties of recycled concrete aggregates compared to natural aggregates, such as less density, higher porosity and higher water absorption, as mentioned in section 2.3.2.2. Various researchers stated that mortar and cement paste which remain attached to recycled concrete aggregates are the main reasons that recycled concrete aggregates are of lower quality compared to natural aggregates (e.g. Etxeberria et al., 2007b; Shayan and Xu, 2003). The crushing process would affect the amount of these materials (Marie and Quiasrawi, 2012). To remove these materials from recycled concrete aggregates, there are also several treatment technologies (Tam et al., 2007). However, the quality of the parent concrete from which recycled concrete aggregate is recovered would affect the quality of recycled concrete aggregates and subsequently the new concrete mix. This implies that recycling operations have limited control over material quality (Malešev et al., 2010). Therefore, recycled concrete aggregates are mostly used as unbound materials, trenches etc. As a result, in this PhD thesis Recycled Cement Concrete (RCC) recycled from CCDW is assumed to replace basic quality natural aggregates (A1) produced in the quarry with lower quality than tertiary category of natural aggregates (A3), which is co-produced with A1 and mainly adequate for structural concrete, see section 2.3.1.1 and 2.3.1.2.

In addition, our literature review shows that, there are still uncertainties about environmental benefits gained from recycling CDW (especially with inert waste materials) and using them as an appropriate alternative to natural resources.

- First, previous LCA studies did not model the quarry process as a multi-output process producing different qualities of natural aggregates from different treatment lines (as discussed in 2.3.1.1and 2.3.1.2).
- Second, although handling and managing CDW is usually affected by local conditions (see sections 2.4 and 2.7), very few LCA studies considered a territorial approach with local production processes. Most studies assumed average transportation distances that results were found to be sensitive to those distances.
- Finally, the LCA results highly depended on the methods chosen to deal with the multi-functionality problems of recycling (discussed in detail in sections 2.6 and 2.7). The main difference between these methods was the way the environmental burdens and benefits from recycling were assigned to the analyzed product system. Our debate is on LCA practitioners who focus on LCA of one of the functions of a product system, while the product system provides multiple functions. Therefore, they apply a method (e.g. partitioning or substitution) to isolate the functional unit from other functions of the product system. This in turn leads to cutting some physical relationships between different functions of the system. These methods depend on the choice of the functional unit for the system as well as the specification of the displaced and avoided processes (e.g. quarry and landfills). However, if the system expansion method (as a method to overcome multi-functionality problems) is performed by expanding the system understudy to include all the functions of the system, rather than being performed as the substitution method, the physical relationships between the functions will be kept. For instance, keeping the physical relationships between the quarry's co-products is a key element especially for the case recycled aggregates replace lower quality natural aggregates (e.g. A1) in the low-grade applications. This is due to the reason that, A1 production is not driven by the recycling process, rather it is driven by the production of the determining co-product of the quarry process. Therefore, it is required to consider the probable accumulation of A1 in the analysis. Probable environmental benefits of recycling can be accounted for , if there is an actual market for recycled materials, and these credits should be performed based on the real quality of the recycled material (van der Harst et al., 2016).

In LCA models, the potential environmental impacts of a product or a service through its life cycle are related to the elementary flows associated with producing a specific amount of a product that is going to be used and not be stored , e.g. due to an inevitable extra production (Elshkaki and van der Voet, 2004). In a case of a joint production (e.g. co-producing), a change in demand of the determining co-product of the process will change the supply of the dependent co-products of that process. If the demand for the dependent co-products is constrained, they will stay in the stocks. Changes in the demand for the dependent co-products will lead to changes in stockpile of these materials. Therefore, it is required to take market mechanisms into account to determine whether there is an accumulation of these materials in the system or there is a demand for these materials in the market. In fact, LCA does not consider stocks of materials, they are systematically neglected (Elshkaki and van der Voet, 2004; Johnson et al., 2013; Schneider et al., 2011). Therefore, material flow analysis (MFA) can be integrated with environmental and economic models to include stocks of the materials and better address the future developments by considering the mass balance in the system (Elshkaki and van der Voet, 2004). This PhD thesis deals with changes of two types of stocks: stocks of materials for which the demand is constrained and landfills (see section 2.8.3). As this PhD concerns a short-term period (e.g. 10 years), changes in stocks-in-use, such as urban stocks-in-use, are considered negligible (Stahel and Clift, 2016), their changes mainly depend on the population (Sandberg et al., 2016), which does not vary rapidly in a short-term period.

According to this synthesis, we aim at defining a system model that accounts for production processes, stocks and markets as well as keeping the relationships between the co-products of the quarry process. The next section presents in detail how the final proposed system has been created step by step, starting from a classical LCA model.

2.10.2 Evolution of a new conceptual model for the territorial CCDW management

Starting from a classical LCA for modeling CCDW recycling into RCC to be used in foundations, rule N°3 is applied (Weidema, 2001). This rule, which is mostly system expansion including avoided burdens, has been used by several authors to model recycling CDW in LCA (as shown in Figure II. 23). The product system under study should be expanded to include the significant affected processes due to the use of RCC in the foundations and to include an alternative production route that produces the same function as RCC, such as quarry process. Under condition rule N°3:

- A1 produced from the quarry process is the displaced product by RCC;
- the displaced A1 production process has zero impacts in the foundation production process, if A1 is totally replaced by RCC;
- environmental burdens of recycling of CCDW are ascribed to the foundation production process;
- environmental benefits from prevented CCDW landfilling due to CCDW recycling are assigned to the foundation production process, which implies subtracting the environmental burdens of landfilling CCDW from the total environmental burdens of the system.

The classical LCA model of CCDW recycling has been indicated in Figure II. 28.

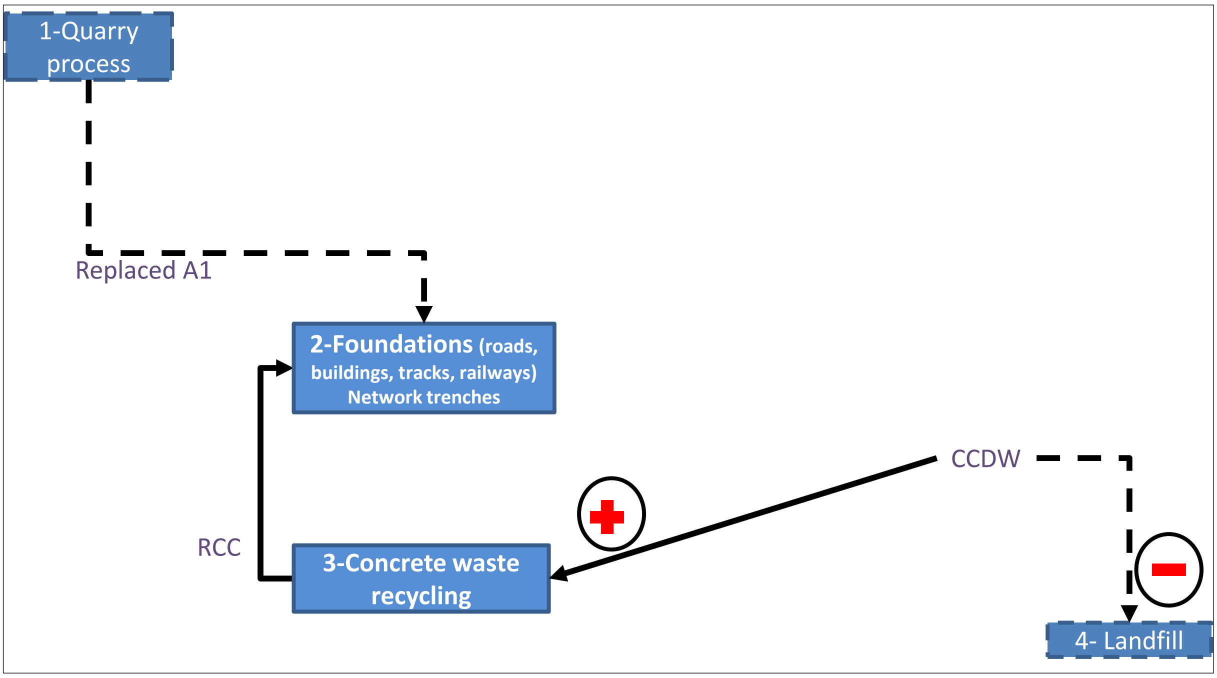


Figure II. 28 Conceptual model of CCDW recycling by using system expansion with the avoided burdens to model recycling in LCA

Legend

Process *Flow*

RCC: Recycled Cement Concrete *A1: primary category of natural aggregates*

CCDW: Cement Concrete Demolition Wastes

When the displaced process of an expanded system produces not only the displaced product, but also other co-products, a new multi-functionality problem may occur. In our case study, the displaced process in the expanded system depicted in Figure II. 28, is the quarry process. Quarry is a co-production process, which produces three categories of natural aggregates with different qualities and applications, including A1, A2 and A3 (see sections 2.3.1.1 and 2.3.1.2). This situation is represented in Figure II. 29.

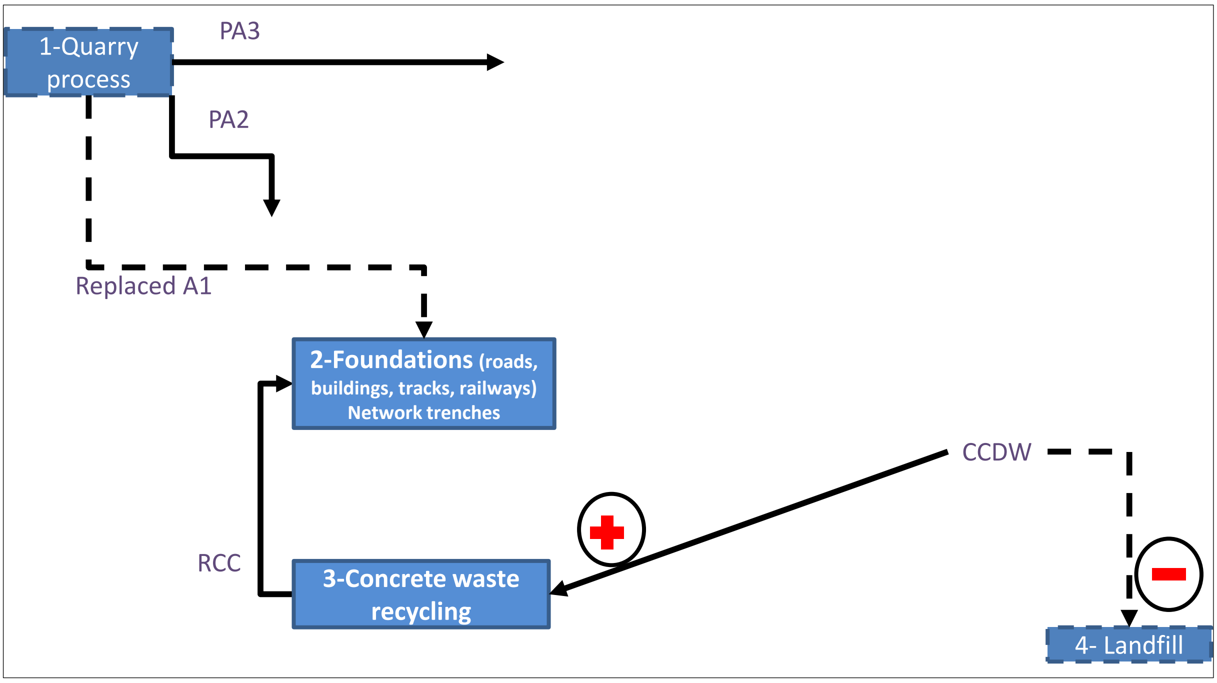


Figure II. 29 Conceptual model of CCDW recycling by using system expansion with the avoided burdens to model recycling in LCA. The system shows the co-producing quarry process.

Legend

Process	→ *Flow*
RCC: Recycled Cement Concrete	A1: primary *category of natural* aggregates
CCDW: Cement Concrete Demolition Wastes	A2: secondary category of natural aggregates
A3: tertiary category of natural aggregates	P_{A2}: produced A2
P_{A3}: produced A3	

Accordingly, the case study shows a complexity regarding not only modeling recycling in LCA but also multi-functionality problems in general for both recycling process and quarry process. How the environmental burdens associated with the quarry process should be attributed to different co-products of the quarry process shown in Figure II. 29?

One may use partitioning to separate the environmental burdens allocated to A1 production to avoid probable endless system expansion. However, this might:

- cut the physical relationship between A1 and other co-products (A2 and A3);
- affect the environmental assessment results, since they would be affected by the choice of methods by an LCA practitioner to overcome allocation problems or the intentions of an actor who is going to use the results;
- show the environmental consequences of using recycled materials from points of view of a recycled material user, not the territory.

It should be noted that, A1 is one of the co-products of the quarry process, whose production is driven by the demand for high quality natural aggregates (A3), rather than the recycling process. A3 is the determining co-product of the quarry process, as it provides the highest revenue to the process. This means that an increase in the demand for A3 will cause an increase in the production of A1, despite the replacement of A1 by RCC.

Accordingly, to avoid these issues and give a better insight of the territory from an environmental point of view, the conceptual model in Figure II. 29 should be expanded to include the demands for A3 in the related markets. There should be a stock of produced A3 in the quarry based on the total demands for A3. The output of this stock determines the total demand for A3 in different markets: bituminous concrete and cement concrete markets. Consequently, we need to consider in our model that production of the quarry process is driven by the demand for A3. These changes are indicated in Figure II. 30.

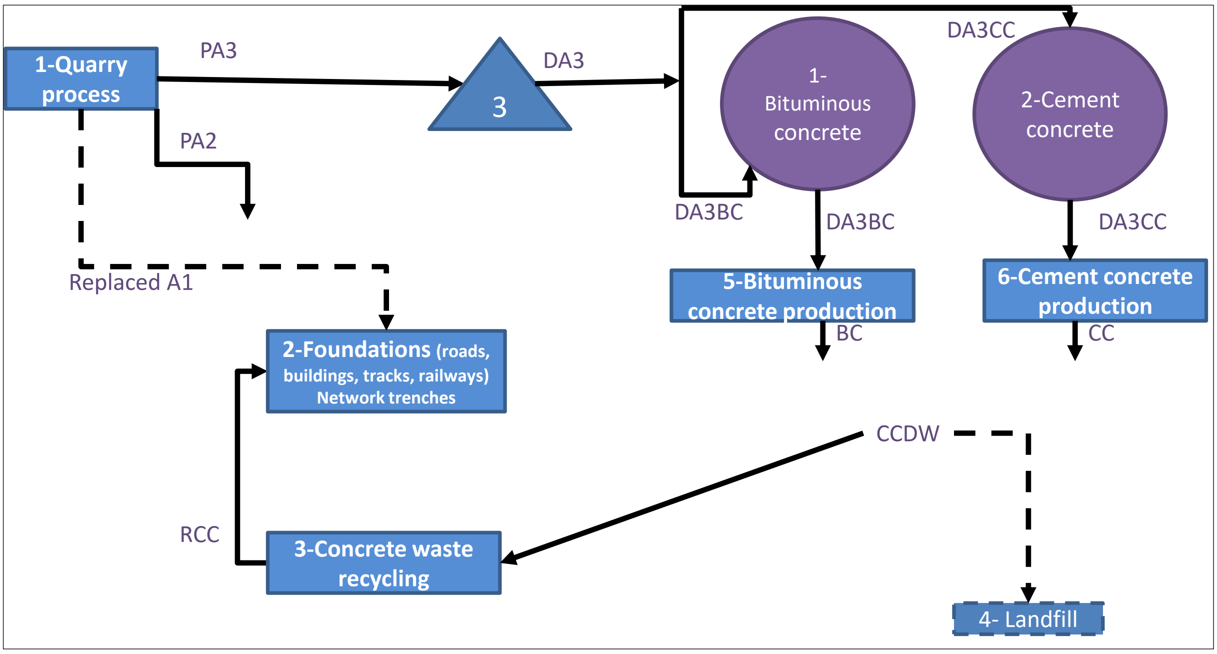


Figure II. 30 conceptual model of the expanded CCDW recycling to include demands for the determining co-products of the quarry process (A3) in the related markets

Legend

Process

Stock

Flow

Market

RCC: Recycled Cement Concrete

A1: primary category of natural aggregates

CCDW: Cement Concrete Demolition Wastes

A2: secondary category of natural aggregates

A3: tertiary category of natural aggregates

P_{A2}: produced A2

P_{A3}: produced tertiary category of natural aggregates in the quarry

Stock 3: stockpile of produced A3 in the quarry

D_{A3}: demand for tertiary category of natural aggregates

D_{A3BC}: demand for A3 in bituminous concrete market

D_{A3CC}: demand for A3 in cement concrete market

Market 2: market for cement concrete

Market 1: market for bituminous concrete

CC: cement concrete

BC: bitumenous concrete

As already mentioned, the demand for A3 causes the production of the dependent co-products (A1 and A2) in the quarry, which in turn may lead to accumulation of these materials inside the quarry. This is due to the fact that, A1 and A2 are demand constrained. As a result, stocks of these materials should be considered in the conceptual model to represent the actual situation. They are presented in Figure II. 31.

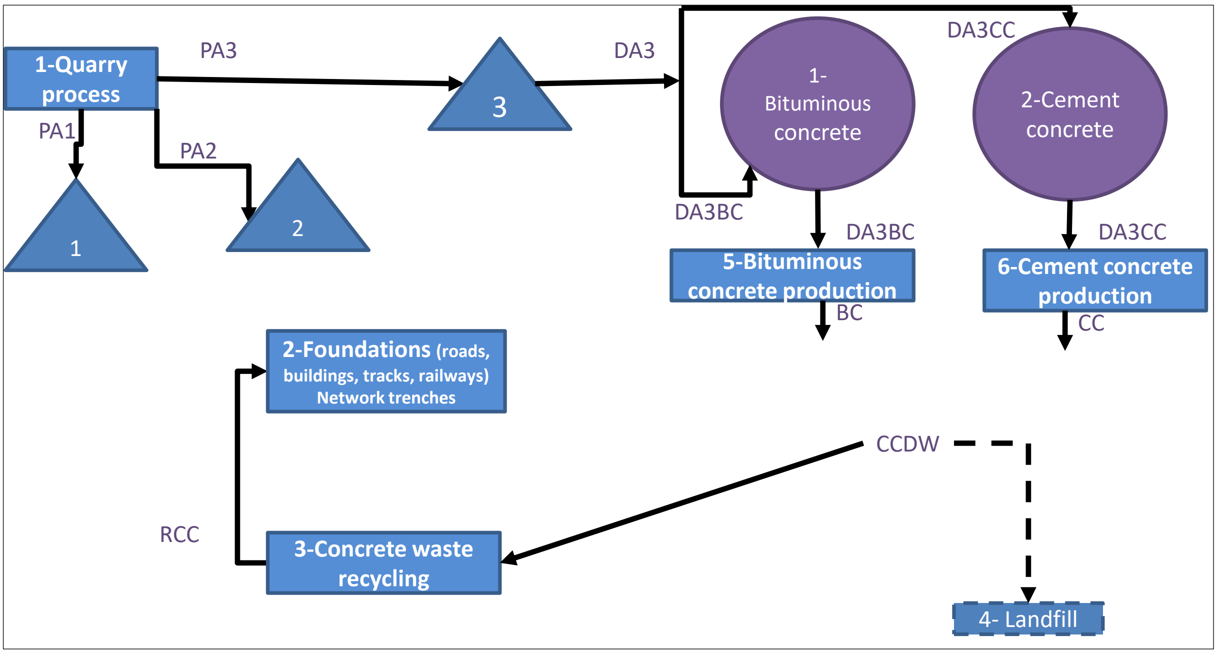


Figure II. 31 Conceptual model of the expanded CCDW recycling to include stocks of dependent co-products of the quarry process (A1 and A2)

Legend

Process

Stock

Flow

Market

RCC: Recycled Cement Concrete

A1: primary category of natural aggregates

CCDW: Cement Concrete Demolition Wastes

A2: secondary category of natural aggregates

A3: tertiary category of natural aggregates

P_{A2}: produced A2

P_{A3}: produced tertiary category of natural aggregates in the quarry

Stock 3: stockpile of produced A3 in the quarry

D_{A3}: demand for tertiary category of natural aggregates

D_{A3BC}: demand for A3 in bituminous concrete market

D_{A3CC}: demand for A3 in cement concrete market

Market 2: market for cement concrete

Market 1: market for bituminous concrete

CC: cement concrete

BC: bitumenous concrete

P_{A1}: produced A1

Stock 1: stockpile of produced A1

Stock 2: stockpile of produced A2

Changes in the stocks of A1 and A2 depend on both changes in the demands for A3 and the demands for A1 and A2. The demands for A1 and A2 depend on the demands of the related markets, which determine the output flows from these stocks. It is assumed that the main demand for A2 is in the road base market. Accordingly, this market should be added to the conceptual model. As already mentioned, the quality of A1 and RCC is mainly adequate for being used in the foundations of different constructions as basic quality aggregates (Section 2.3.1.2; Behera et al. 2014; Marinković et al. 2010). Therefore, market for the basic quality aggregates should be added to the conceptual model. The demand of the basic quality aggregate market will reveal the total demand for A1 as well as the total amount of CCDW that is required to be recycled. Related markets for A1 and RCC as well as A2 are shown in Figure II. 32.

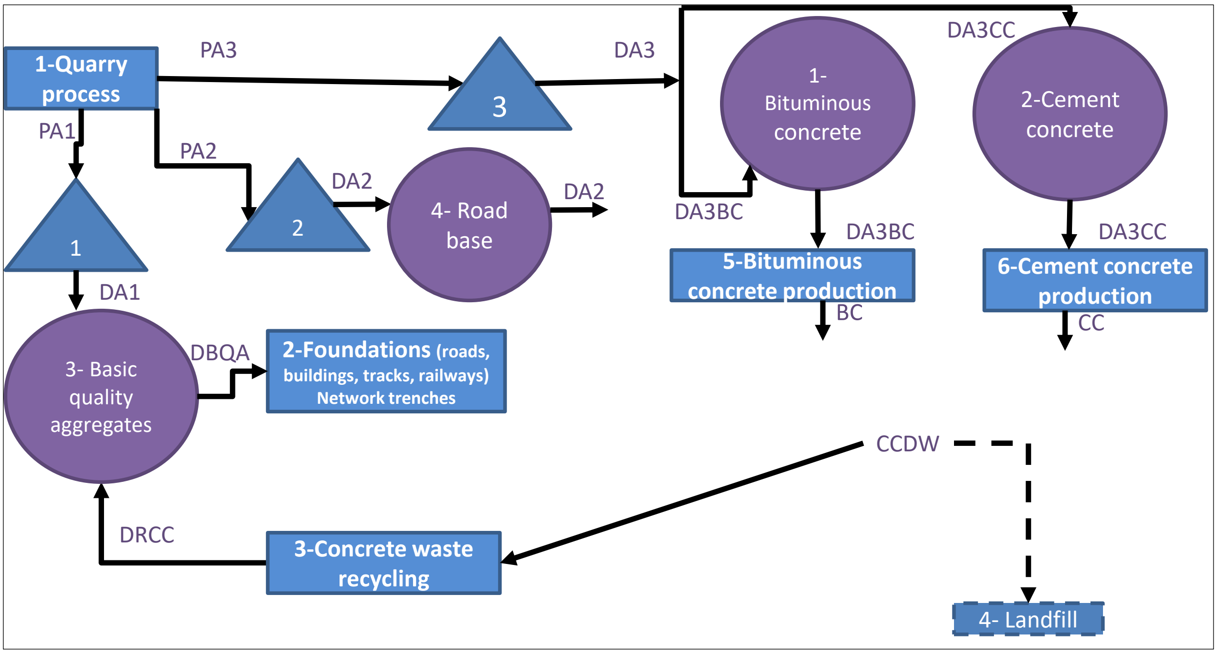


Figure II. 32 Conceptual model of the expanded CCDW recycling to include markets for A1 (and RCC) and A2.

Legend

Process

Stock

Flow

Market

RCC: Recycled Cement Concrete

A1: primary category of natural aggregates

CCDW: Cement Concrete Demolition Wastes

A2: secondary category of natural aggregates

A3: tertiary category of natural aggregates

P_{A2}: produced A2

P_{A3}: produced tertiary category of natural aggregates in the quarry

Stock 3: stockpile of produced A3 in the quarry

D_{A3}: demand for tertiary category of natural aggregates

D_{A3BC}: demand for A3 in bituminous concrete market

D_{A3CC}: demand for A3 in cement concrete market

Market 2: market for cement concrete

Market 1: market for bituminous concrete

CC: cement concrete

BC: bitumenous concrete

P_{A1}: produced A1

Stock 1: stockpile of produced A1

Stock 2: stockpile of produced A2

D_{A1}: demand for A1 in basic quality aggregate market

D_{A2}: demand for A2 in road base market

Market 3: market for basic quality aggregates

Market 4: market for road base

D_{RCC}: demand for RCC

D_{BQA}: demand for basic quality aggregates

As the basic quality aggregate market (Market 3 in Figure II. 32) has two suppliers, A1 and RCC, there should be a competition between these two resources. Mechanisms in Market 3 would determine the results of the competition. Mechanisms imply the conditions that affect the demands for A1 and RCC in the market. Therefore, it is required to identify the parameters that affect the demands.

In general the recycling operation should overcome the risks for quality, feedstock availability and the price (Dahlbo et al., 2015; Wilburn and Goonan, 1998). As mentioned earlier, RCC is a suitable alternative to A1, therefore they have similar qualities. Feedstock availability in the recycling facilities is affected by the choice of waste suppliers. This in turn is affected by nearby competitors and landfills, transportation distances, tipping fees for recycling facilities and disposals. Recycling fees should be low enough to attract waste suppliers and high enough to be able to cover the recycling process costs (Wilburn and Goonan, 1998). According to personal communication with some recycling facilities (presented in Appendix A), we do not believe they produce RCC and wait for it to be sold. They stock CCDW to produce RCC when they have demand. In the case of a huge demand for RCC, some CCDW can be diverted from the landfill. Therefore, it is assumed that recycling facilities do not need to overcome the challenge of having an access to a flow of waste when they need it.

Therefore, the main challenge for the recycling facilities is assumed to be the price of the product they produce. It should be high enough to cover their expenses and low enough to be sold in the market. The price is usually affected by the local price of natural aggregates and the presence of quarries in the vicinity of the recycled facilities (Wilburn and Goonan, 1998). This is mainly due to the reason that there is usually a much greater amount of natural aggregates available compared to recycled aggregates.

Accordingly, it is expected that there is a competition between A1 and RCC in the market based on their prices, that the results of this competition will reveal the total demands for A1 and RCC and subsequently shares of A1 and RCC in the market. It should be noted that, the total price that a buyer pays in the market includes also transportation prices. Therefore, distances between buyers and sellers can play an important role in the choices of buyers in the market. Development of the market mechanism model for Market 3 and estimation of the total prices of the resources and transportation distances between the buyers and sellers in Market 3 will be discussed in detail in the next chapter. However, there is a cultural barrier towards promoting CDW recycling (as discussed in section 2.5) that shows clients' mistrust of recycled aggregates' quality. Therefore, this parameter will be tested too to determine whether it affects the market share or not.

The supply of CCDW is determined by the total building demolition activities taking place in a given territory in a given year. However, it is not needed to include the demolition process in the expanded system in Figure II. 32, since demolition activities take place regardless of the demand for RCC. But CCDW landfilling should be added to the expanded system in Figure II. 32, as the amount of CCDW landfilled is assumed to vary according to the changes in the amount of CCDW recycled. If the amount of CCDW recycled is lower than the total CCDW generated in the given territory, the rest of CCDW is assumed to be disposed in the landfills. As a result, Figure II. 33 shows the final conceptual model for CCDW management at a territorial level.

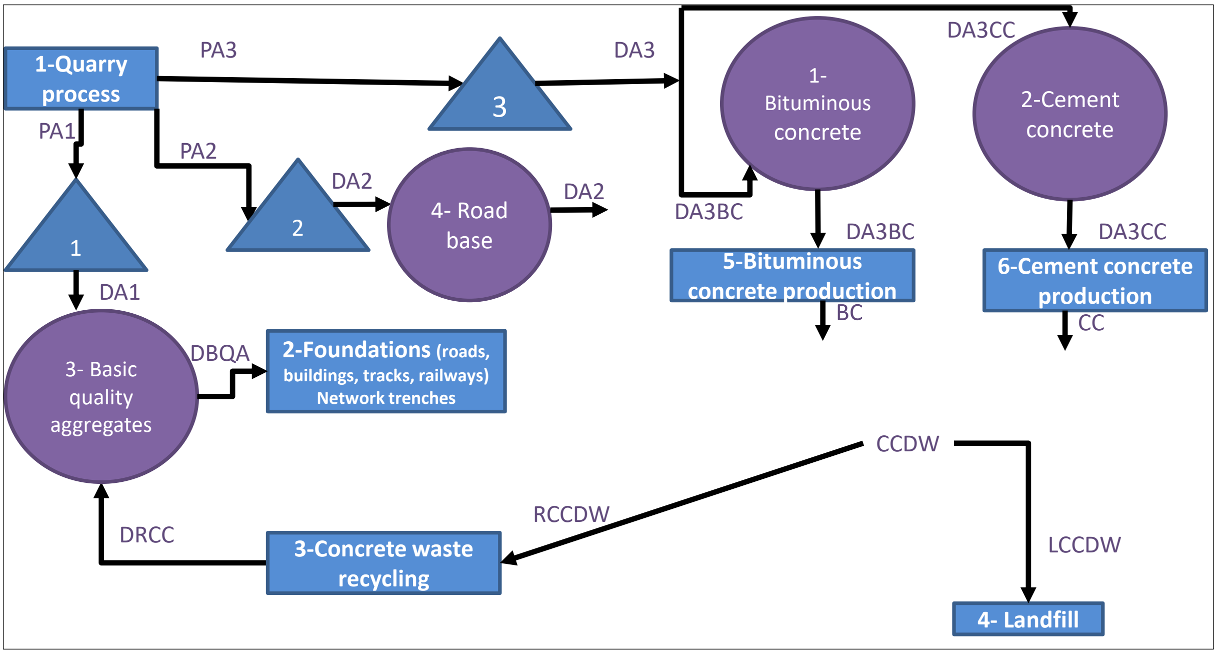


Figure II. 33 Final conceptual model of the territorial environmental assessment of CCDW management including processes involved and affected by the waste management in a given territory.

Legend

Process | *Flow*

Stock | Market

RCC: Recycled Cement Concrete | A1: primary category of natural aggregates

CCDW: Cement Concrete Demolition Wastes | A2: secondary category of natural aggregates

A3: tertiary category of natural aggregates | P_{A2}: produced A2

P_{A3}: produced tertiary category of natural aggregates in the quarry | Stock 3: stockpile of produced A3 in the quarry

D_{A3}: demand for tertiary category of natural aggregates | D_{A3BC}: demand for A3 in bituminous concrete market

D_{A3CC}: demand for A3 in cement concrete market | Market 2: market for cement concrete

Market 1: market for bituminous concrete | CC: cement concrete

BC: bitumenous concrete | P_{A1}: produced A1

Stock 1: stockpile of produced A1 | Stock 2: stockpile of produced A2

D_{A1}: demand for A1 in basic quality aggregate market | D_{A2}: demand for A2 in road base market

Market 3: market for basic quality aggregates | Market 4: market for road base

D_{RCC}: demand for RCC | D_{BQA}: demand for basic quality aggregates

RCCDW: *fraction (R) of CCDW sent to the recycling facilities* | LCCDW: *fraction (L) of CCDW sent to the inert landfill*

The foundation, bituminous concrete and cement concrete processes (process 2, 5 and 6 respectively) are excluded from the scope of the study. Market 4 is also excluded from the scope of the analysis, but its demand is considered in the analysis. As a result, Figure II. 34

shows the system boundary considered for evaluating the environmental performance of CCDW management in the given territory.

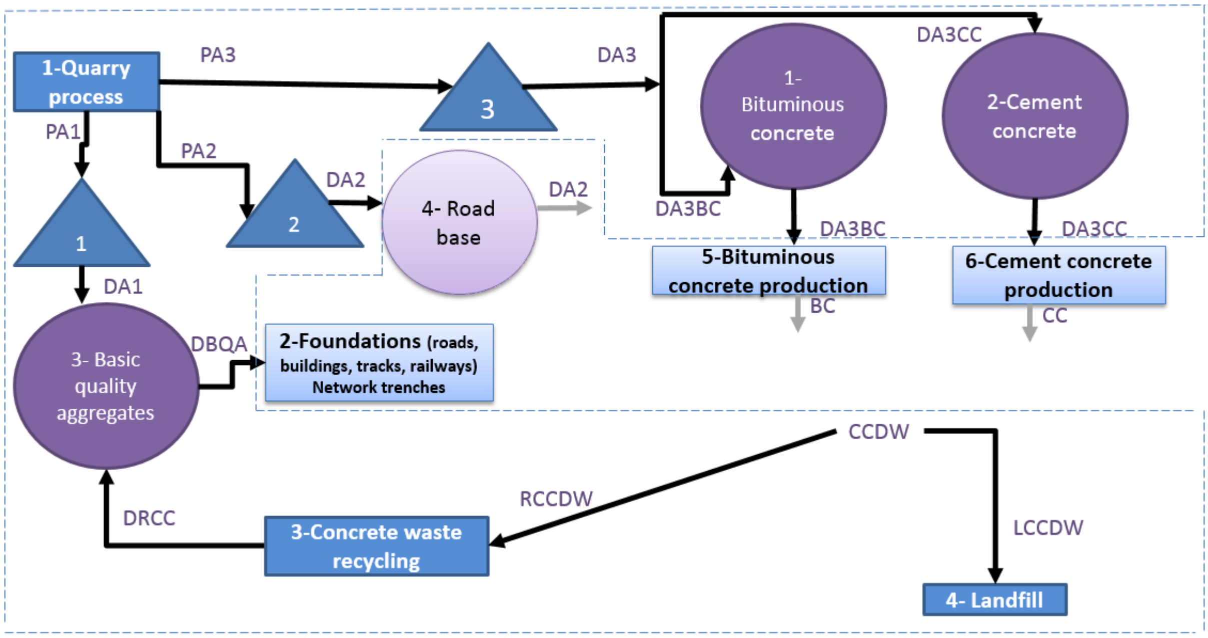


Figure II. 34 Final conceptual model of the territorial environmental modeling of CCDW management with the defined system boundary and elements included in the scope of the study. (Dashed lines show the system boundary).

Legend

Process	Flow
Stock	Market
RCC: Recycled Cement Concrete	A1: primary category of natural aggregates
CCDW: Cement Concrete Demolition Wastes	A2: secondary category of natural aggregates
A3: tertiary category of natural aggregates	P_{A2}: produced A2
P_{A3}: produced tertiary category of natural aggregates in the quarry	Stock 3: stockpile of produced A3 in the quarry
D_{A3}: demand for tertiary category of natural aggregates	D_{A3BC}: demand for A3 in bituminous concrete market
D_{A3CC}: demand for A3 in cement concrete market	Market 2: market for cement concrete
Market 1: market for bituminous concrete	CC: cement concrete
BC: bitumenous concrete	P_{A1}: produced A1
Stock 1: stockpile of produced A1	Stock 2: stockpile of produced A2
D_{A1}: demand for A1 in basic quality aggregate market	D_{A2}: demand for A2 in road base market
Market 3: market for basic quality aggregates	Market 4: market for road base
D_{RCC}: demand for RCC	D_{BQA}: demand for basic quality aggregates
RCCDW: *fraction (R) of CCDW sent to the recycling facilities*	LCCDW: *fraction (L) of CCDW sent to the landfill*

2.11 **Summary and research questions**

To sum up, the scope of the study has been expanded to include different processes involved in the territory to avoid multi-functionality problems and give a better insight of the territory in terms of environmental performance (Figure II. 34). The core of the territorial environmental model of CCDW management is the demand for A3, the determining co-product of the quarry process, which drives the total production of the quarry process and causes accumulation of A1 and A2 in the stocks. The model contains the upstream and downstream flows related to consumption and production activities taking place in the territory to better represent the environmental performance of waste management in the territory. Therefore, the territorial model includes multiple functions (or translated into different reference flows). This territorial environmental modeling approach is close to the definition of the territorial LCA, since:

- It is a multifunctional system including different reference flows such as natural aggregates, RCC and CCDW;
- The territory's responsibility for environmental impacts due to its consumption and production activities associated with CCDW management is taken into account in the boundary selection;
- The scope of the study is at regional level;
- In the studied system, processes linked to the production and consumption activities associated with CCDW management in the territory are included in the inventory.

However, the modeling approach in this thesis cannot be named as territorial LCA, since:

- This subject is very comprehensive and its different aspects have not been studied in this thesis;
- Land use function is not considered in this thesis;
- The inventory of the study is used to assess the environmental performance of CCDW management in the territory in terms of different environmental impact categories. Therefore, there is just on vector as an output (unlike the territorial method);
- A territorial LCA studies the interaction of the territory understudy with other territories, but this is not the case in this thesis.

To sum up, LCA is used as the main methodology to calculate the potential environmental impacts of CCDW management in a given territory. MFA is also applied to provide an understanding of material uses and accumulations as well as CCDW management at a territorial level. MFA enables us to analyze and quantify the input and output material flows as well as their accumulations in a given territory based on mass conservation law. Therefore, an LCA model will be combined with MFA and market mechanism model (related to Market 3) to evaluate the environmental performance of CCDW management in the given territory.

As a result, it is required to develop methodologies to be solved in the next chapters:

- developing the model based on the system presented in Figure II. 34;
- developing a local market mechanism model for Market 3 and investigating whether it reflects the current shares of A1 and RCC in the market;

- collecting local data related to the given territory and creating a database according to the requirements of our conceptual model;
- using the model to evaluate the environmental performance of CCDW management for current situation in the territory;
- using the model as a basis to evaluate the environmental performance of CCDW management for prospective and defined scenarios.

The territorial environmental model of CCDW management can be applied to any territory by using local data. The territory understudy in this PhD thesis is *Loire-Atlantique*, one of the departments of *Pays de la Loire* region on the west coast of France.

CHAPTER III Methodology: integrating LCA with MFA and Market Mechanism

3.1 Introduction

In the previous chapter we developed a conceptual model for a territorial environmental assessment of Cement Concrete Demolition Waste (CCDW) management (Figure II. 34). This chapter will present how different elements included in Figure II. 34 are modeled and how they are interacting one another.

Moreover, in this chapter, a combination of different methodologies is proposed to evaluate the environmental performance of CCDW management in a given territory: material flow analysis (MFA) to investigate consumptions and productions of materials as well as stocks of materials, Life Cycle Assessment (LCA) to estimate the potential environmental impacts of the system understudy, and a market mechanism model including different parameters to discover the flow of CCDW through the waste management system and the output flow from the demand constrained stock, Stock of A1, in the given territory.

3.2 Material Flow Analysis (MFA)

Material flow analysis (MFA) is applied to determine the input and output material flows related to CCDW management in a given territory. This will be discussed in detail in sections 3.2.1 - 3.2.8 for the conceptual model presented in Figure II. 34.

3.2.1 Production proportion of products in the quarry

As mentioned in section 2.3.1.1 and 2.3.1.2, a quarry is a co-producing process that produces A1 (primary category of natural aggregates), A2 (secondary category of natural aggregates) and A3 (tertiary category of natural aggregates) with fixed relative output volumes. A3 is the determining co-product of the quarry process, because it provides the largest revenue for the process. The proportions of A1, A2 and A3 productions are shown by α, $\boldsymbol{\beta}$ and Υ respectively in Figure III. 1. Production proportions of the products in the quarry depend on different parameters, including geological issues, nature and quality of the rocks. Based on these parameters, the production proportions of the products would be different in each quarry. In section 4.2.1.2 we will discuss how they are estimated for the territory understudy in this PhD thesis.

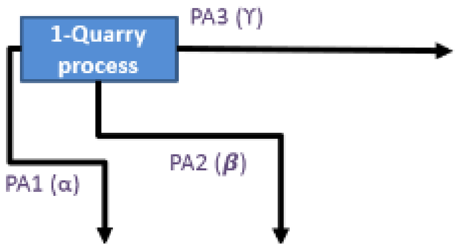


Figure III. 1 Quarry process in the conceptual model of territorial environmental modeling of CCDW management (Figure II. 34) in the given territory.

3.2.2 Stock of A3 (tertiary category of natural aggregates) in the quarry

The accumulation of A3 in Stock 3 (see Figure II. 34) in year Y_n could be estimated from differences between the input and output flows of the stock (Stock 3 is shown in Figure III. 2).

$$Stock\ 3(Y_n) = P_{A3}(Y_n) - D_{A3}(Y_n) \quad \text{III. 1}$$

Where Stock 3 is accumulation of A3 (ton) in the quarry in year Y_n, P_{A3} is the total production of A3 (ton) in process 1 (see Figure II. 34) in the given territory in year Y_n and D_{A3} is the total demand of the given territory for A3 (ton) in year Y_n.

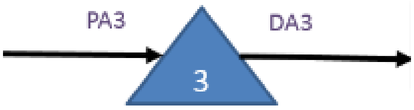


Figure III. 2 Stock of A3 (Stock 3) in the conceptual model of the territorial environmental modeling of CCDW management (Figure II. 34) in the given territory.

As A3 is the determining co-product of the quarry process, we assume that it is produced as much as it is demanded. Therefore, there is no accumulation of A3 in the quarry. As a result:

$$P_{A3}(Y_n) = D_{A3}(Y_n) \quad \text{III. 2}$$

3.2.3 Total demand for A3 in the territory in year Y_n (D_{A3} in Figure II. 34)

The total demand for A3 needs to be identified (D_{A3}). The bituminous concrete market and cement concrete market (Market 1 and Market 2 in Figure II. 34 respectively) require A3 to be used in bituminous concrete and cement concrete productions respectively. These markets and the input and output flows are shown in Figure III. 3.

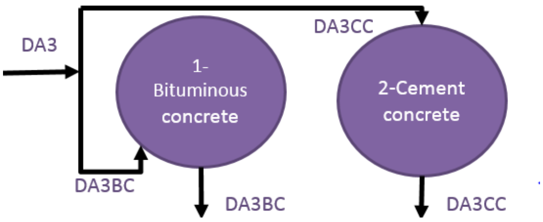


Figure III. 3 Market 1 and Market 2 in the conceptual model of the territorial environmental modelling of CCDW management (Figure II. 34) in the given territory.

As a result, D_{A3} in year Y_n can be estimated as follows:

$$D_{A3}(Y_n) = D_{A3CC}(Y_n) + D_{A3BC}(Y_n) \quad \text{III. 3}$$

Where D_{A3} is the total demand of the given territory for A3 (ton) in year Y_n, D_{A3CC} and D_{A3BC} are the total demands for A3 (ton) in the markets of cement concrete and bituminous concrete respectively in the same year. D_{A3CC} and D_{A3BC} can be respectively estimated from the total consumed cement concrete and bituminous concrete in the territory in year Y_n.

D_{A3CC} in year Y_n can be estimated from equation (III. 4).

$$D_{A3CC}(Y_n) = M_{A3CC} * vol.CC(Y_n) \quad \text{III. 4}$$

Where M_{A3CC} is the mass of A3CC (ton) used to produce 1 m^3 of cement concrete and vol.CC is the total volume of cement concrete (m^3) consumed in the territory in year Y_n.

According to the literature, cement concrete with 40 MPa compressive strength has been assumed for the structural purposes (Etxeberria et al., 2007a). To produce the mentioned strength, M_{A3CC} must be 1.207 (ton/m^3 of cement concrete) (Etxeberria et al., 2007a). This is consistent with the average cement concrete mix in France.

D_{A3BC} in year Y_n can be estimated from equation in (III. 5).

$$D_{A3BC}(Y_n) = MI_{A3BC} * vol.BC \qquad \text{III. 5}$$

Where MI_{A3BC} is the mass intensity of A3BC (ton) in 1 ton of bituminous concrete and vol.BC is the total volume of bituminous concrete (ton) consumed in the territory in year Y_n. MI_{A3BC} is about 95% (Ventura et al., 2008).

3.2.4 **Production of A1 and A2 in the quarry (P_{A1} and P_{A2} in Figure II. 34)**

Now that we have discovered the key element of the model, which is the yearly demand for A3 and the ensuing production of A3, we will investigate the productions of A1 and A2 (P_{A1} and P_{A2}, see Figure II. 34), as they are driven by the demand for A3. See equations (III. 6) and (III. 7).

$$P_{A1}(Y_n) = \frac{\alpha}{\Upsilon} * D_{A3}(Y_n) \qquad \text{III. 6}$$

Where $P_{A1}(Y_n)$ is the total production of A1 (ton) in the quarry in the given territory in year Y_n, $D_{A3}(Y_n)$ is the total demand for A3 (ton) in year Y_n, which is estimated by equation (III. 3) and α and Υ are mass ratios of A1 and A3 respectively (see section 3.2.1).

$$P_{A2} = \frac{\beta}{\Upsilon} * D_{A3}(Y_n) \qquad \text{III. 7}$$

Where $P_{A2}(Y_n)$ is the total production of A2 (ton) in the quarry in the given territory in year Y_n, $D_{A3}(Y_n)$ is the total demand for A3 (ton) in year Y_n, which is estimated by equation (III. 3) and β and Υ are mass ratios of A2 and A3 respectively (see section 3.2.1).

3.2.5 **Total demand for A2 (D_{A2})**

The main demand for A2 is in the road base market. Its value depends on the local market.

3.2.6 **Basic quality aggregate market (Market 3 in Figure II. 34)**

The basic quality aggregate market (Market 3 in Figure II. 34) has two suppliers: recycling facilities, which provide Recycled Cement Concrete (RCC) and quarries, which provide A1. Both A1 and RCC are used as the supply of basic quality aggregates in Market 3. The market share from A1 and RCC can be calculated with the following equations.

$$f1 = \frac{D_{A1}}{D_{BQA}}(Y_n) \qquad \text{III. 8}$$

D_{A1} is the total demand for A1 (ton) in Market 3 in year Y_n, D_{BQA} is the total demands for basic quality aggregates (ton) or output from Market 3 in year Y_n and f1 is the fraction of D_{BQA} that is from A1 or share of Market 3 from A1.

$$f2 = \frac{D_{RCC}}{D_{BQA}}(Y_n) \qquad \text{III. 9}$$

D_{RCC} is the total demand for RCC (ton) in Market 3, D_{BQA} is the total demand for basic quality aggregates (ton) or output from Market 3 in year Y_n and f2 is the fraction of D_{BQA} that is from RCC or the share of Market 3 from RCC.

3.2.7 **Stocks of A1 and A2 in the quarry (Stock 1 and Stock 2)**

Accumulations of A1 and A2 (Stock 1 and Stock 2 in Figure II. 34) can be estimated from equations (III. 10) and (III. 11) respectively. Stock 1 and Stock 2 and their inputs and outputs are shown in Figure III. 4 as well.

$$Stock1(Y_n) = P_{A1}(Y_n) - D_{A1}(Y_n) \qquad \text{III. 10}$$

Where Stock 1 is the accumulation of A1 (ton) in the quarry in year Y_n, P_{A1} is the total production of A1 (ton) obtained from equation (III. 6) in the same year and D_{A1} is the total demand for A1 (ton) in Market 3 in Figure II. 34 in the same year.

$$Stock2\ (Y_n) = P_{A2}(Y_n) - D_{A2}(Y_n) \qquad \text{III. 11}$$

Where Stock 2 is the accumulation of A2 (ton) in the quarry in year Y_n, P_{A2} is the total production of A2 (ton) obtained from equation (III. 7) in the same year and D_{A2} is the total demand for A2 in Market 4 in Figure II. 34 in the same year.

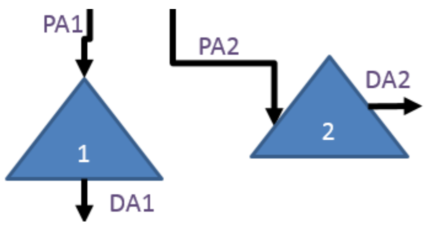


Figure III. 4 Stock 1 and Stock 2 in the conceptual model of the territorial environmental modeling of CCDW management (Figure II. 34) in the given territory.

3.2.8 **Cement Concrete Demolition Waste (CCDW) management system**

Conditions in Market 3 in Figure II. 34 will determine the amount of waste that is recycled or landfilled. CCDW management system in Figure II. 34 is shown in Figure III. 5 as well.

It is expected that changes in the flow of CCDW sent to the recycling facilities (RCCDW) affect the flow of CCDW disposed in the landfills (LCCDW). As a result, LCCDW can be expressed by equation (III. 12).

$$M_{LCCDW} = M_{CCDW}(Y_n) - M_{RCCDW}Y_n) \qquad \text{III. 12}$$

Where M_{LCCDW} is the total mass of CCDW (ton) that is disposed into the landfill in year Y_n, M_{CCDW} is the total mass of CCDW (ton) generated in the same year and M_{RCCDW} is the total mass of CCDW (ton) which is sent to the recycling process in the same year.

Conditions in Market 3 would determine M_{RCCDW}. M_{RCCDW} can be estimated as follow:

$$M_{RCCDW}(Y_n) = D_{RCC}(Y_n)/TRE \qquad \text{III. 13}$$

Where M_{RCCDW} is the total amount of CCDW (ton) that is sent to recycling facilities in year Y_n to produce required RCC in the basic quality aggregate market, D_{RCC} is the total demand for RCC in the given territory in year Y_n, and TRE is the technical efficiency of the recycling facility.

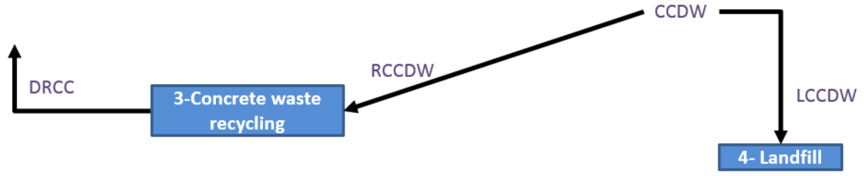


Figure III. 5 CCDW management system in the territorial environmental modeling of CCDW management (Figure II. 34) in the given territory

3.3 Life Cycle Assessment (LCA)

In the following sections (3.3.1-3.3.5), physical processes and elements included in Figure II. 34, in which environmental impacts take place, are discussed in detail. They are included in the ecoinvent cut-off version 3.01 database with some adaptions to France and developed in UMBERTO software. The LCA model is developed in UMBERTO software is used to model these processes and elements. In section 3.3.6 LCIA methods used in this PhD are presented.

3.3.1 Quarry process (process 1 in Figure II. 34)

Process "gravel production, crushed [CH]" has been chosen from ecoinvent cut-off version 3.01 in order to be adapted to the quarry process with three different treatment lines (as discussed in section 2.3.1.1).The quarry process (process 1 in Figure II. 34) has been shown in detail in Figure III. 6. As can be seen from Figure III. 6, each treatment line is a multi-output process, which produces two outputs with different mass ratios, while the quarry process in the ecoinvent database has one single product. Therefore, process "gravel production, crushed [CH]" in ecoinvent cut-off v3.01 has been modified to correspond to each treatment line in the quarry.

The mass ratio of each output flow has been shown in bracket in Figure III. 6. They are calculated as follow:

$$a = 100 - \alpha; b = \Upsilon = a - \beta \qquad III.\ 14$$

Where α is the mass ratio of A1 produced from the first treatment line, a is the mass ratio of the crushed aggregates produced from the first treatment line and sent to the second treatment line, β is the mass ratio of A2 produced from the second treatment line, b is the mass ratio of the crushed aggregate produced from the second treatment line and sent to the third treatment line and Υ is the mass ratio of A3 produced from the third treatment line.

Values of flows have been adapted differently according to the type of flow:

- For each treatment line in the quarry, the infrastructure flows of the process "gravel production, crushed [CH]" in ecoinvent cut-off version 3.01 have been divided by three, since they are shared between three treatment lines.
- Elementary and operational flows in each treatment line have been multiplied by mass ratio of the product of each treatment line.

Therefore, for each flow the quantities of the treatment lines together will be equal to the original quantity of the "gravel production, crushed [CH]" process in ecoinvent cut-off v3.01

for that specific flow. Electricity production and heat and power co-generation processes have been adapted to the case of France.

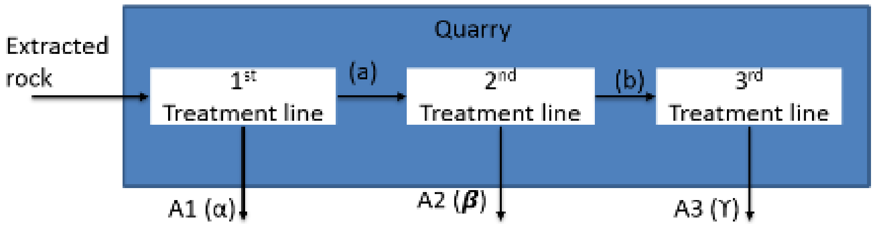


Figure III. 6 quarry process (process 1 in Figure II. 34) with three different treatment lines and three categories of products (A1, A2, A3) (parameters in the brackets are the mass rations of the output flows).

3.3.2 **Stock (stock 1, stock2, stock3 in Figure II. 34)**

Stocks in Figure II. 34 have been assumed to be similar to the process "process-specific burdens production, inert material landfill [CH]" in the ecoinvent cut-off v3.01 database, but without transportation and infrastructure flows. Because these stocks are located in the quarries. Electricity production and heat and power co-generation processes have been adapted to the case of France.

3.3.3 **Bituminous concrete market, cement concrete market and basic quality aggregate market (Market1, Market 2 and Market 3 in Figure II. 34)**

Markets in the conceptual model (Figure II. 34) have been considered according to the definition of the ecoinvent v3 database. A market is an activity that does not transform inputs, but transfers intermediate inputs from one process to another process, where they are consumed (Ecoinvent 3, n.d.). Therefore, transportation processes need to be considered in the markets.

Process "transport, freight, lorry >32 metric ton, EURO5 [RER]" in the ecoinvent cut-off v3.01 database has been considered as the transportation process in the conceptual model (Figure II. 34) for the given territory. Transportation distances in Market 1 and Market 2 (Figure II. 34) have been assumed to be 30 km. It is an average transportation distance from quarries to the cement concrete and bituminous concrete plants (Ventura et al., 2008). Transportation distances for travelling A1 and Recycled Cement Concrete (RCC) from respectively quarries and recycling facilities to the consumers are estimated by the market mechanism model, which will be discussed in detail in section 3.4.

3.3.4 **Recycling process (process 4 in Figure II. 34)**

The process "gravel production, crushed [CH]" in the ecoinvent cut-off v3.01 database has been considered as the recycling process in the territorial environmental model of CCDW management (Figure II. 34). This is due to the fact that the recycling process of CCDW is similar to crushing of aggregates in the quarry.

We considered three different types of recycling facilities. Facilities that are dedicated to the recycling process, facilities that are jointly operating with landfills and facilities that are jointly operating with quarries. According to the type of recycling facility, some changes are made to the process "gravel production, crushed [CH]" in ecoinvent v3.01 as follows:

- **Dedicated recycling facilities:** “occupation, lake, artificial [natural resource/land]” and “transformation, to lake, artificial [natural resource/land]” flows are removed from process “gravel production, crushed [CH]” in the ecoinvent v3.01 because these two flows are related to the extraction sites, but not to the recycling process. Infrastructure flows in this process should be multiplied by ‘IF’ presented in equation (III. 15).

$$IF = \frac{OTC}{OTF} * \frac{1}{3} \qquad \text{III. 15}$$

Where OTC is the operation time of the crushers in the recycling facilities and equals 3 weeks, since crushers are mobile crushers and they are in operation for 3 weeks in a year, and OTF is the operation time of the facilities in one year and equals 52 weeks. In addition, the infrastructural flows are divided by 3, since the recycling process is assumed to correspond to one treatment line in the quarry process. Other flows in process “gravel production, crushed [CH]” should be kept the same as their origin in the ecoinvent v3.01 database.

- **Recycling facility jointly operating with landfills:** the recycling process in such facilities is the same as the recycling process considered for the dedicated recycling facilities, but with some differences. “Operation, mineral extraction site [natural resource/land]”, “transformation, from unspecified [natural resource/land]” and “transformation, to mineral extraction site [natural resource/land]” are removed from the process, since we assume they concern the quarry.
- **Recycling facilities jointly operating with quarries:** the recycling process in such facilities is the same as recycling process considered for the recycling facilities jointly operating with landfills, but with some changes. All infrastructure flows are removed from the process, since we assume that they are attributed to the quarry.

3.3.5 Inert landfilling process (process 5 in Figure II. 34)

The process “treatment of waste concrete, inert material landfill [CH]” in the ecoinvent cut-off v3.01 database has been considered as an inert landfilling process in the territorial environmental model of CCDW (Figure II. 34). Electricity production and heat and power co-generation processes have been adapted to the case of France.

3.3.6 Life cycle impact assessment (LCIA) methods

ILCD (European Commission, 2011) is used as the main life cycle impact assessment (LCIA) method in the LCA tool, UMBERTO, to calculate different environmental impact indicators related to the case study of this PhD. However, some LCIA methods recommended by ILCD for impact indicators cannot be found in UMBERTO. Therefore, the other preferences of the ILCD are used for those indicators. Table III. 1 presents 12 environmental impact indicators calculated in the case study of this PhD and their related LCIA methods. In addition, normalization factor from (Sala et al., 2017) related to each environmental impact indicator is presented in the table.

Table III. 1 LICA methods used for calculating different environmental impact indicators and related normalization factors.

Environmental Impact Category	LCIA method	Indicator	Normalization factors

Acidification potential, average European	*CML 2001	Kg SO_2- Eq	17.8E-1
Eutrophication potential, average European	*CML 2001	Kg NOx- Eq	606.4E-1
Resources, depletion of abiotic resources	CML 2001	Kg antimony- Eq	63.2E-3
Stratospheric ozone depletion, ODP total	*EDIP2003	Kg CFC-11- Eq	23.4E-3
Climate change, GWP 100a	IPCC 2007	Kg CO_2- Eq	84E+2
Ionizing radiation, IRP_HE	ReCiPe Midpoint (H)	Kg U235- Eq	42.2E+2
Urban land occupation, ULOP	ReCiPe Midpoint (H)	m^2a	137.3E-1
Human health, respiratory effects, average	TRACI	Kg PM2.5- Eq	-
Ecotoxicity, total	USEtox	CTU	-
Human toxicity, total	USEtox	CTU	-
Fossil cumulative energy demand	*Cumulative energy demand	MJ- Eq	653E+2
Nuclear cumulative energy	*Cumulative energy demand	MJ- Eq	-

*These methods are not recommended by ILCD as the first choice.

3.4 Basic quality aggregate market mechanism model

As already mentioned, the basic quality aggregate market (Market 3 in Figure II. 34) has two suppliers: quarries and recycling facilities. In this section, we aim at developing a local market mechanism model related to Market 3 to discover the shares of A1 and RCC in the market_ $f1$ and $f2$ respectively in equations (III. 8) and (III. 9) _ and subsequently traveling distances between buyers and sellers of basic quality aggregates.

As discussed in section 2.10.2, the share of Market 3 from A1 and RCC is assumed to be affected by the total prices of the products in the market. Total prices correspond to the sum of the selling prices of the products in the platforms and transportation prices. Therefore, our model requires estimating the total prices and a decision procedure based on which buyers make a choice between A1 provided by quarries and RCC provided by recycling facilities.

Therefore, this section explains our model and its assumptions mainly guided by the available data to us.

3.4.1 Total price of a resource in the market

The total prices a buyer should pay in the market when buys a given resource (A1 or RCC) can be estimated by equation (III. 16).

$$P_{resource} = D_{resource} * UP_{resource} + Tprice_{resource} \quad \text{III. 16}$$

Where $P_{resource}$ is the total price of a resource (€) in the market, $D_{resource}$ is the demand for a given resource (ton) that is needed for a given use, $UP_{resource}$ is price per one ton of the resource (€/ton), which a buyer should pay to a given platform, and $Tprice_{resource}$ is the transportation price (€) that can be calculated by equation (III. 17).

$$Tprice_{resource} = T_{cost} + E * T_{cost} \qquad III.\ 17$$

Where $Tprice_{resource}$ is the transportation price (€), T_{cost} is the transportation cost (€) that transportation companies go through for the whole operation and E represents the overhead expenses and profits of a transportation company. It is assumed to be arround 20% of the transportation cost. This value could vary.

The transport cost can be calculated by equation (III. 18), which is from the CNR website (CNR, n.d.). The means of transport for the construction materials is assumed to be a heavy truck with a 40 tons-capacity. Equation (III. 18) represents transportation cost for 40 tons of the resource.

$$T_{cost} = CK * d + CC * OPhrs + CJ * OPdays \qquad III.\ 18$$

Where T_{cost} is transportation cost (€), cost that a transportation company would go through, CK is kilometer range (€/km) and equal to 0.477 €/km, d is the total transport distance from a facility to a delivery place (km), CC is hour range (€/hr) and equal to 19.61 €/hr, OPhrs is the total operation hours of the vehicle (hr), which 100 km of traveling by truck corresponds to 1.96 hours of travelling, CJ is daily range (€/day) and equal to 165.88 €/day, which one working day corresponds to 10 hours according to this website, and OPdays is total numbers of days that the vehicle is used (day).

Accordingly, it is required to measure transportation distances (d) to estimate the transportation prices and subsequently the total prices of a resource. This is discussed in detail in the next section.

3.4.2 **Transportation distances between buyers and sellers**

Estimating the transportation distances traveled between sellers and buyers of basic quality aggregates requires knowing:

- The locations of the sellers of basic quality aggregates (discussed in section 3.4.2.1)
- The locations of the buyers of basic quality aggregates (discussed in section 3.4.2.2)
- The demand of each buyer for basic quality aggregates based on which a buyer travels to different sellers to meet his demand (discussed in section 3.4.2.3)
- The total amount of basic quality aggregates each seller can provide for his clients (discussed in section 3.4.2.4)

3.4.2.1 **Where are the sellers located in the given territory?**

There are two types of suppliers or sellers in Market 3 in Figure II. 34: quarries and recycling facilities. It is required to provide a list of sellers with their geographical locations in the given territory. The list of quarries and recycling facilities in the territory understudy in this PhD is presented in section 4.2.1.

3.4.2.2 **Where are the buyers located in the given territory?**

In order to find out how the basic quality aggregate market is structured in the given territory, the locations of the buyers (consumers) of the basic quality aggregates should be positioned on the map of the territory.

Since it is not possible to identify the real physical locations of the "basic quality aggregate" buyers on the map, the map of the given territory is divided into different segments. For this purpose, a Geographical Information System (GIS) tool is used. The locations of the buyers in each segment are estimated based on the center of gravity of the segment regarding the cities' populations in that segment, not the real physical locations of the buyers. The center of gravity is assumed to represent the location of the consolidated buyers in a given segment. As a result, the numbers of buyers will equal the numbers of segments that are considered. Equations (III. 19) and (III. 20) show how the center of gravity in each segment is estimated.

$$X_m = \frac{\sum x_{j,m} * Pop_{j,m}}{\sum Pop_{j,m}} \quad \text{III. 19}$$

Where $x_{j,m}$ is the position of city j^{th} in segment m^{th} from X axis and $Pop_{j,m}$ is the population of the city j^{th} in segment m^{th}. m is the numbers of the segments on the given map.

$$Y_m = \frac{\sum y_{j,m} * Pop_{j,m}}{\sum Pop_{j,m}} \quad \text{III. 20}$$

Where $y_{j,m}$ is the position of city j^{th} in segment m^{th} from Y axis and $Pop_{j,m}$ is the population of the city j^{th} in segment m^{th}. m is the numbers of the segments on the given map.

As a result, equations (III. 19) and (III. 20) give one position on the map in each segment with X value equals X_m and Y value equals Y_m , which represents the position of buyer m^{th} on the map in segment m^{th}. X-Y coordinates of the cities can be identified from the DoGeocodeur website (DoGeocodeur, n.d.).

3.4.2.3 **Demand of each buyer for basic quality aggregates in each segment**

According to (Sandberg et al., 2016) the demand for construction materials is usually proportional to the population. We assume that this can be applied at local level, i.e. at segmental level. Therefore, one underlying assumption is made: where there is a higher population, there is higher demand. Therefore, according to the proportion of population in each segment compared to the total population of the territory, the demand of a buyer in a segment for basic quality aggregates can be estimated, see equation (III. 21).

$$D_{BQA_m}(Y_n) = \frac{Pop_m\,(Y_n)}{Pop_{territory}\,(Y_n)} * D_{BQA_{territory}}(Y_n) \quad \text{III. 21}$$

Where $D_{BQA_m}\,(Y_n)$ is the demand of buyer m^{th} in segment m^{th} for basic quality aggregates (ton) in year Y_n, Pop_m (Y_n) and $Pop_{territory}$ (Y_n) are total population of segment m^{th} and total population of the given territory respectively in year Y_n and $D_{BQA_{territory}}$ (Y_n) is the total demand for or consumption of basic quality aggregates (ton) in the territory in year Y_n, which can be obtained from statistical data on consumptions of materials in the given territory.

3.4.2.4 **Production volume of the facilities: quarry and recycling facility**

3.4.2.4.1 Production volume of the quarries

Quarries have an authorized production capacity, which refers to the production volume they are permitted to produce each year. These data can be found from the BRGM website (brgm, 2016). However, according to the experts' opinions, the amount that usually needs to be produced to respond to the demand in the market is less than this capacity, which is called actual production of the quarries. This will be discussed in section 4.2.1.1 for the case study of this PhD.

3.4.2.4.2 Production volume of the recycling facilities

Production volumes of the recycling facilities mostly correspond to the demand for RCC. This will be discussed in section 4.2.1.3 for the case study of this PhD.

3.4.3 **Decision procedures of the buyers to make choices between sellers at local scale**

It is expected that the market mechanism is mainly structured according to the choices of buyers, which are mostly affected by the price. Accordingly, an algorithm has been written in MATLAB (see Figure III. 7) to model the mechanisms of Market 3 with the aim of specifying the share of the market from A1 and RCC as well as traveling distances between the buyers and sellers of basic quality aggregates.

The algorithm in Figure III. 7 is based on comparing the total prices of 1 ton of the resources of basic quality aggregates (A1 and RCC) that the basic quality aggregates' buyers pay in the market for all their choices.

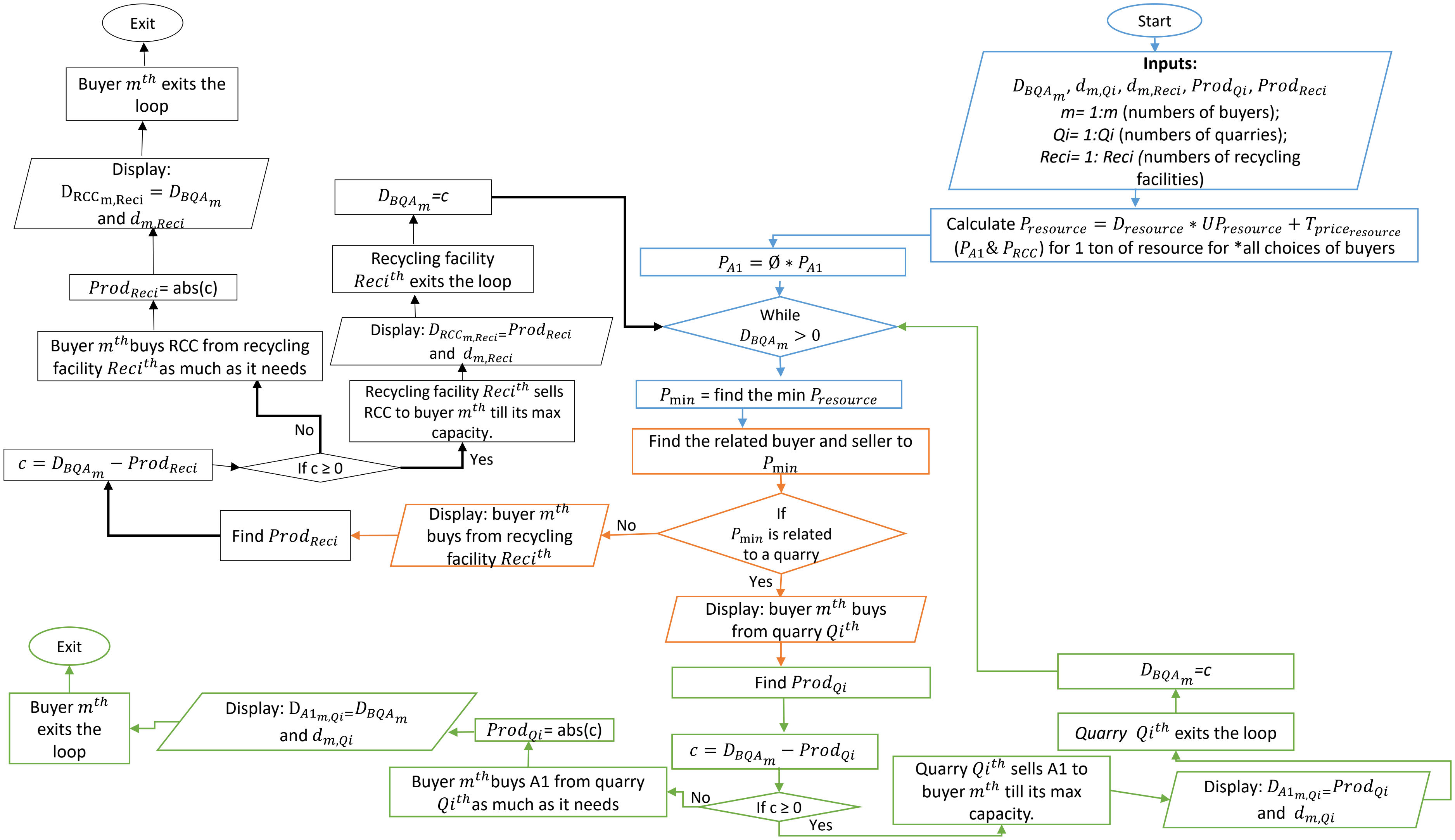
This algorithm first identifies the minimum total price among all the total prices (estimated from equation III. 16) buyers pay in the market for all existing choices (existing sellers in the market). This step is shown in blue in Figure III. 7. This enables us to determine the seller and the resource (A1 or RCC) that gets the market as well as the buyer, who is the consumer of this resource, shown in orange in Figure III. 7.

As the next step, the algorithm tests whether the chosen seller (steps in orange) can meet the demand of the given buyer (steps in orange) as follows (if a quarry and A1 gets the market, green colors in Figure III. 7 are concerned, otherwise the black colors are concerned in the figure):

- If the demand of the given buyer for basic quality aggregates is more than the production of the seller, the seller sells as much of the product as it can produce and cannot sell basic quality aggregates anymore to other buyers ("the seller exits the loop").
- Otherwise, the buyer buys basic quality aggregates as much as he requires and will not buy basic quality aggregates anymore from other sellers ("the buyer exits the loop").

The routine is iterated until the demands of all buyers for basic quality aggregates are met (all buyers have exited the loop).

Figure III. 7 includes a parameter, shown by $\emptyset$ (in blue), which represents the confidence degree of buyers in RCC's quality. This $\emptyset$ factor is used to define different scenarios (Scenario 1, Scenario 2 and Scenario 3) that are discussed in detail in sections 3.5.2 and 3.5.3.



*All existing sellers (quarries and recycling facilities) can be all choices of basic quality aggregates' buyers

D_{BQA_m}	*Total demand of buyer m^th for basic quality aggregates (ton) (equation III. 21)*
$d_{m,Qi}$	*Transportation distance between buyer m^th and quarry Qi^th (km)*
$d_{m,Reci}$	*Transportation distance between buyer m^th and recycling facility Reci^th (km)*
$Prod_{Qi}$	*Production volume of A1 in quarry Qi^th (ton)*
$Prod_{Reci}$	*Production volume of RCC in recycling facility Reci^th (ton)*
$P_{resource}$	*Total price (€) of a resource (equation III. 16)*
P_{A1}	*Total price (€) of A1 (equation III. 16)*
P_{RCC}	*Total price (€) of RCC (equation III. 16)*
Ø	*A factor that shows trust or mistrust of the buyers on the quality of RCC. $Ø < 1$ is mistrust factor and $Ø \geq 1$ is trust factor. Ø is 1, 0.85 and 1.15 for Scenarios 1, 2 and 3 respectively.*
$D_{A1_{m,Qi}}$	*Demand of buyer m^th for A1 from quarry Qi^th (ton)*
$D_{RCC_{m,Reci}}$	*Demand of buyer m^th for RCC from recycling facility Reci^th (ton)*

Figure III. 7 An algorithm for modeling the basic quality aggregate market mechanisms (Market 3 in Figure II. 34) based on the total prices of the resources (A1 and RCC) in the market including different parameters.

Consequently, the outputs of Figure III. 7 are: demands of a buyer for a resource (A1/RCC) from different facilities ($D_{A1_{m,Qi}}$/ $D_{RCC_{m,Reci}}$) and traveling distances between the buyers and different sellers ($d_{m,Qi}$ / $d_{m,Reci}$). Subsequently, the total demands for A1 and RCC in Market 3 and *f1* (share of A1 in the market) and *f2* (share of RCC in the market) in Market 3 can be calculated. As a result, the total ton-kilometers (transport of the demanded resource over a specific distance) for each resource (A1 and RCC) can be estimated as follows:

$$D_{A1}.d_Q = \sum_{Qi=1:Qi,\ \ m=1:m} D_{A1_{m,Qi}} * d_{m,Qi} \qquad \text{III. 22}$$

Where $D_{A1}.d_Q$ is the total ton-kilometer resulting from the demand of A1's buyers from different quarries in the territory, $D_{A1_{m,Qi}}$ is the demand of buyer m^th for A1 from quarry Qi^th (ton) and $d_{m,Qi}$ is the distance between buyer m^th and quarry Qi^th (km). m is the number of segments defined in 3.4.2.2 and Qi is the numbers of quarries.

$$D_{RCC}.d_{Rec} = \sum_{Reci=1:i,\ \ m=1:m} D_{RCC_{m,Reci}} * d_{m,Reci} \qquad \text{III. 23}$$

Where $D_{RCC}.d_{Rec}$ is the total ton-kilometer resulting from the demands of RCC's buyers from different recycling facilities in the territory, $D_{RCC_{m,Reci}}$ is the demand of buyer m^th for RCC from recycling facility Reci^th (ton) and $d_{m,RCCi}$ is the distance between buyer m^th and recycling facility Reci^th (km). m is the number of segments defined in 3.4.2.2 and Reci is the numbers of recycling facilities.

Finally, the market share resulting from three scenarios (discussed in sections 3.5.2 and 3.5.3) is compared with a reference scenario, which represents the current situation in the territory and current shares of A1 and RCC in Market 3 based on the statistical data available to us. This will enable us to validate the market mechanism model in Figure III. 7 including ø factor as well as determine whether this factor significantly affects the environmental impacts. The results will be presented in the next chapter.

3.5 Investigated scenarios

3.5.1 Reference scenario: current situation in the territory including current situation in Market 3

The reference scenario represents the current situation in the territory including the current shares of A1 and RCC in Market 3 that are obtained from the statistical data available to us.

Thus, there is no need to estimate the shares of A1 and RCC in Market 3 by comparing the total prices of A1 with those of RCC. However, it is required to estimate transportation distances between sellers of each resource (quarries or recycling facilities) and the buyers of each resource.

The buyers of each resource are expected to compare the transportation prices to get the cheapest ones. This in turn leads to choosing the closest sellers. Accordingly, the same procedures in Figure III. 7 are run separately for the demanded A1 and demanded RCC, but based on comparing the transportation prices. Therefore, some parameters and steps that are just required for comparing the total prices of A1 with those of RCC are shaded. Procedures in Figure III. 8, which are run for the demanded A1, exclude all data concerning RCC and recycling facilities as well as the steps in black in Figure III. 7. On the contrary, procedures in Figure III. 9, which are run for the demanded RCC, exclude all data concerning A1 and quarries as well as the steps in green in Figure III. 7. In both Figure III. 8 and Figure III. 9, the ø factor is not considered, since there is no comparison between the prices of A1 and those of RCC. As a result, Figure III. 8 and Figure III. 9 result in optimum transportation distances for the buyers of A1 and the buyers of RCC respectively.

In the reference scenario, the total demands for A1 and RCC in the territory and subsequently the shares of A1 and RCC in Market 3 are already known. Therefore, based on assumptions considered in equation (III. 21), the demand of a buyer in a segment for each resource (A1 / RCC) is estimated as follows:

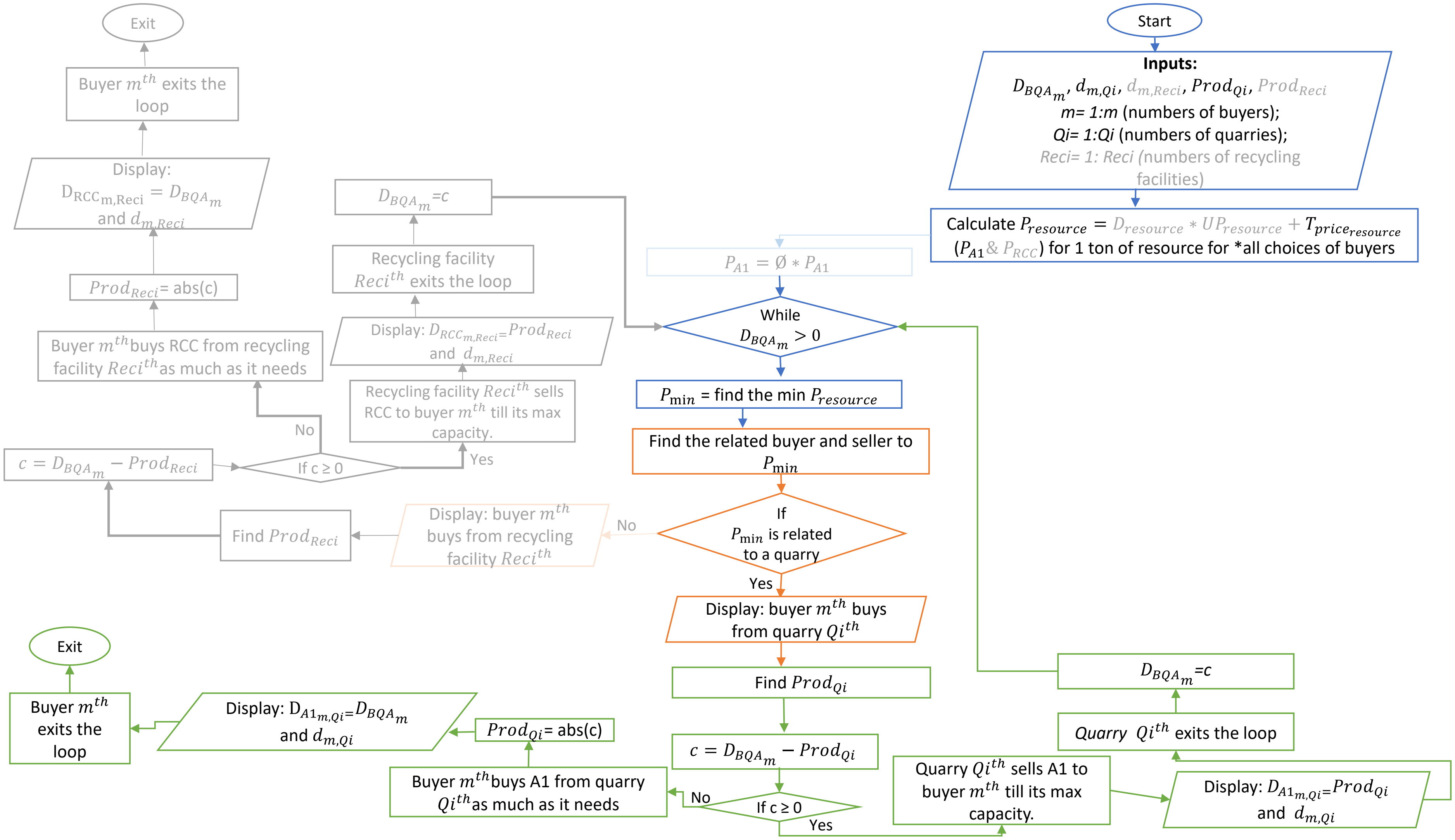
$$D_{A1_m}(Y_n) = \frac{Pop_m\ (Y_n)}{Pop_{territory}\ (Y_n)} * D_{A1_{territory}}(Y_n) \qquad III.\ 24$$

Where $D_{A1_m}\ (Y_n)$ is the demand of buyer m^{th} in segment m^{th} for A1 (ton) in year Y_n, $Pop_m\ (Y_n)$ and $Pop_{territory}\ (Y_n)$ are the total population of segment m^{th} and total population of the territory respectively in year Y_n and $D_{A1_{territory}}(Y_n)$ is the total demand for A1 (ton) in the territory in year Y_n.

$$D_{RCC_m}(Y_n) = \frac{Pop_m\ (Y_n)}{Pop_{territory}\ (Y_n)} * D_{RCC_{territory}}(Y_n) \qquad III.\ 25$$

Where $D_{RCC_m}\ (Y_n)$ is the demand of buyer m^{th} in segment m^{th} for RCC (ton) in year Y_n , $Pop_m\ (Y_n)$ and $Pop_{territory}\ (Y_n)$ are the total population of segment m^{th} and total population of the territory respectively in year Y_n and $D_{RCC_{territory}}(Y_n)$ is the total demand for A1 (ton) in the territory in year Y_n.

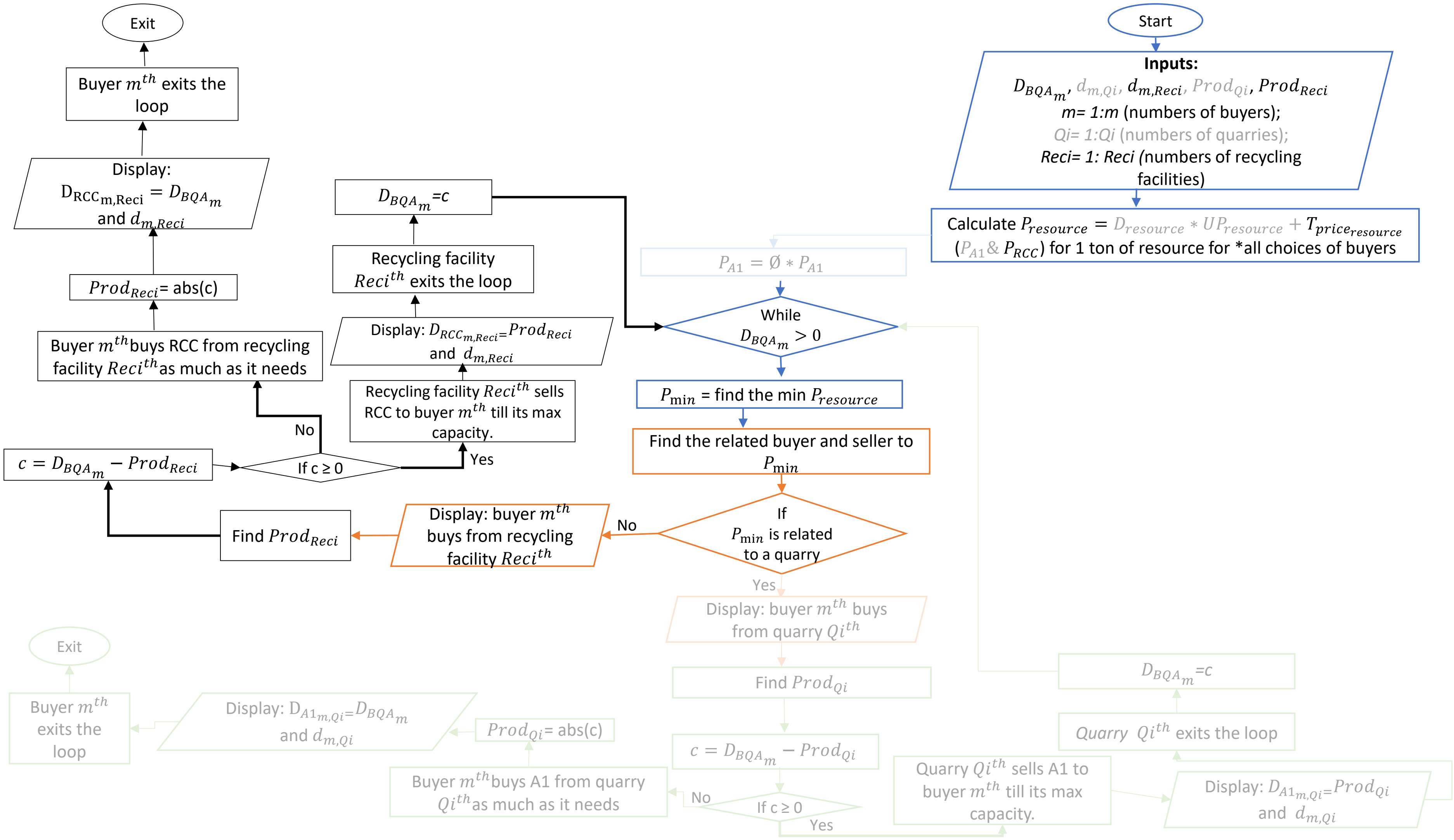
Consequently, the outputs of Figure III. 8 and Figure III. 9 are respectively: demands of a buyer for A1 from different quarries ($D_{A1_{m,Qi}}$), the distances traveled between the buyers of A1 and different quarries ($d_{m,Qi}$) and total ton-kilometers for A1 calculated from equation (III. 22) and demands of a buyer for RCC from different recycling facilities ($D_{RCC_{m,Reci}}$), the distances travelled between the buyers of RCC and different recycling facilities ($d_{m,Reci}$) and total ton-kilometers for RCC calculated from equation (III. 23).



*All existing sellers (quarries) can be all choices of basic quality aggregates' buyers.

D_{BQA_m}	Total demand of buyer m^th for basic quality aggregates (ton) (equation III. 21)
$d_{m,Qi}$	Transportation distance between buyer m^th and quarry Qi^th (km)
$Prod_{Qi}$	Production volume of A1 in quarry Qi^th (ton)
$P_{resource}$	Total price (€) of a resource (equation III. 16)
P_{A1}	Total price (€) of A1 (equation III. 16)
$D_{A1_{m,Qi}}$	Demand of buyer m^th for A1 from quarry Qi^th (ton)

Figure III. 8 An algorithm for discovering the transportation distances between the buyers of A1 and quarries in Market 3.



*All existing sellers (recycling facilities) can be all choices of basic quality aggregates' buyers.

D_{BQA_m}	Total demand of buyer m[th] for basic quality aggregates (ton) (equation III. 21)
$d_{m,Reci}$	Transportation distance between buyer m[th] and recycling facility Reci[th] (km)
$Prod_{Reci}$	Production volume of RCC in recycling facility Reci[th] (ton)
$P_{resource}$	Total price (€) of a resource (equation III. 16)
P_{RCC}	Total price (€) of RCC (equation III. 16)
$D_{RCC_{m,Reci}}$	Demand of buyer m[th] for RCC from recycling facility Reci[th] (ton)

Figure III. 9 An algorithm for discovering the transportation distances between the buyers of RCC and recycling facilities in Market 3

3.5.2 Scenario 1: price-based market mechanism model

Scenario 1 is defined as a price-based market mechanism model, which makes no difference between the quality of RCC and A1 for the buyers. In Scenario 1 we assume that the buyers have confidence in the quality of RCC to the same extent as they do in the quality of A1.

Therefore, their choices in the market is only based on the total prices of the resources (A1 and RCC). Accordingly, when the condition in equation (III. 26) is met, we assume that buyers of basic quality aggregates buy RCC, otherwise they buy A1.

$$P_{RCC} < \text{Ø} * P_{A1} \qquad \textit{III. 26}$$

Where P_{RCC} and P_{A1} are the total prices of RCC and A1 respectively estimated from equation (III. 16) and Ø is a trust factor that equals 1 for Scenario 1, as distinguished in Figure III. 7 for each scenario.

Consequently, procedures in Figure III. 7 for Scenario 1 result in optimum prices for the buyers in the market.

3.5.3 Scenarios 2 & 3: price-based market mechanism model including a mistrust / trust factor

We aim at analyzing the sensitivity of the price-based market mechanism model to the buyers' confidence in the quality of products.

As a matter of fact, one of the main barriers towards promoting the use of recycled concrete in the construction work is cultural barriers (as mentioned in the literature review in section 2.5). It mostly results in low confidence of the consumers in the quality of recycled materials.

Accordingly, it is expected that, based on some personal communications, some buyers are ready to pay a higher price in the market to buy natural resources instead of recycled resources, even though, RCC can be technically equivalent for Market 3. This willingness to pay a higher price reflects the buyers' mistrust in RCC's quality. According to the experts' opinions in Charier Company (Appendix A), the buyers of basic quality aggregates might prefer to pay up to 15% (this can vary) more in order to buy A1. Therefore, this condition (15% competitive price advantage for A1) is integrated into the price-based market mechanism model in favor of A1 to define Scenario 2. Accordingly, we assume that Ø in equation (III. 26) equals 0.85 for Scenario 2 (as the value of this parameter is distinguished for different scenarios in Figure III. 7). Under the assumption of Scenario 2 ($\text{Ø} = 0.85$), if the condition in equation (III. 26) is met, the buyers of basic quality aggregates will buy RCC, otherwise they will buy A1.

Accordingly, we expect that the shares of A1 and RCC (f1 and f2 respectively) and subsequently the total demands for A1 and RCC in Market 3 as well as the total ton-kilometer obtained from equations (III. 22) and (III. 23) for each resource would change compared to Scenario 1.

On the other hand, the sensitivity of the price-based market mechanism model to the case that the buyers of basic quality aggregates not only have trust in the quality of RCC as much as they do in the quality of A1, but also buy RCC even if it is up to 15% more expensive, is analyzed. This scenario reflects that some buyers would prefer using recycled resources due to their environmental concerns. Therefore, this condition (15% competitive price advantage for RCC) is integrated into the price-based market mechanism model in favor of RCC to define Scenario 3. Accordingly, we assume that Ø in equation (III. 26) equals 1.15 for Scenario 3 (as shown in Figure III. 7). Under the assumption of Scenario 3 ($\text{Ø} = 1.15$), if the condition in equation (III. 26) is met, the buyers of basic quality aggregates will buy RCC, otherwise they will buy A1.

The results obtained from Scenarios 2 and 3 will be presented in Chapter 4.

3.5.4 Scenario 4: legal obligation to use RCC (100% RCC in Market 3_ *f2*= 100%)

Scenario 4 is a prospective scenario. It is assumed that there is a law according to which RCC must be used instead of A1 in the foundations in the territory. Accordingly, the total demand for basic quality aggregates in Market 3 is only met by the recycling facilities in the territory.

If such a legal obligation were imposed, there would be a need for a system to finely anticipate the match between the local demand for basic quality aggregates and the local production capacity of the recycling facilities. However, if the local production volumes of the recycling facilities were not sufficient to meet the demands of basic quality aggregates' buyers in the territory, while there is an adequate supply of CCDW in the territory, we assume that the production volume of a recycling facility in the territory would increase according to equation (III. 27).

$$Prod._{RF} = \frac{D_{BQA_{territory}}(Y_n)}{N_{RF}} \qquad \textit{III. 27}$$

Where prod.$_{RF}$ is production volume (ton) of each recycling facility in the territory, $D_{BQA_{territory}}(Y_n)$ is the total demand (ton) for basic quality aggregates in the territory in Y_n and N_{FR} is total numbers of recycling facilities in the territory.

Therefore, under assumption in equation (III. 27) each recycling facility in the territory has the same production of RCC, in such a way that the total production of the facilities can meet the total demand for basic quality aggregates in Market 3. Traveling distances between the buyers and different recycling facilities in the territory to meet the total demand of the buyers for basic quality aggregates are identified by Figure III. 9.

3.5.5 Scenario 5: legal obligation to use A1 (100% A1 in Market 3_ *f1*= 100%)

On the contrary to scenario 4, scenario 5 refers to an obligatory use of A1 instead of RCC.

Accordingly, the total demand for basic quality aggregates in Market 3 is only met by the quarries in the territory. Traveling distances between the buyers and different quarries in the territory to meet the total demand of the buyers for basic quality aggregates are identified by Figure III. 8.

3.6 **Synthesis**

This chapter has proposed to integrate LCA, MFA and market mechanism models into an integrated model to assess the environmental performance of CCDW management in a given territory.

MFA provides us with information concerning the production and consumption of materials as well as stocks of materials in the given territory. Stocks included in Figure II. 34 are related to the stocks of materials that are demand constrained, such as stocks of A1 and A2 (the dependent co-product of the quarry process). This is due to the fact that their productions are driven by the demand for A3 (the determining co-product of the quarry process), but their consumptions depend on the existence of the demand in the related markets.

However, the main focus of this PhD is on CCDW management that RCC recycled from CCDW is considered as an alternative to A1. Therefore, a market mechanism model with a number of parameters has been developed for the basic quality aggregate market (Market 3) to investigate the shares of A1 and RCC in the market. This in turn determines the accumulation of A1 in the stock and flows of CCDW through two waste handling practices (recycling and inert landfilling).

Parameters considered in the market mechanism model are: confidence in the quality of RCC and enforcement of a law to push market share. Based on these parameters we have different scenarios:

- Scenario 1: a price-based market mechanism model that considers no psychological obstacles for buyers to use RCC and buyers of basic quality aggregates make choices between A1 and RCC based on the total prices of A1 and RCC.
- Scenario 2: a price-based market mechanism model including a mistrust factor in the quality of RCC.
- Scenario 3: a price-based market mechanism model including a trust factor in the quality of RCC.
- Scenario 4: obligatory use of RCC instead of A1 in the foundations.
- Scenario 5: obligatory use of A1 instead of RCC in the foundations.

In Chapter 4, the assumptions made for the market mechanism model in Figure III. 7, including different parameters (trust factor and mistrust factor), will be validated based on the current situation in Market 3, which is obtained from the statistical data. The current situation in Market 3 is considered as a reference scenario with which five above mentioned scenarios are compared in terms of 12 environmental impacts to determine whether these scenarios significantly affect the environmental performance of CCDW management in the territory. The results of comparative environmental impact assessment will be presented in the next chapter.

The territorial environmental model of CCDW management can be applied to any territory by using local data to assess the environmental performance of waste management. In the next chapter the territory understudy in this PhD for CCDW management will be introduced.

CHAPTER IV RESULTS

4.1 Introduction

In this chapter, the territory understudy for Cement Concrete Demolition Waste (CCDW) management is introduced. It is the department of *Loire-Atlantique* on the west coast of France. In order to reflect the current situation in *Loire-Atlantique*, various data concerning input and output flows and process parameters required for the territorial environmental model of CCDW management (Figure II. 34) have been collected or calculated.

Then, the results are presented for each scenario defined in chapter 3 including the total demand respectively for A1 and RCC in Market 3, shares of A1 and RCC in Market 3 and transportation distances between the buyers and sellers of basic quality aggregates in the territory as well as environmental impacts caused by each scenario.

In the last sections of this chapter, the scenarios are compared with the reference scenario in terms of market share and 12 environmental impacts. The comparison aims at analyzing whether different shares of A1 and RCC in Market 3, which are estimated in the scenarios, significantly affect the environmental performance of CCDW management in *Loire-Atlantique*. We aim at determining if the environmental performance will be improved when the share of RCC increases in Market 3.

4.2 Territorial situation and data related to the territorial CCDW management for the *Loire-Atlantique* case study

Loire-Atlantique, as the territory understudy, is one of the departments of the *Pays de la Loire* region on the west coast of France. In the next sections (4.2.1-4.2.3), data used in this PhD thesis concerning the case of *Loire-Atlantique* will be discussed. The most recent available data were from year 2012. However, some of data were from the average values of 5 years, between 2011 and 2016. Therefore, in this PhD the current situation in the territory mainly refers to year 2012.

4.2.1 Database creation for quarries and recycling facilities in *Loire-Atlantique* (sellers of basic quality aggregates)

A list of quarries with their postal addresses in *Loire-Atlantique* was obtained from the BRGM website (brgm, 2016). This list of quarries is presented in Table F. 1 in Appendix F.

To obtain a list of recycling facilities in *Loire-Atlantique* containing different types of facilities (as discussed in section 3.3.4) different sources have been used as well as different assumptions have been made. The summary of assumptions made to create the list of recycling facilities in *Loire-Atlantique* is presented in Figure IV. 1. They are explained below.

The French administration for Environment, Planning and Housing (DREAL) classifies all economic activities according to the [10]"nomenclature of classified installations". A database of all classified activities with their postal addresses can be obtained on their website (DREAL, 2014). The classification numbers of quarries, recycling facilities and inert landfills that have been considered in this PhD are as follows:

- 2510 : quarry operation (exploitation de carrières)
- 2515 : grinding, crushing, ... and other mineral products or inert non-hazardous waste (« Broyage, concassage, ...et autres produits minéraux ou déchets inertes non dangereux »)
- 2517: mineral products with non-hazardous waste inerts (transit) (« produits minéraux ou déchets inertes non dangereux (transit) »)

Accordingly, the lists of activities (2510, 2515 and 2517) were extracted from the DREAL website (DREAL, 2014) for *Loire-Atlantique*. The identification of the recycling facilities was conducted using the following procedure:

- Activities '2515' that had common addresses with activities '2517' were assumed to be recycling facilities jointly operating with the landfills. We know according to the facility owners that, some inert landfills can rent mobile crushers that crush demolished wastes to produce recycled products.
- Activities '2515' that had common addresses with activities '2510' were assumed to be crushers for natural aggregates, not for the mineral wastes.
- Activities '2515' that had a common address with both activities '2517' and '2510' were assumed to be recycling facilities jointly operating with the quarries. Indeed, this implies that quarries receive wastes beside quarry operation.
- Activities '2515' that had no common addresses with both activities '2517' and '2510' were assumed to be dedicated recycling facilities.

Finally, the list of recycling facilities obtained was compared with the recycling facilities found on the FFB website (FFB, 2016) and [11]Charier Company's recycling facilities. Accordingly, some recycling facilities that had not been found on the DREAL website were added to the list of recycling facilities. The final list of recycling facilities in *Loire-Atlantique* is presented in Table F. 2 in Appendix F.

Technical efficiency of the recycling facilities (TER in equation III. 13) in *Loire-Atlantique* is about 90% (CERC, 2013).

---

[10] "nomenclature des installations classées"
[11] Charier Company is one of the largest producers of natural aggregates and recycled concrete in the region of Pays de la Loire.

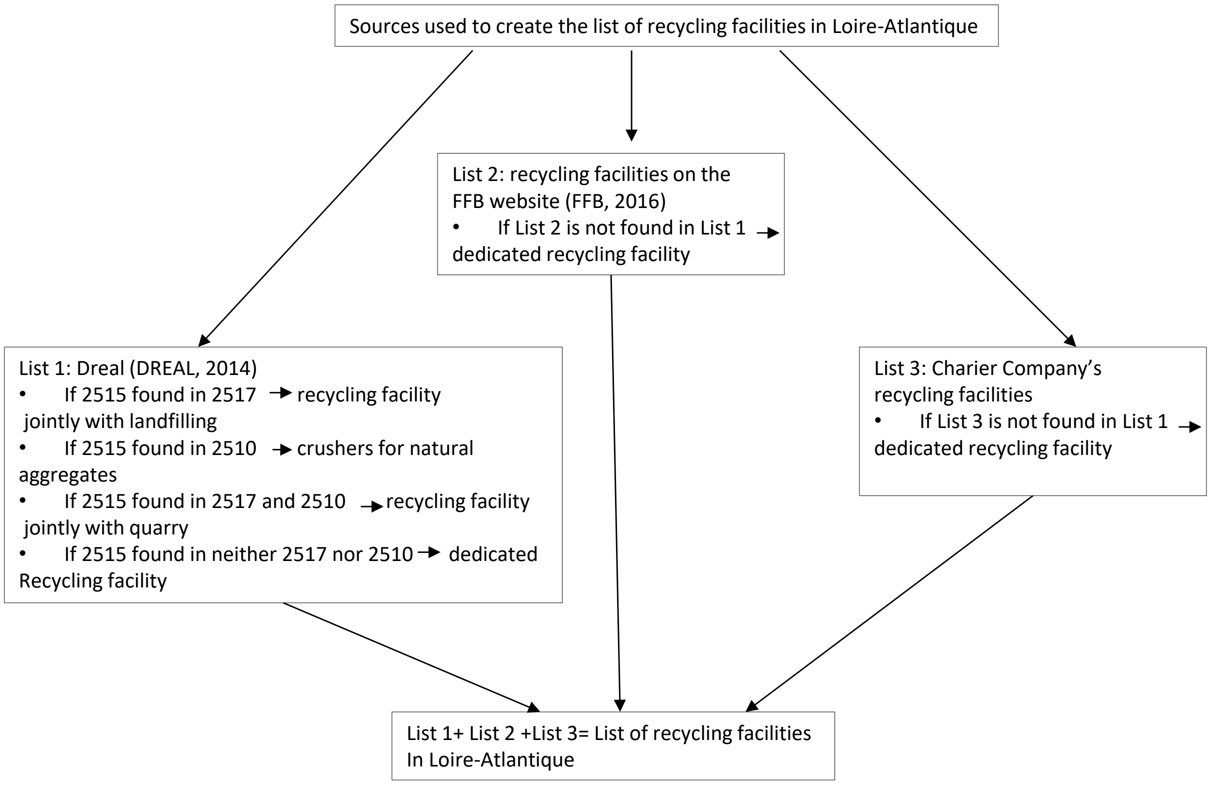


Figure IV. 1 summary of sources used and assumptions made to create the list of recycling facilities in Loire-Atlantique

4.2.1.1 Production volume of quarries in *Loire-Atlantique*

Information regarding the annual authorized production of the quarries are provided on the Brgm website (brgm, 2016). Our model requires actual production of the quarries in a given year, but such an information is not available on the Brgm website. Therefore, some assumptions needed to be made.

The actual production of the quarries in Charier Company is known, which is the average of annual productions of the quarries during 5 years (from 2011 to 2016). The linear relationship found between the actual production and authorized production of Charier Company's quarries (Figure IV. 2) is used to estimate the missing data for other quarries. This relation could be representative of the economic situation between 2011 and 2016 in the territory, as quarries in Charier Company would represent one third of the production in the region of *Pays de la Loire* (based on personal communication with Charier Company). The authorized and actual productions of the quarries in *Loire-Atlantique* are shown in Table F. 1 in Appendix F.

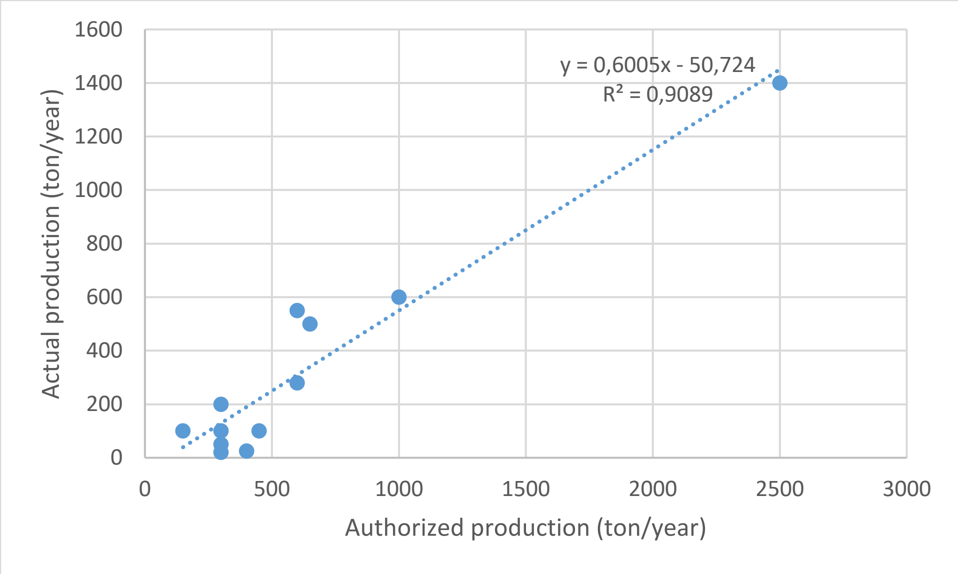


Figure IV. 2 Actual production versus authorized production in the quarries of Charier Company

4.2.1.2 Proportion of A1, A2 and A3 production in the quarries in *Loire-Atlantique*

As already mentioned in section 3.2.1, a quarry is a co-producing process from which 3 different co-products (A1, A2 and A3) are produced at the same time, whose output volumes cannot vary independently. Production proportions of the products in the quarry depend on different parameters, including geological issues, nature and quality of the rocks. Based on these parameters, the production proportions of the products are expected to be different in each quarry. These production proportions for each quarry in *Loire-Atlantique* were not available. Therefore, some assumptions were made to estimate production volume of each category of aggregates in the quarries.

The mass ratios of A1, A2 and A3 in the quarry have been shown by coefficients α, $\boldsymbol{\beta}$, ϒ respectively (see section 3.2.1). These coefficients have been estimated from the average of annual productions between 2011 and 2016 in Charier Company's quarries (shown in Table IV. 1).

Table IV. 1 production and mass ratios of the products in Charier Company's quarries located in Pays de la Loire, France

Products in the quarries	**Production in Charier Company's quarries (ton)**	**Mass ratio (%)**
A1	1,408,000	37.7
A2	698,000	18.7
A3	1,632,000	43.6
Total	3,738,000	100

As a result, the values of α, $\boldsymbol{\beta}$ and ϒ are obtained from Table IV. 1. They are presented in equation (IV. 1).

$$\alpha = 37.7\%;\ \beta = 18.7\%;\ \Upsilon = 43.6\% \qquad \textit{IV. 1}$$

Where α, $\boldsymbol{\beta}$ and ϒ are mass ratios of A1, A2 and A3 respectively in the quarries in Loire-Atlantique.

Consequently, production of A1 in each quarry can be estimated according to equation (IV. 1), knowing the actual production volume in each quarry. These values are presented in Table F. 1 in Appendix F.

4.2.1.3 **Production volume of the recycling facilities in *Loire-Atlantique***

There were no data available as regards the production volumes of the recycling facilities. Therefore, we assumed that the production volume of each facility equals the average production of 13 recycling facilities of Charier Company located in *Pays de la Loire*. The production volumes of the recycling facilities in *Loire-Atlantique* are presented in Table F. 2 in Appendix F. It should be noted that two of the recycling facilities located in *Loire-Atlantique* belong to Charier Company, therefore their actual production is considered.

4.2.1.4 **Selling prices of A1 and RCC at quarries and recycling facilities**

According to the experts' opinions in Charier Company, it has been assumed that the quarries sell A1 for 5€/ton and the recycling facilities sell RCC for 4.5€/ton in *Loire-Atlantique*. The values are for the variable '$UP_{resource}$' in equation (III. 16). They are average prices for A1 and RCC at facilities and are assumed to be constant.

4.2.2 **Locations of buyers and sellers of basic quality aggregates on the map of *Loire-Atlantique***

QGIS as a GIS tool has been used to divide the map of *Loire-Atlantique* into different segments, estimate the populations of each segment, specify the center of gravity of each segment and measure the road distances between sellers and buyers of basic quality aggregates.

As explained in section 3.4.2.2, the map of *Loire-Atlantique* has been divided into 9 segments, mainly based on having similar population in each segment (see Figure IV. 3). Except segments 4 and 5 which have much higher populations compared to other segments, since they are related to the main cities of *Loire-Atlantique* (Saint-Nazaire and Nantes respectively). Table IV. 2 presents the population of each segment in Figure IV. 3. Information regarding the total population in *Loire-Atlantique* is obtained from statistical data in 2012.

As mentioned in section 3.4.2.2, it is assumed that the center of gravity of a segment (based on the cities' populations in that segment) represents the consolidated buyers of basic quality aggregates in that segment. Therefore, the nine center of gravities are representative of the basic quality aggregates' buyers in *Loire-Atlantique*.

Locations of the "basic quality aggregates" sellers in *Loire-Atlantique* have been marked on the map (Figure IV. 3) according to the postal codes of the created lists of the sellers_ quarries and recycling facilities_ (presented in Table F. 1 and Table F. 2 in Appendix F).

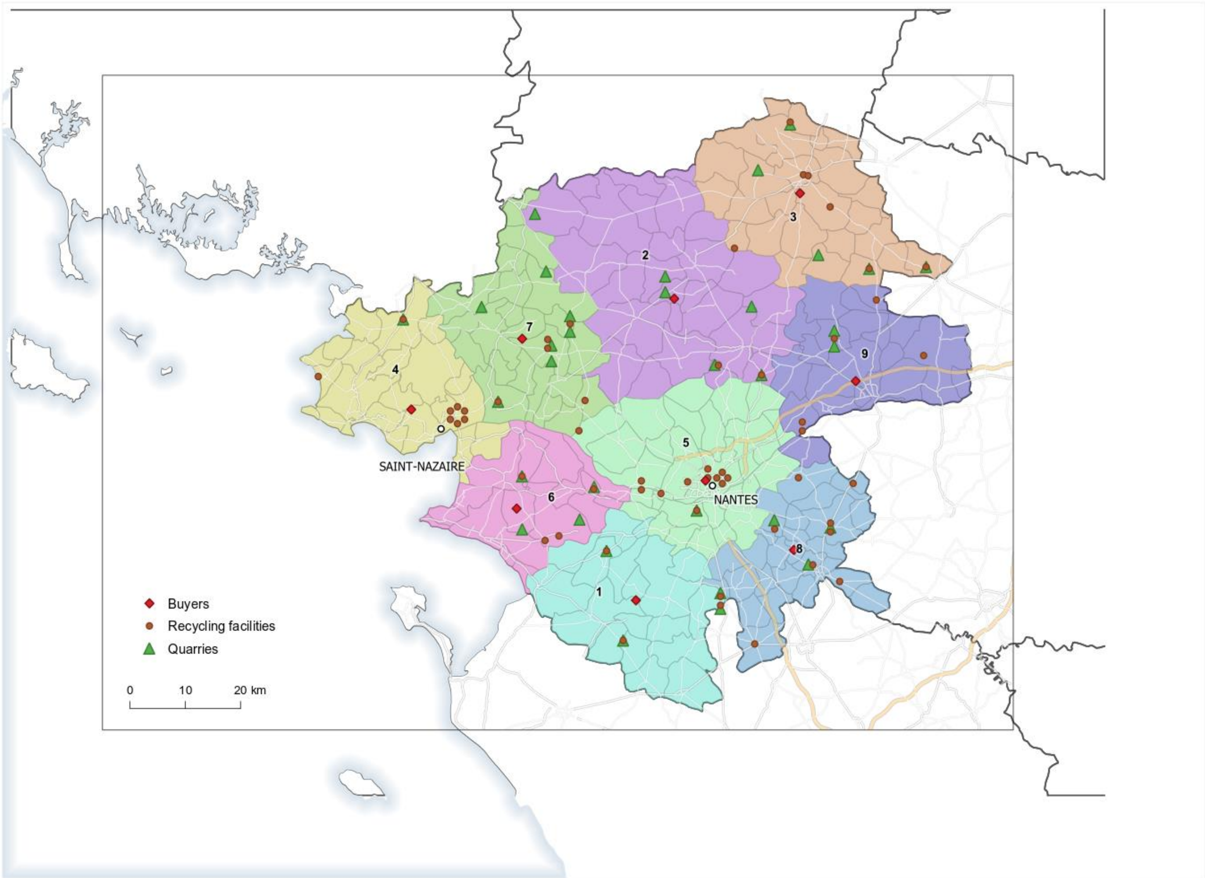


Figure IV. 3 Map of Loire-Atlantique divided into nine segments, with all sellers (quarries and recycling facilities) and nine buyers (center of gravities of each segment) of basic quality aggregates in Loire-Atlantique, France, using GIS.

Table IV. 2 Populations of the segments in Figure IV. 3

Segment	**Population of the segment (year 2012)**
1	62,739
2	79,170
3	40,420
4	192,771
5	657,536
6	60,229
7	76,960
8	94,673
9	63,145
Total population of Loire-Atlantique (year 2012)	**1, 327,643**

As can be noticed in Figure IV. 3, quarries are mainly located in the areas with low population. There are few quarries in segments 4 and 5, which have the highest population and subsequently is expected to have higher demands for basic quality aggregates. On the contrary, recycling facilities are mainly located in the highly populated areas. They are close to the places where there is higher demand.

4.2.3 Productions and consumptions of materials in *Loire-Atlantique*

Data from literature, statistics and facilities have been used to estimate the productions and consumptions of materials in the territorial environmental model of CCDW management (Figure II. 34) in *Loire-Atlantique* in 2012. All data required for our model are not provided, especially the total CCDW generation and detailed demands for A1 and A2. Therefore, some assumptions needed to be made. They are discussed in detail in this section. Values concerning the productions and consumptions of materials in *Loire-Atlantique* in 2012 are presented in Table G. 1 in Appendix G.

Data on the total CCDW generated from building demolition in *Loire-Atlantique* have been estimated from literature. The total amount of Construction and Demolition Waste (CDW) generated per capita in France is assumed to be about 5.9 tons/year (Pacheco-Torgal et al., 2013). Therefore, total CDW generated in *Loire-Atlantique* in 2012 can be estimated as follow:

$$M_{CDW_{Loire-Atlantique}}(Y_n) = Pop_{Loire-Atlantique}\,(Y_n) * CDW_{capita} \qquad \text{IV. 2}$$

Where $M_{CDW_{Loire-Atlantique}}(Y_n)$ is the total CDW generated (ton) in Loire-Atlantique in 2012, $Pop_{Loire-Atlantique}(Y_n)$ is the population of Loire-Atlantique in 2012 (can be found in Table IV. 2) and CDW_{capita} is CDW generated (ton) per capita in France, which is assumed to be 5.9 tons.

It is assumed that about 40% of the total CDW is concrete waste (Sonawane and Pimplikar, 2013). Therefore, CCDW generated in *Loire-Atlantique* in 2012 can be estimated from equation (IV. 3).

$$M_{CCDW_{Loire-Atlantique}}(Y_n) = m_{CCDW} * M_{CDW_{Loire-Atlantique}}(Y_n) \qquad \text{IV. 3}$$

$M_{CCDW_{Loire-Atlantique}}(Y_n)$ is the total CCDW generated (ton) in Loire-Atlantique in year 2012, m_{CCDW} is the mass ratio of CCDW in the total CDW generated, which is assumed to be 40%, and $M_{CDW_{Loire-Atlantique}}(Y_n)$ is the total CDW generated (ton) in Loire-Atlantique in the same year (see equation IV. 2).

In order to figure out the total consumption of materials in the territorial environmental model of CCDW management in *Loire-Atlantique* in 2012, CERC database (CERC, n.d.) has been used as the main source. However, some assumptions have been made based on Charier Company's database to obtain some missing data. They are discussed in detail as follows.

The CERC database provides the total consumption of cement concrete in *Loire-Atlantique* in 2012 from which the total demand for A3CC can be calculated based on equation III. 4. The CERC database also provides data regarding bituminous concrete production in 2012 in *Loire-Atlantique*, but not consumption. Therefore, it has been assumed that bituminous concrete is produced as much as it is consumed. As a result, from equation (III. 5) the total demand for A3BC is calculated. Accordingly, the total demand for A3 in 2012 in *Loire-Atlantique* is obtained from equation (III. 3).

Subsequently, the total productions of A1 and A2 are estimated from equations (III. 6) and (III. 7) respectively, using mass ratios in equation (IV. 1). However, no precise data were found regarding the demands for A1 and A2. The total demands for A1, A2 and A3 from Charier Company's quarries are known (presented Table IV. 3). Accordingly, the demand proportions for A1, A2, and A3 in Charier Company's quarries are estimated. We assume that they are representative of all quarries in *Loire-Atlantique*. Therefore, these proportions have been used to estimate the total demands for A1 and A2, D_{A1} and D_{A2} respectively, in Loire-Atlantique in 2012, given that the total demand for A3 in Loire-Atlantique is known.

Table IV. 3 demand for the products and related mass ratios in Charier Company's quarries.

Products in the quarries	**Demanded product from Charier Company's quarries in (ton)**	**Mass ratio (%)**
A1	1,197,500	34.1
A2	719,000	20.5
A3	1,596,000	45.4
Total	3,512,500	100

In addition, CERC database provides the total demand for RCC, D_{RCC}, in Loire-Atlantique in 2012 (see Table G. 1 in Appendix G*)*.

As basic quality aggregates can be provided by both quarries and recycling facilities, the total demand for basic quality aggregates, D_{BQA}, in the basic quality aggregate market (Market 3 in Figure II. 34) in *Loire-Atlantique* in 2012 is the summation of D_{A1} and D_{RCC} in 2012 in *Loire-Atlantique*. Subsequently, the total demand of each of the nine buyers for basic quality aggregates in each of nine segments (see Figure IV. 3) can be estimated as well from equation (III. 21), and they have been presented in Table G. 2 in appendix G.

Data presented in this section on production and consumption of materials in the territorial environmental model of CCDW management in *Loire-Atlantique* in 2012 (Figure II. 34) are considered as the current situation in the territory and as a reference scenario for the environmental analysis to be compared with other scenarios. It should be noted that, since these data are mostly related to year 2012, thus current situation refers to year 2012.

4.3 Reference scenario: current situation in *Loire-Atlantique* associated with CCDW management

In this section results related to the reference scenario, which reflects the current situation in *Loire-Atlantique* (as discussed in section 4.2.3), are presented.

4.3.1 MFA of CCDW management in *Loire-Atlantique*

Figure IV. 4 shows the material flows of the territorial CCDW management in *Loire-Atlantique* for the reference scenario. As can be seen from Figure IV. 4, approximately 4,908.2 kilotons of natural aggregates are produced in the territory to meet the demands of Market 1, Market 2, Market 3 and Market 4. A3 is the largest natural aggregates consumed to produce cement concrete and bituminous concrete. According to Figure IV. 4, 13% of the total A1 produced in the quarry is stored in the stock, since for which there is no demand in Market 3.

A large amount of CCDW is generated in *Loire-Atlantique* in 2012 (3,133.2 kilotons) of which 96% (LCCDW) is disposed in the landfill in the reference scenario. It should be noted that LCCDW also represents the amount of CCDW that is used for quarry filling. Although from a regulation perspective quarry filling is considered as waste valorization rather than landfilling, quarry filling and landfilling are similar from an environmental point of view. Therefore, they are shown as the same process. Flow of CCDW to the recycling process (RCCDW) is calculated according to equation (III. 13) and considering 90% technical efficiency for the recycling facilities in *Loire-Atlantique*.

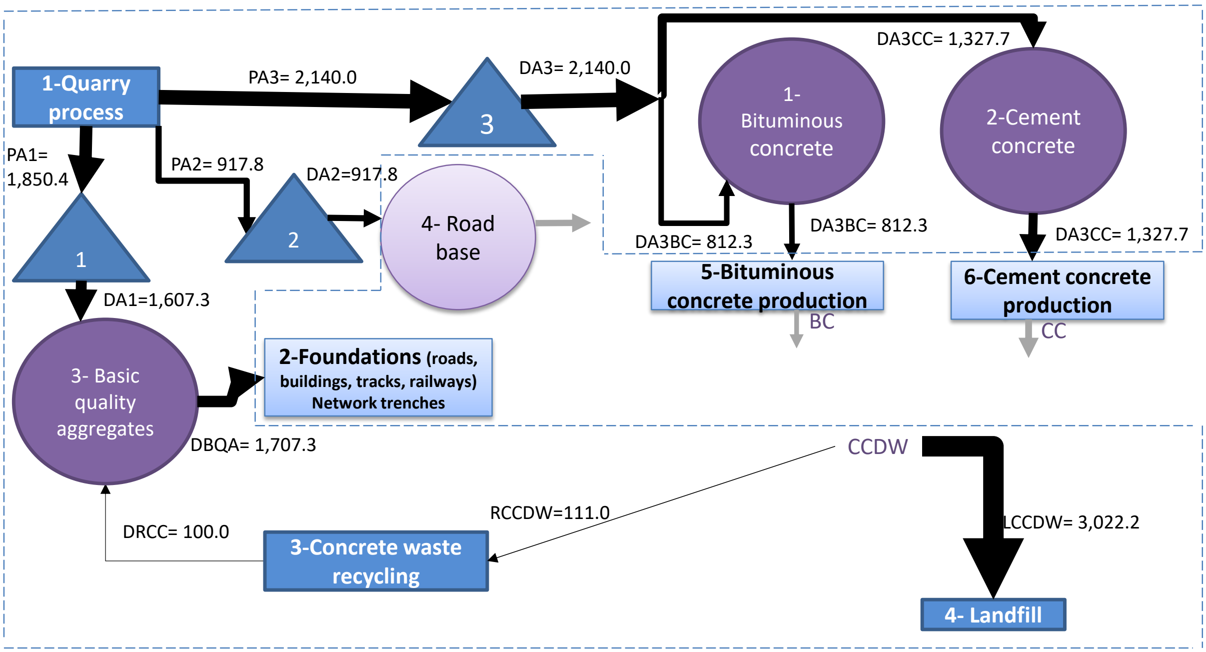


Figure IV. 4 MFA of CCDW management in Loire-Atlantique in 2012 for the "reference scenario". All units are kiloton (Kt).

Legend

Process

Stock

Flow

Market

RCC: Recycled Cement Concrete

A1: primary category of natural aggregates

CCDW: Cement Concrete Demolition Wastes

A2: secondary category of natural aggregates

A3: tertiary category of natural aggregates

P_{A2}: produced A2

P_{A3}: produced tertiary category of natural aggregates in the quarry

Stock 3: stockpile of produced A3 in the quarry

D_{A3}: demand for tertiary category of natural aggregates

D_{A3BC}: demand for A3 in bituminous concrete market

D_{A3CC}: demand for A3 in cement concrete market

Market 2: market for cement concrete

Market 1: market for bituminous concrete

CC: cement concrete

BC: bitumenous concrete

P_{A1}: produced A1

Stock 1: stockpile of produced A1

Stock 2: stockpile of produced A2

D_{A1}: demand for A1 in basic quality aggregate market

D_{A2}: demand for A2 in road base market

Market 3: market for basic quality aggregates

Market 4: market for road base

D_{RCC}: demand for RCC

D_{BQA}: demand for basic quality aggregates

RCCDW: *fraction (R) of CCDW sent to the recycling facilities*

LCCDW: *fraction (L) of CCDW sent to the landfill*

4.3.2 Total demand for A1 and RCC and transportation distances of the demanded A1 and RCC

The total demands for A1 and RCC in Market 3 for the reference scenario were calculated from the statistical data and different assumptions (as discussed in section 4.2.3). The values are presented in Appendix G, Table G. 1. Therefore, the demand of each buyer for A1 and RCC is calculated from equation (III. 24) and equation (III. 25) respectively. Algorithms presented in Figure III. 8 and Figure III. 9 are used to investigate how the total demands for A1 and RCC are distributed between different quarries and recycling facilities respectively.

Table IV. 4 and Table IV. 6 resulting from Figure III. 8 and Figure III. 9 show the demands of the nine buyers for A1 and RCC respectively from different quarries and recycling facilities. Table IV. 5 and Table IV. 7 resulting from Figure III. 8 and Figure III. 9 respectively show transportation distances between the buyers and different quarries and recycling facilities.

As can be seen from Table IV. 4, each buyer travels to several quarries to meet his demand for A1, except for buyers 3, 6 and 8. According to Table IV. 6, almost one recycling facility is enough for the buyers to meet their demands for RCC, except for buyers 4 and 5, since they have the highest population and subsequently the highest demand for basic quality aggregates. Based on the procedures illustrated in Figure III. 8 and Figure III. 9, buyers were expected to select the closest sellers. This can be seen from Table IV. 5 and Table IV. 7. Recycling facilities chosen by the buyers are located in the same segment as the one of the buyers.

From Table IV. 4 and Table IV. 5 and equation (III. 22) the total ton-kilometer for the demanded A1 from different quarries is estimated. Likewise, from Table IV. 6 and Table IV. 7 and equation (III. 23) the total ton-kilometer for the demanded RCC from different recycling facilities is estimated. The values related to the reference scenario are shown in equation (IV. 4)

$$D_{A1}.\, d_{Q_{ref.scenario}} = 25{,}202{,}782.9\ ;\ D_{RCC}.\, d_{Rec_{ref.scenario}} = 626{,}556.0 \qquad \text{IV. 4}$$

*Where $D_{A1}.\, d_{Q_{ref.scenario}}$ and $D_{RCC}.\, d_{RCC_{ref.scenario}}$ are the total ton-kilometer resulting from the demands of A1's buyers from different quarries and the total ton-kilometers resulting from the demands of RCC's buyers from different recycling facilities in Loire-Atlantique respectively related to the reference scenario. The values are in ton*km.*

Table IV. 4 Demands of the nine buyers for A1 from different quarries ($D_{A1_{m,Qi}}$) resulting from Figure III. 8 and the total demand for A1 in Market 3 in 2012 for the reference scenario. Figures in the table are in metric tons.

Quarries / $\boldsymbol{D_{A1_{m,Qi}}}$**(ton)**	$\boldsymbol{D_{A1_{1,Qi}}}$	$\boldsymbol{D_{A1_{2,Qi}}}$	$\boldsymbol{D_{A1_{3,Qi}}}$	$\boldsymbol{D_{A1_{4,Qi}}}$	$\boldsymbol{D_{A1_{5,Qi}}}$	$\boldsymbol{D_{A1_{6,Qi}}}$	$\boldsymbol{D_{A1_{7,Qi}}}$	$\boldsymbol{D_{A1_{8,Qi}}}$	$\boldsymbol{D_{A1_{9,Qi}}}$	**Total demand for A1 from each quarry**
La Mariais				226,200.0						226,200.0
Les Maraîchères					207,265.6					207,265.6
La Faubretière et Les Rocherons					207,350.0					207,350.0
La Margerie								114,616.5		114,616.5
La Clarté				7,179.4						7,179.40
La Coche	48,794.0									48 794.0
Les Mortiers									26,155.0	26,155.0
La Guibourgère									37,474.2	37,474.2
Le Bois de la Roche			48,934.7							48,934.7
Le Petit Betz							37,700.0			37,700.0
Landes Coeffard		10,421.0					6,678.5			17,099.5
La Métairie Neuve							48,793.5			48,793.5
La Bobatière	18,850.0									18,850.0
La Vallée		14,835.0								14,835.0
L'Ennerie						72,916.6				72,916.6
La Recouvrance					116,710.2					116,710.2
La Lande du Cens		14,835.3								14,835.3
La Guillonnais		15,834.0								15,834.0
La Pommeraie		39,922.4			107,532.0				12,817.7	160,272.1
La Gagnerie	8,311.4				51,801.6					60,113.0
La Grande Garde					105,390.7					105,390.7
Total demand of each buyer for A1 ($\boldsymbol{D_{A1_m}}$**)**	75,955.4	95,847.7	48,934.7	233,379.4	796,050.1	72,916.6	93,172.0	114,616.5	76,446.9	$\boldsymbol{D_{A1}}$ **=1, 607,319.3**

Legend

$D_{A1_{m,Qi}}$ *Demand of buyer mth for A1 from quarry Qith (ton).*

D_{A1_m} *Total demand of buyer mth for A1 (ton)*

D_{A1} *Total demand for A1 in Market 3 (ton)*

Table IV. 5 Transportation distances between the nine buyers of A1 and different quarries ($d_{m,Qi}$) resulting from Figure III. 8 for the reference scenario. Distances were measured by QGIS tool. Figures in the table are in kilometer.

Quarries / $d_{m,Qi}$**(km)**	$d_{1,Qi}$	$d_{2,Qi}$	$d_{3,Qi}$	$d_{4,Qi}$	$d_{5,Qi}$	$d_{6,Qi}$	$d_{7,Qi}$	$d_{8,Qi}$	$d_{9,Qi}$
La Mariais				18.93					
Les Maraîchères					9.57				
La Faubretière et Les Rocherons					16.56				
La Margerie								5.57	
La Clarté				20.93					
La Coche	13.29								
Les Mortiers									12.59
La Guibourgère									12.59
Le Bois de la Roche			11.95						
Le Petit Betz							10.94		
Landes Coeffard		25.91					10.94		
La Métairie Neuve							10.76		
La Bobatière	9.07								
La Vallée		17.07							
L'Ennerie						2.74			
La Recouvrance					23.23				
La Lande du Cens		1.95							
La Guillonnais		1.95							
La Pommeraie		26.67			25.14				19.36
La Gagnerie	22.23				24.20				
La Grande Garde					24.20				

Legend

$d_{m,Qi}$ *Transportation distance between buyer mth and quarry Qith (km).*

Table IV. 6 Demands of the nine buyers for RCC from different recycling facilities ($D_{RCC_{m,Reci}}$) resulting from Figure III. 9 and the total demand for RCC in Market 3 in 2012 for the reference scenario. Figures are in metric tons.

Recycling facilities / $D_{RCC_{m,Reci}}$**(ton)**	$D_{RCC_{1,RCCi}}$	$D_{RCC_{2,RCCi}}$	$D_{RCC_{3,RCCi}}$	$D_{RCC_{4,RCCi}}$	$D_{RCC_{5,RCCi}}$	$D_{RCC_{6,RCCi}}$	$D_{RCC_{7,RCCi}}$	$D_{RCC_{8,RCCi}}$	$D_{RCC_{9,RCCi}}$	**Total demand for RCC from each facility**
FOCAST CHATEAUBRIANT			3,044.5							3,044.5
Sablières de l'Atlantique				12,319.0						12,319
OTCM				2,200.8						2,200.8
LAFARGE GRANULATS FRANCE (CHAUMES EN RETZ)						4,536.5				4,536.5
CARRIERE AUBRON ET MECHINEAU								7,130.9		7,130.9
CARRIERES GSM (TEILLE)									4,756.2	4,756.2
SOCAC-STE DES CARRIERES DE CAMPBON							5,796.7			5,796.7
TIMAC AGRO SAS					12,319.0					12,319.0
SAREMER					250.6					250.6
2B RECYCLAGE					12,319.0					12,319.0
ALCEA					12,319.0					12,319.0
SYNDICAT MIXTE CENTRE NORD ATLANTIQUE		5,963.2								5,963.2
GUINGAMP	4,725.6									4,725.6
TEN (TOLERIE EMAILLERIE NANTAISE)					12,319.0					12,319.0
Total demand of each buyer for RCC (D_{RCC_m})	4,725.6	5,963.2	3,044.5	14,519.8	49,526.6	4,536.5	5,796.7	7,130.9	4,756.2	D_{RCC} =100,000.0

Legend

$D_{RCC_{m,Reci}}$	*Demand of buyer m^th for RCC from recycling facility Reci^th (ton).*
D_{RCC_m}	*Total demand of buyer m^th for RCC (ton).*
D_{RCC}	*Total demand for RCC in Market 3 (ton).*

Table IV. 7 Transportation distances between the nine buyers and different recycling facilities resulting from Figure III. 9 for the reference scenario. Distances were measured by QGIS tool. Figures are in kilometer.

Recycling facilities / $d_{m,Reci}$ **(km)**	$d_{1,Reci}$	$d_{2,Reci}$	$d_{3,Reci}$	$d_{4,Reci}$	$d_{5,Reci}$	$d_{6,Reci}$	$d_{7,Reci}$	$d_{8,Reci}$	$d_{9,Reci}$
FOCAST CHATEAUBRIANT			3.53						
Sablières de l'Atlantique				10.02					
OTCM				10.02					
LAFARGE GRANULATS FRANCE (CHAUMES EN RETZ)						5.96			
CARRIERE AUBRON ET MECHINEAU								5	
CARRIERES GSM (TEILLE)									12.59
SOCAC-STE DES CARRIERES DE CAMPBON							10.94		
TIMAC AGRO SAS					4.31				
SAREMER					4.31				
2B RECYCLAGE					1.75				
ALCEA					1.75				
SYNDICAT MIXTE CENTRE NORD ATLANTIQUE		16.39							
GUINGAMP	9.07								
TEN (TOLERIE EMAILLERIE NANTAISE)					3.77				

Legend

$d_{m,Reci}$ *Transportation distance between buyer m^th^ and recycling facility Reci^th^ (km).*

4.3.3 Current share of Market 3 from A1 and RCC (*f1* and *f2*)

According to the data presented in section 4.2.3, shares of A1 and RCC in Market 3 related to the reference scenario or current situation in the territory can be estimated from equations (III. 8) and (III. 9) respectively. Their values are presented in equation (IV. 5):

$$f1_{ref.scenario} = 94\%; f2_{ref.scenario} = 6\% \qquad \text{IV. 5}$$

Where $f1_{ref.scenario}$ and $f2_{ref.scenario}$ are shares of A1 and RCC respectively in Market 3 related to the reference scenario.

4.3.4 Environmental impact assessment results

Table IV. 8 illustrates the contributions of the territorial environmental model of CCDW management related to the reference scenario (Figure IV. 4) to a range of environmental impacts. In addition, Table IV. 8 shows a given environmental impact translated into the number of European inhabitants which would generate the same impact, using the normalization factors in Table III. 1 and also their proportion to the total population of *Loire-Atlantique*.

Table IV. 8 Environmental impact indicator results of the territorial environmental model of CCDW management (Figure IV. 4) in Loire-Atlantique for the reference scenario and normalized values of the environmental impacts.

Environmental Impact Category	**Total amount**	**Unit**	**Normalized value (European inhabitant/year)**	**Normalized value relative to Loire-Atlantique's population (%)**
Acidification potential, average European	1,682,694.4	Kg SO_2- Eq	946,397.3	71.3
Eutrophication potential, average European	1,022,723.9	Kg NOx- Eq	16,865.5	1.3
Resources, depletion of abiotic resources	2,603,304.0	Kg antimony- Eq	41,191,519.0	31 times of Loire-Atlantique's population
Stratospheric ozone depletion, ODP total	245.9	Kg CFC-11- Eq	10,508.5	0.8
Climate change, GWP 100a	322,790,715.6	Kg CO_2- Eq	38,427.5	2.9
Ionizing radiation, IRP_HE	2,117,584,779.1	Kg U235- Eq	501,797.3	37.8
Urban land occupation, ULOP	6,938,052.8	m^2a	505,320.7	38.1
Human health, respiratory effects, average	429,574.2	Kg PM2.5- Eq	-	-
Ecotoxicity, total	1,302,845,056.8	CTU	-	-
Human toxicity, total	163.6	CTU	-	-
Fossil cumulative energy demand	4,419,992,986.5	MJ- Eq	67,687.5	5.1
Nuclear cumulative energy	27,366,109,799.8	MJ- Eq	-	-

Normalized values in Table IV. 8 reveal that the acidification, depletion of abiotic resource, Ionizing radiation and urban land occupation indicators are more considerable than other environmental impacts. The contribution to ionizing radiations and urban land occupation is about 40% of *Loire-Atlantique* inhabitants and around 70% for acidification. The contribution

of the territory to the depletion of the abiotic resources is about 3100% of *Loire-Atlantique*'s population. This result shows that, *Loire-Atlantique* is likely above other European regions concerning construction and aggregate production.
Figure IV. 5 shows the relative contributions of the processes included in Figure IV. 4 to 12 environmental impact categories presented in Table IV. 8 for the reference scenario. As can be noticed from Figure IV. 5, the main contributor to the environmental impact categories is the production of D_{A3CC} for Market 2, except for "urban land occupation" to which CCDW landfilling is the main contributor (43.9%). This is mainly due to the assumption that we made, that CCDW which is not recycled is disposed into the landfill (and quarry filling considered having the same environmental impacts as landfill). In this reference scenario a significant part of CCDW is landfilled (96%). The production of D_{A1} and D_{RCC} for Market 3 is the second contributor after the production of D_{A3CC} for Market 2 (with a slight difference _ 6%). Stock of unused A1 contributes to 3.1-3.8% of the total environmental impacts.

According to Figure IV. 5, transportation in Markets 1, 2 and 3 does not contribute to the environmental impacts significantly compared to other processes included in the territory. The result is reasonable, as regarding to Figure IV. 4 huge amounts of natural aggregates are produced in the quarry. However, transportation distances for heavy materials, such as construction materials, are usually limited due to the transportation prices. Transportation distance in Market 1 and 2 has been considered to be 30 km, as an average distance between quarries and bituminous concrete plants/ cement concrete plants.

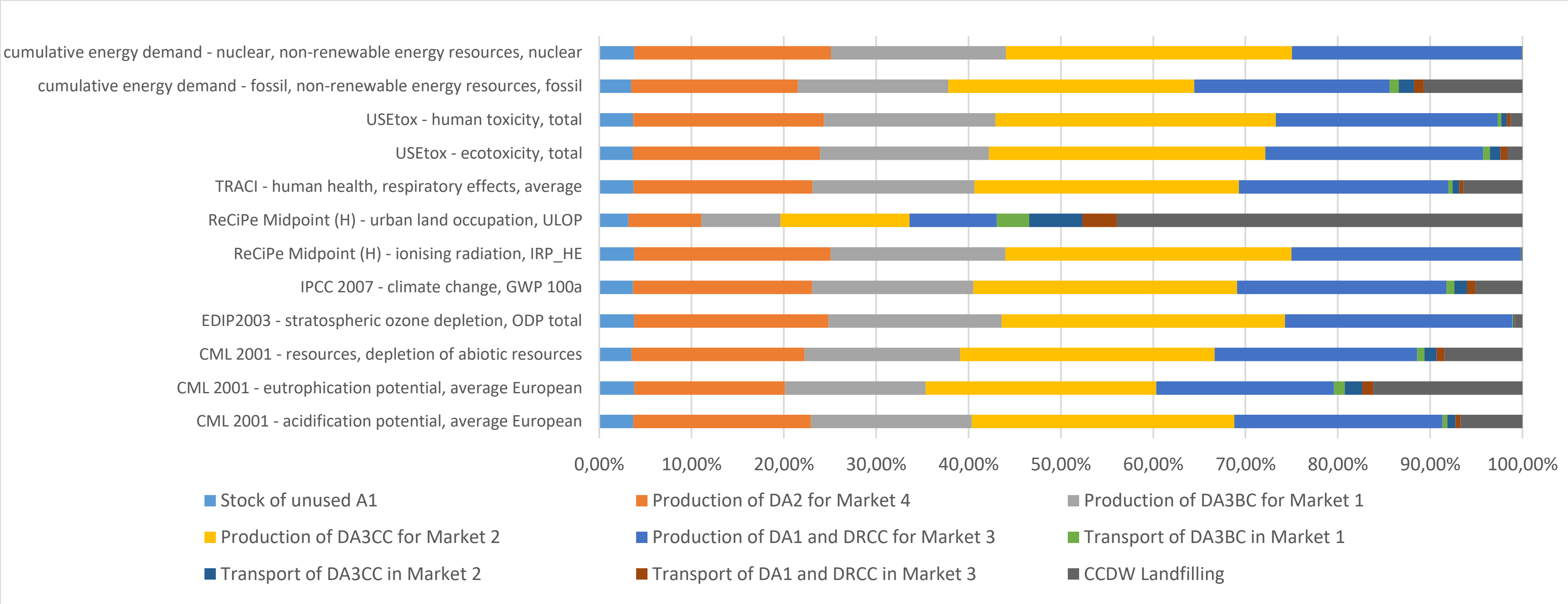


Figure IV. 5 Relative contributions of the processes included in the territorial environmental model of CCDW management (Figure IV. 4) to 12 environmental impact categories for the reference Scenario. Stock of unused A1 includes the environmental impacts from production of unused A1 and stock itself, production of the demanded A2 (D_{A2}) in Market 4, production of the demanded A3BC (D_{A3BC}) in the bituminous concrete market (Market 1), production of the demanded A3CC (D_{A3CC}) in the cement concrete market (Market 2), production of the demanded RCC (D_{RCC}) and demanded A1 (D_{A1}) in the basic quality aggregate market (Market 3), transport distance between the distributers and the users of A3BC and A3CC considered 30km, Transport of D_{A1} and D_{RCC} in Market 3= transportation distances of D_{A1} and D_{RCC} from the quarries and the recycling facilities respectively to the related buyers, CCDW landfilling= landfilling of unused CCDW in the territory.

4.4 Scenario 1: Price-based market mechanism

This section presents the results of Scenario 1. In Scenario 1, we have assumed that the mechanisms in Market 3 are price-based and there is no psychological obstacle to use RCC. Therefore, the nine buyers of basic quality aggregates make choices in the market based on the total prices of A1 and RCC (as discussed in detail in section 3.5.13.5.2).

4.4.1 MFA of CCDW management in *Loire-Atlantique*

Figure IV. 6 shows the material flows of the territorial CCDW management in *Loire-Atlantique* for Scenario 1. As can be seen from Figure IV. 6, approximately 4,908.2 kilotons of natural aggregates are produced in the territory to meet the demands of Market 1, Market 2, Market 3 and Market 4. A3 is the largest natural aggregates consumed to produce cement concrete and bituminous concrete. According to Figure IV. 6, 43% of the total A1 produced in the quarry is stored in the stock. 33% of the total CCDW generated in the territory is recycled in Scenario 1.

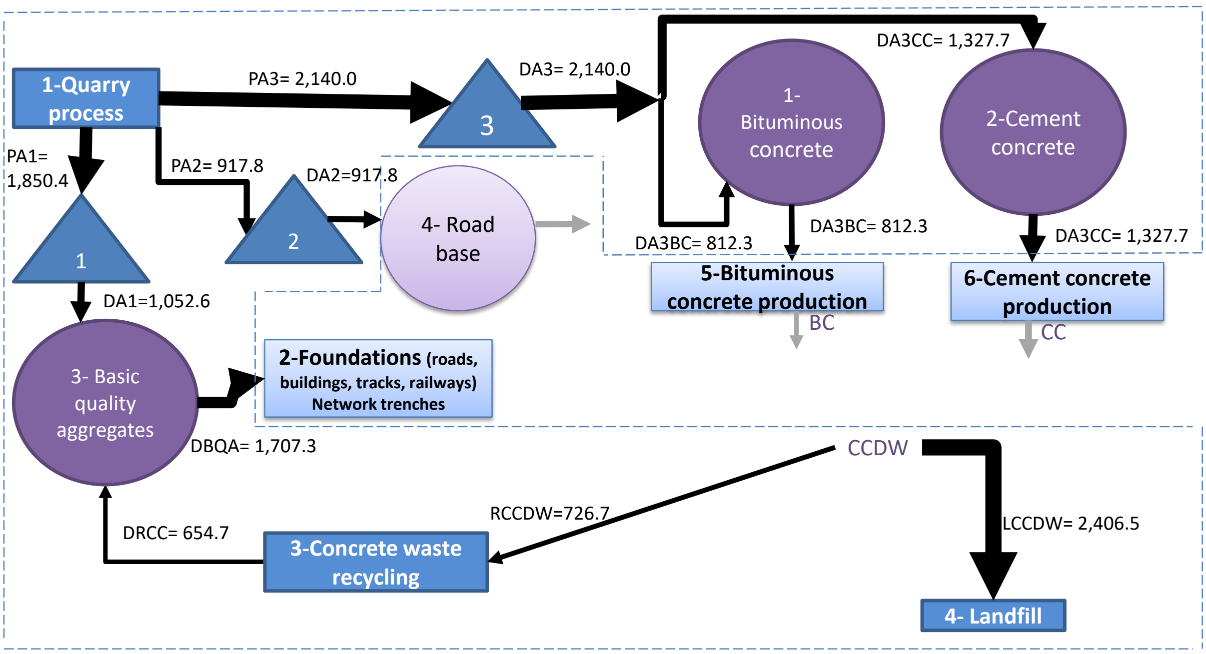


Figure IV. 6 MFA of CCDW management in Loire-Atlantique for "Scenario 1". All units are kiloton (Kt).

Legend

Process | Flow

Stock | Market

RCC: Recycled Cement Concrete

A1: primary category of natural aggregates

CCDW: Cement Concrete Demolition Wastes

A2: secondary category of natural aggregates

A3: tertiary category of natural aggregates

P_{A2}: produced A2

P_{A3}: produced tertiary category of natural aggregates in the quarry

Stock 3: stockpile of produced A3 in the quarry

D_{A3}: demand for tertiary category of natural aggregates

D_{A3BC}: demand for A3 in bituminous concrete market

D_{A3CC}: demand for A3 in cement concrete market

Market 2: market for cement concrete

Market 1: market for bituminous concrete

CC: cement concrete

BC: bitumenous concrete

P_{A1}: produced A1

Stock 1: stockpile of produced A1

Stock 2: stockpile of produced A2

D_{A1}: demand for A1 in basic quality aggregate market

D_{A2}: demand for A2 in road base market

Market 3: market for basic quality aggregates

Market 4: market for road base

D_{RCC}: demand for RCC

D_{BQA}: demand for basic quality aggregates

RCCDW: *fraction (R) of CCDW sent to the recycling facilities*

LCCDW: *fraction (L) of CCDW sent to the landfill*

4.4.2 Total demand for A1 and RCC and transportation distances of the demanded A1 and RCC

Table IV. 9 and Table IV. 11 resulting from Figure III. 7 for Scenario 1show the demands of the nine buyers for A1 and RCC and the total demands for A1 and RCC in Market 3. Table IV. 10 and Table IV. 12 resulting from Figure III. 7 for Scenario 1 show traveling distances between the buyers and different quarries/recycling facilities to meet their demand for basic quality aggregates.

Based on the procedures in Figure III. 7 for Scenario 1, the nine buyers of basic quality aggregates choose RCC when a recycling facility and a quarry have the same location. This is due to the 0.5 € difference between the price of 1 ton of A1 in the quarries and prices of 1 ton of RCC in the recycling facilities (see section 4.2.1.4). Results of Table IV. 10 and Table IV. 12 show that in some cases the basic quality aggregates' buyers chose RCC, even if they had to travel longer distances, since the total price of 1 ton of RCC was less than that of A1. For instance, buyer 5 chose the recycling facility "BAGLIONE SA" first, which is 23.45 km away from buyer 5, and then chose the quarry "Les Maraîchères", which is 9.57 km away from the buyer.

From Table IV. 9 and Table IV. 10 and equation (III. 22) the total ton-kilometer for the demanded A1 from different quarries is estimated. Likewise, from Table IV. 11 and Table IV. 12 and equation (III. 23) the total ton-kilometer for the demanded RCC from different recycling facilities is estimated. The values related to Scenario 1 are shown in equation (IV. 6).

$$D_{A1}.\, d_{Q_{Sc1}} = \ 16{,}987{,}784.1\ ;\, D_{RCC}.\, d_{Rec_{Sc1}} = 8{,}290{,}328.8 \qquad \text{IV. 6}$$

*Where $D_{A1}.\, d_{Q_{Sc1}}$ and $D_{RCC}.\, d_{RCC_{Sc1}}$ are the total ton-kilometer resulting from the demands of A1's buyers from different quarries and the total ton-kilometer resulting from the demands of RCC's buyers from different recycling facilities in Loire-Atlantique respectively related to Scenario 1. The values are in ton*km.*

Table IV. 9 Demands of the nine buyers for A1 from different quarries ($D_{A1_{m,Qi}}$) and the total demand for A1 in Market 3 resulting from Figure III. 7 for Scenario 1. Figures in the table are in metric tons.

Quarries / $D_{A1_{m,Qi}}$**(ton)**	$D_{A1_{1,Qi}}$	$D_{A1_{2,Qi}}$	$D_{A1_{3,Qi}}$	$D_{A1_{4,Qi}}$	$D_{A1_{5,Qi}}$	$D_{A1_{6,Qi}}$	$D_{A1_{7,Qi}}$	$D_{A1_{8,Qi}}$	$D_{A1_{9,Qi}}$	**Total demand for A1 from each quarry**
La Mariais				154,065.2						154,065.2
Les Maraîchères					207,265.5					207,265.5
La Faubretière et Les Rocherons					207,350.0					207,350.0
La Margerie								35,514.3		35,514.3
La Coche	12,555.0									12,555.0
Les Mortiers									3,492.3	3,492.3
Le Petit Betz		37,700.0								37,700.0
Landes Coeffard		6,287.3								6,287.3
La Métairie Neuve							37,373.8			37,373.8
La Bobatière	18,850.0									18,850.0
La Vallée		14,835.3								14,835.3
L'Ennerie						28 177.2				28,177.2
La Recouvrance					116,710.1					116,710.1
La Lande du Cens		14,835.3								14,835.3
La Guillonnais		15,834.0								15,834.0
La Gagnerie					60,113.0					60,113.0
La Grande Garde					81,672.0					81,672.0
Total demand of each buyer for A1 (D_{A1_m})	31,405.0	89,491.9	0.0	154,065.2	673,110.6	28,177.2	37,373.8	35,514.3	3,492.3	D_{A1} **= 1 ,052,630.3**

Legend

$D_{A1_{m,Qi}}$ *Demand of buyer mth for A1 from quarry Qith (ton).*

D_{A1_m} *Total demand of buyer mth for A1 (ton)*

D_{A1} *Total demand for A1 in Market 3 (ton)*

Table IV. 10 Transportation distances between the nine buyers of A1 and different quarries ($d_{m,Qi}$) resulting from Figure III. 7 for Scenario 1. Distances were measured by QGIS tool. Figures in the table are in kilometer.

Quarries / $d_{m,Qi}$**(km)**	$d_{1,Qi}$	$d_{2,Qi}$	$d_{3,Qi}$	$d_{4,Qi}$	$d_{5,Qi}$	$d_{6,Qi}$	$d_{7,Qi}$	$d_{8,Qi}$	$d_{9,Qi}$
La Mariais				18.93					
Les Maraîchères					9.57				
La Faubretière et Les Rocherons					16.56				
La Margerie								5.57	
La Coche	13.29								
Les Mortiers									12.59
Le Petit Betz		25.91							
Landes Coeffard		25.91							
La Métairie Neuve							10.76		
La Bobatière	9.07								
La Vallée		17.07							
L'Ennerie						2.74			
La Recouvrance					23.23				
La Lande du Cens		1.95							
La Guillonnais		1.95							
La Gagnerie					24.20				
La Grande Garde					24.20				

Legend

$d_{m,Qi}$ *Transportation distance between buyer m^{th} and quarry Qi^{th} (km).*

Table IV. 11 Demands of the nine buyers for RCC from different recycling facilities ($D_{RCC_{m,Reci}}$) and the total demand for RCC in Market 3 resulting from Figure III. 7 for Scenario 1. Figures are in metric tons.

Recycling facilities / $D_{RCC_{m,Reci}}$(ton)	$D_{RCC_{1},RCCi}$	$D_{RCC_{2},RCCi}$	$D_{RCC_{3},RCCi}$	$D_{RCC_{4},RCCi}$	$D_{RCC_{5},RCCi}$	$D_{RCC_{6},RCCi}$	$D_{RCC_{7},RCCi}$	$D_{RCC_{8},RCCi}$	$D_{RCC_{9},RCCi}$	**Total demand for RCC from each facility**
FOCAST CHATEAUBRIANT			12,319.0							12,319.0
CHARIER CM - CARRIERES ET MATERIAUX							12,319.0			12,319.0
SOCIETE DES CARRIERES CHASSE					12,319.0					12,319.0
ARC EN CIEL					12,319.0					12,319.0
BAGLIONE SA					12,319.0					12,319.0
LAFARGE GRANULATS FRANCE(BOUGUENAIS)					12,319.0					12,319.0
EDF SA					12,319.0					12,319.0
SOFERTI					12,319.0					12,319.0
Pf Le Bréhet				7,601.0						7,601.0
Sablières de l'Atlantique				12,319.0						12,319.0
OTCM				12,319.0						12,319.0
IMERYS Metalcasting France				12,319.0						12,319.0
EQIOM				12,319.0						12,319.0
CHARIER TP				12,319.0						12,319.0
CETRA GRANULATS				12,319.0						12,319.0
SOCACHEM						12,319.0				12,319.0
CHARIER CM - CARRIERES ET MATERIAUX (LA HAIE FOUASSIERE)								12,319.0		12,319.0
CHARIER CM - CARRIERES ET MATERIAUX (Herbignac)				12,319.0						12,319.0
LAFARGE GRANULATS FRANCE (CHAUMES EN RETZ)						12,319.0				12,319.0
GAUTIER VALORISATION								12,319.0		12,319.0
CARRIERE BLANLOEIL								12,319.0		12,319.0
AGERA									12,319.0	12,319.0
CARRIERES GSM(ST PAZANNE)	12,319.0									12,319.0
CARRIERS ET MATERIAUX DU GRAND OUEST					12,319.0					12,319.0

CARRIERE AUBRON ET MECHINEAU								12,319.0		12,319.0
CARRIERES GSM (ROUANS)						12,319.0				12,319.0
CARRIERES GSM (TEILLE)									12,319.0	12,319.0
SOCIETE DRAGAGES D'ANCENIS			2,703.2						9,615.8	12,319.0
SOCAC - STE DES CARRIERES DE CAMPBON							12,319.0			12,319.0
SOCAC							12,319.0			12,319.0
LAFARGE GRANULATS FRANCE (CAMBON)							12,319.0			12,319.0
BOUYER LEROUX Structure SAS								12,319.0		12,319.0
TIMAC AGRO SAS					12,319.0					12,319.0
SAREMER					12,319.0					12,319.0
LAFARGE GRANULATS FRANCE - Secteur Ouest					12,319.0					12,319.0
GSM OUEST Pays de la Loire					12,319.0					12,319.0
2B RECYCLAGE					12,319.0					12,319.0
ALCEA					12,319.0					12,319.0
SYNDICAT MIXTE CENTRE NORD ATLANTIQUE		12,319.0								12,319.0
PHILVALOR									12,319.0	12,319.0
ECOTERRE DU CELLIER									6,500.0	6,500.0
BARBAZANGES TRI OUEST			12,319.0							12,319.0
GUINGAMP	12,319.0									12,319.0
DEDIENNE AUTOMOTIVE								12,319.0		12,319.0
BLANCHARD TP ECOCENTRE								12,319.0		12,319.0
TEN (TOLERIE EMAILLERIE NANTAISE)					12,319.0					12,319.0
ACTIPLAST									12,319.0	12,319.0
GROUPE MEAC SAS			12,319.0							12,319.0
TECHNA FRANCE NUTRITION							12,319.0			12,319.0
LAFARGE GRANULATS FRANCE			12,319.0							12,319.0
CARRIERES CHASSE (PETIT MARS)									12,319.0	12,319.0

LAFARGE GRANULATS FRANCE (ST COLOMBAN)	12,319.0									12,319.0
CARRIERES GSM (ST COLOMBAN)	12,319.0									12,319.0
CARRIERES CHASSE (ST VIAUD)						12,319.0				12,319.0
Total demand of each buyer for RCC (D_{RCC_m})	49,276.0	12,319.0	51,979.2	93,834.0	172,466.0	49,276.0	61,595.0	86,233.0	77,710.8	D_{RCC} = **654,689.0**

Legend

$D_{RCC_{m,Reci}}$ *Demand of buyer mth for RCC from recycling facility Recith (ton).*

D_{RCC_m} *Total demand of buyer mth for RCC (ton).*

D_{RCC} *Total demand for RCC in Market 3 (ton).*

Table IV. 12 Transportation distances between the nine buyers and different recycling facilities resulting from Figure III. 7 for Scenario 1. Distances were measured by QGIS tool. Figures in the table are in kilometer.

Recycling facilities / $d_{m,Reci}$ **(km)**	$d_{1,Reci}$	$d_{2,Reci}$	$d_{3,Reci}$	$d_{4,Reci}$	$d_{5,Reci}$	$d_{6,Reci}$	$d_{7,Reci}$	$d_{8,Reci}$	$d_{9,Reci}$
FOCAST CHATEAUBRIANT			3.53						
CHARIER CM - CARRIERES ET MATERIAUX							15.85		
SOCIETE DES CARRIERES CHASSE					14.32				
ARC EN CIEL					14.32				
BAGLIONE SA					23.45				
LAFARGE GRANULATS FRANCE(BOUGUENAIS)					9.57				
EDF SA					26.69				
SOFERTI					10.71				
Pf Le Bréhet				21.71					
Sablières de l'Atlantique				10.02					
OTCM				10.02					
IMERYS Metalcasting France				10.02					

EQIOM				10.02					
CHARIER TP				10.02					
CETRA GRANULATS				10.02					
SOCACHEM						8.97			
CHARIER CM - CARRIERES ET MATERIAUX (LA HAIE FOUASSIERE)								6.21	
CHARIER CM - CARRIERES ET MATERIAUX (Herbignac)				20.93					
LAFARGE GRANULATS FRANCE (CHAUMES EN RETZ)						5.96			
GAUTIER VALORISATION								9.74	
CARRIERE BLANLOEIL								9.74	
AGERA									20.67
CARRIERES GSM(ST PAZANNE)	13.29								
CARRIERS ET MATERIAUX DU GRAND OUEST					33.61				
CARRIERE AUBRON ET MECHINEAU								5	
CARRIERES GSM (ROUANS)						15.01			
CARRIERES GSM (TEILLE)									12.59
SOCIETE DRAGAGES D'ANCENIS			23.97						24.95
SOCAC - STE DES CARRIERES DE CAMPBON							10.94		
SOCAC							10.94		
LAFARGE GRANULATS FRANCE (CAMBON)							10.94		
BOUYER LEROUX Structure SAS								18.67	
TIMAC AGRO SAS					4.31				
SAREMER					4.31				
LAFARGE GRANULATS FRANCE - Secteur Ouest					4.31				
GSM OUEST Pays de la Loire					4.31				
2B RECYCLAGE					1.75				
ALCEA					1.75				

SYNDICAT MIXTE CENTRE NORD ATLANTIQUE		16.39							
PHILVALOR									15.94
ECOTERRE DU CELLIER									15.94
BARBAZANGES TRI OUEST			4.37						
GUINGAMP	9.07								
DEDIENNE AUTOMOTIVE								11.98	
BLANCHARD TP ECOCENTRE								13.83	
TEN (TOLERIE EMAILLERIE NANTAISE)					3.77				
ACTIPLAST									17.86
GROUPE MEAC SAS			9.85						
TECHNA FRANCE NUTRITION							23.32		
LAFARGE GRANULATS FRANCE			13.84						
CARRIERES CHASSE (PETIT MARS)									19.36
LAFARGE GRANULATS FRANCE (ST COLOMBAN)	22.23								
CARRIERES GSM (ST COLOMBAN)	22.23								
CARRIERES CHASSE (ST VIAUD)						9.88			

Legend

$d_{m,Reci}$ *Transportation distance between buyer m^th and recycling facility Reci^th (km).*

4.4.3 Share of Market 3 from A1 and RCC (*f1* and *f2*)

According to Table IV. 9 and Table IV. 11 resulting from Figure III. 7 for Scenario 1 and equations (III. 8) and (III. 9), the shares of A1 and RCC in Market 3 for Scenario 1 are calculated. Their values are shown in equation (IV. 7).

$$f1_{Sc1} = 62\%; f2_{Sc1} = 38\% \quad \text{IV. 7}$$

Where $f1_{Sc1}$ and $f2_{Sc1}$ are the shares of A1 and RCC in Market 3 respectively for Scenario 1 obtained from Figure III. 7 for Scenario 1.

According to equation (IV. 7), it is evident that the shares of A1 and RCC in Market 3 obtained from Scenario 1 are very different from those of the reference scenario (94% A1 and 6% RCC in Market 3) (see IV. 5). This means that if there was no preference for the buyers between A1 and RCC for basic quality aggregates in Market 3 and that their choices were exclusively based on the total prices of the products, the share of RCC in the market would reach 38%.

4.4.4 Environmental impact assessment results

Table IV. 13 illustrates the contributions of the territorial environmental model of CCDW management related to Scenario 1 (Figure IV. 6) to a range of environmental impacts. In addition, Table IV. 13 shows a given environmental impact translated into the number of European inhabitants which would generate the same impact, using normalization factors in Table III. 1 and also their proportion to the total population of *Loire-Atlantique*.

Table IV. 13 Environmental impact indicator results of the territorial environmental model of CCDW management (Figure IV. 6) in Loire-Atlantique for Scenario 1 and normalized values of the environmental impacts.

Environmental Impact Category	**Total amount**	**Unit**	**Normalized value (European inhabitant/ year)**	**Normalized value relative to Loire-Atlantique's population (%)**
Acidification potential, average European	1, 677,382.0	Kg SO_2- Eq	943,409.4	71.1
Eutrophication potential, average European	1, 019,747.7	Kg NOx- Eq	16,816.4	1.3
Resources, depletion of abiotic resources	2, 576,955.2	Kg antimony-Eq	40, 774,607.6	30 time of Loire-Atlantique's population
Stratospheric ozone depletion, ODP total	246.1	Kg CFC-11-Eq	10,517.1	0.8
Climate change, GWP 100a	322,090,166.8	Kg CO_2- Eq	38,344.1	2.9
Ionizing radiation, IRP_HE	2, 121, 381,273.5	Kg U235-Eq	502,697.0	37.9
Urban land occupation, ULOP	6, 624,867.7	m^2a	482,510.4	36.3
Human health, respiratory effects, average	428,633.7	Kg PM2.5-Eq	-	-
Ecotoxicity, tota	1, 301, 901,414.2	CTU	-	-
Human toxicity, total	163.58	CTU	-	-
Fossil cumulative energy demand	4, 361, 445,055.9	MJ- Eq	66,790.9	5

Nuclear cumulative energy	27, 417, 528,755.4	MJ- Eq	-	-

Normalized values in Table IV. 13 show that the acidification, depletion of abiotic resource, Ionizing radiation and urban land occupation indicators are more considerable than other environmental impacts as found for the reference scenario.
Figure IV. 7 shows the relative contributions of the processes included in Figure IV. 6 to 12 environmental impact categories presented in Table IV. 13 for Scenario 1.

As can be noticed from Figure IV. 7, the main contributor to the environmental impact categories is the production of D_{A3CC} for Market 2, except for “urban land occupation” to which CCDW landfilling is the main contributor (36.6%). This is mainly due to the assumption that we made, that CCDW which is not recycled is disposed into the landfill. In Scenario 1, 77% of CCDW is landfilled. The production of D_{A2} for Market 4 is the second contributor after the production of D_{A3CC} for Market 2. Stock of unused A1 contributes to 10.7-12.3% of the total environmental impacts.

According to Figure IV. 7, transportation in Markets 1, 2 and 3 does not contribute to the environmental impacts significantly compared to other processes included in the territory. The result is reasonable, as regarding to Figure IV. 6 huge amounts of natural aggregates are produced in the quarry. However, transportation distances for heavy materials, such as construction materials, are usually limited. Transportation distance in Market 1 and 2 has been considered to be 30 km, as an average distance between quarries and bituminous concrete plants/ cement concrete plants.

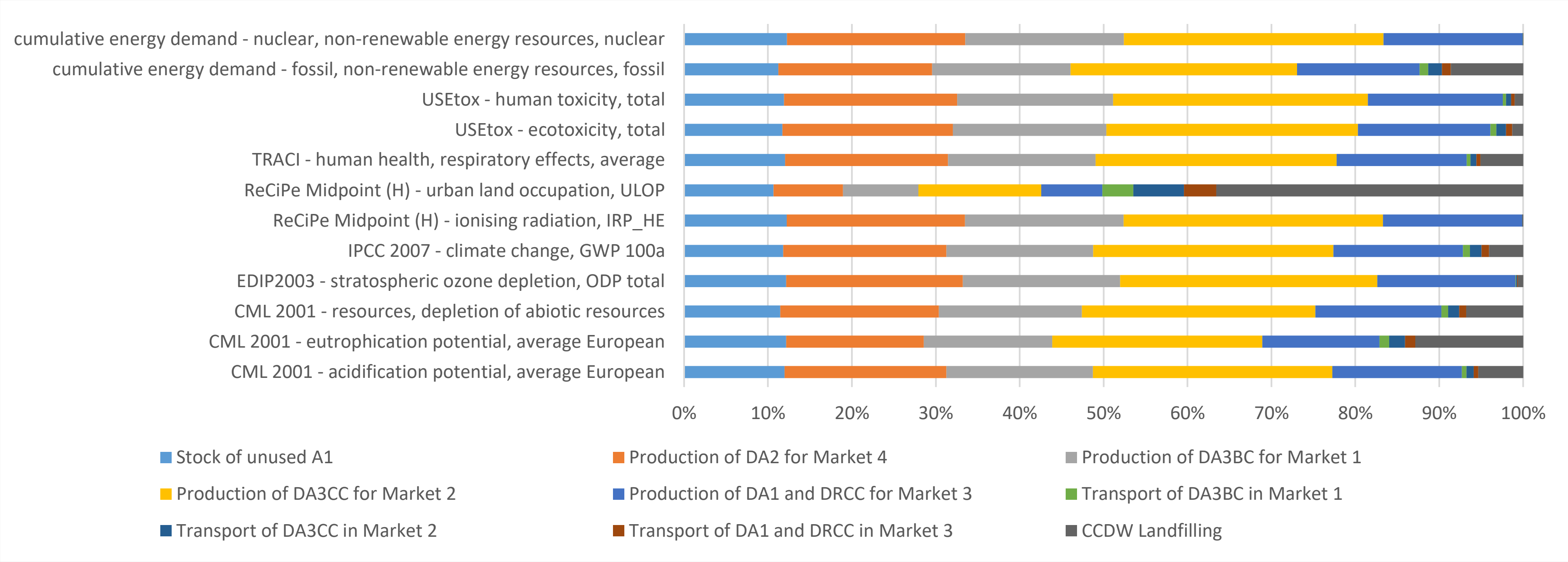


Figure IV. 7 Relative contributions of the processes included in the territorial environmental model of CCDW management (Figure IV. 6) to 12 environmental impact categories for Scenario 1. Stock of unused A1 includes the environmental impacts from production of unused A1 and stock itself, production of the demanded A2 (D_{A2}) in Market 4, production of the demanded A3BC (D_{A3BC}) in the bituminous concrete market (Market 1), production of the demanded A3CC (D_{A3CC}) in the cement concrete market (Market 2), production of the demanded RCC (D_{RCC}) and demanded A1 (D_{A1}) in the basic quality aggregate market (Market 3), transport distance between the distributers and the users of A3BC and A3CC considered 30km, Transport of D_{A1} and D_{RCC} in Market 3= transportation distances of D_{A1} and D_{RCC} from the quarries and the recycling facilities respectively to the related buyers, CCDW landfilling= landfilling of unused CCDW in the territory.

4.5 Scenario 2: price-based market mechanism model including a mistrust factor

This section presents the results of Scenario 2. In Scenario 2, we aimed at analyzing the sensitivity of the price-based market mechanism (Scenario 2) to the buyers' confidence in the quality of RCC. We have assumed that the nine buyers have less confidence in the quality of RCC than they do in the quality of A1, as discussed in section 3.5.33.5.3.

4.5.1 MFA of CCDW management in *Loire-Atlantique*

Figure IV. 8 shows the material flows of the territorial CCDW management in *Loire-Atlantique* for Scenario 2. As can be seen from Figure IV. 8, approximately 4,908.2 kilotons of natural aggregates are produced in the territory to meet the demands of Market 1, Market 2, Market 3 and Market 4. A3 is the largest natural aggregates consumed to produce cement concrete and bituminous concrete. According to Figure IV. 8, 17% of the total A1 produced in the quarry is stored in the stock. 6% of the total CCDW generated in the territory is recycled in Scenario 2.

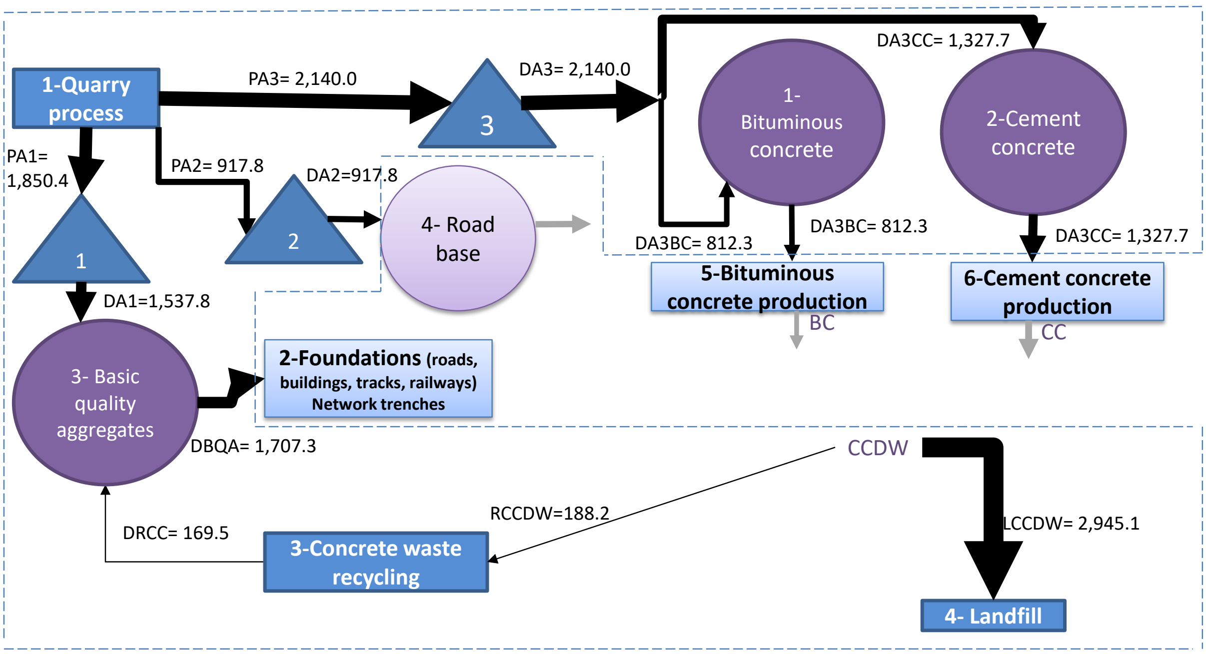


Figure IV. 8 MFA of CCDW management in Loire-Atlantique for "Scenario 2". All units are kilotons (Kt).

RCC: Recycled Cement Concrete

A1: primary category of natural aggregates

CCDW: Cement Concrete Demolition Wastes

A2: secondary category of natural aggregates

A3: tertiary category of natural aggregates

P_{A2}: produced A2

P_{A3}: produced tertiary category of natural aggregates in the quarry

Stock 3: stockpile of produced A3 in the quarry

D_{A3}: demand for tertiary category of natural aggregates

D_{A3BC}: demand for A3 in bituminous concrete market

D_{A3CC}: demand for A3 in cement concrete market

Market 2: market for cement concrete

Market 1: market for bituminous concrete

CC: cement concrete

BC: bitumenous concrete	P_{A1}: produced A1
Stock 1: stockpile of produced A1	Stock 2: stockpile of produced A2
D_{A1}: demand for A1 in basic quality aggregate market	D_{A2}: demand for A2 in road base market
Market 3: market for basic quality aggregates	Market 4: market for road base
D_{RCC}: demand for RCC	D_{BQA}: demand for basic quality aggregates
RCCDW: *fraction (R) of CCDW sent to the recycling facilities*	LCCDW: *fraction (L) of CCDW sent to the landfill*

4.5.2 Total demand for A1 and RCC and transportation distances of the demanded A1 and RCC

Table IV. 14 and Table IV. 16 resulting from Figure III. 7 for Scenario 2 show the demands of the nine buyers for A1 and RCC and the total demands for A1 and RCC in Market 3. Table IV. 15 and Table IV. 17 resulting from Figure III. 7 for Scenario 2 show travelling distances between the buyers and different quarries/recycling facilities in the territory to meet their demand for basic quality aggregates.

Unlike Scenario 1, the results of Scenario 2 show that the nine buyers of basic quality aggregates chose A1 when a quarry and a recycling facility had the same location. This is due to the condition considered in Figure III. 7 for Scenario 2 (a mistrust factor, Ø = 0.85). This prevented the buyers from traveling longer distances to meet their demand for basic quality aggregates, since the quarries in *Loire-Atlantique* have higher production compared to the recycling facilities (see Appendix F).

Considering the mistrust factor (Ø=0.85) in the procedures in Figure III. 7 for Scenario 2 also decreases the real difference between the total prices of 1 ton of A1 and the total prices of 1 ton of RCC in favor of A1. Accordingly, traveling distances in Scenario 2 are shorter that those in Scenario 1.

From Table IV. 14 and Table IV. 15 and equation (III. 22) the total ton-kilometer for the demanded A1 from different quarries is estimated. Likewise, from Table IV. 16 and Table IV. 17 and equation (III. 23) the total ton-kilometer for the demanded RCC from different recycling facilities is estimate. The values related to Scenario 2 are shown in equation (IV. 8).

$$D_{A1}.\,d_{Q_{Sc2}} = \ 23{,}108{,}506.7\ ; D_{RCC}.\,d_{Rec_{Sc2}} = 1{,}233{,}743.5 \qquad \text{IV. 8}$$

Where $D_{A1}.\,d_{Q_{Sc2}}$ *and* $D_{RCC}.\,d_{RCC_{Sc2}}$ *are the total ton-kilometer resulting from the demands of A1's buyers from different quarries and the total ton-kilometer resulting from the demands of RCC's buyers from different recycling facilities in Loire-Atlantique respectively related Scenario 2. The values are in ton*km.*

Table IV. 14 Demands of the nine buyers for A1 from different quarries ($D_{A1_{m,Qi}}$) and the total demand for A1 in Market 3 resulting from Figure III. 7 for Scenario 2. Figures in the table are in metric tons.

Quarries / $D_{A1_{m,Qi}}$**(ton)**	$D_{A1_{1,Qi}}$	$D_{A1_{2,Qi}}$	$D_{A1_{3,Qi}}$	$D_{A1_{4,Qi}}$	$D_{A1_{5,Qi}}$	$D_{A1_{6,Qi}}$	$D_{A1_{7,Qi}}$	$D_{A1_{8,Qi}}$	$D_{A1_{9,Qi}}$	**Total demand for A1 from each quarry**
La Mariais				226,200.0						226,200.0
Les Maraîchères					207,265.6					207,265.6
La Faubretière et Les Rocherons					207,350.0					207,350.0
La Margerie								121,747.4		121,747.4
La Coche	48,793.6									48,793.6
Les Mortiers									26,155.0	26,155.0
La Guibourgère									37,474.0	37,474.0
Le Bois de la Roche			51,979.2							51,979.2
Le Petit Betz							37,700.0			37,700.0
Landes Coeffard		4,625.0					12,475.0			17,100.0
La Métairie Neuve							48,793.8			48,793.8
La Bobatière	18,850.0									18,850.0
La Vallée		14,835.0								14,835.0
L'Ennerie						77,453.1				77,453.1
La Recouvrance					116,710.0					116,710.0
La Lande du Cens		14,835.0								14,835.0
La Guillonnais		15,834.0								15,834.0
La Pommeraie		51,682.0			13,957.0				17,574.0	83,213.0
La Gagnerie	718.4				59,395.0					60,113.4
La Grande Garde					105,390.0					105,390.0
Total demand of each buyer for A1 (D_{A1_m}**)**	68,362.0	101,811.0	51,979.2	226,200.0	710,067.6	77,453.1	98,968.8	121,747.4	81,203.0	$\boldsymbol{D_{A1} = 1,537,792.1}$

Legend

$D_{A1_{m,Qi}}$ *Demand of buyer m^{th} for A1 from quarry Qi^{th} (ton).*

D_{A1_m} *Total demand of buyer m^{th} for A1 (ton)*

D_{A1} *Total demand for A1 in Market 3 (ton)*

Table IV. 15 Transportation distances between the nine buyers of A1 and different quarries ($d_{m,Qi}$) resulting from Figure III. 7 for Scenario 2. Distances were measured by QGIS tool. Figures in the table are in kilometer.

Quarries / $d_{m,Qi}$**(km)**	$d_{1,Qi}$	$d_{2,Qi}$	$d_{3,Qi}$	$d_{4,Qi}$	$d_{5,Qi}$	$d_{6,Qi}$	$d_{7,Qi}$	$d_{8,Qi}$	$d_{9,Qi}$
La Mariais				18,93					
Les Maraîchères					9,57				
La Faubretière et Les Rocherons					16,56				
La Margerie								5,57	
La Coche	13,29								
Les Mortiers									12,59
La Guibourgère									12,59
Le Bois de la Roche			11,95						
Le Petit Betz							10,94		
Landes Coeffard		25,91					10,94		
La Métairie Neuve							10,76		
La Bobatière	9,07								
La Vallée		17,07							
L'Ennerie						2,74			
La Recouvrance					23,23				
La Lande du Cens		1,95							
La Guillonnais		1,95							
La Pommeraie		26,67			24,14				19,36
La Gagnerie	22,23				24,2				
La Grande Garde					24,2				

Legend

$d_{m,Qi}$ *Transportation distance between buyer m*th *and quarry Qi*th *(km).*

Table IV. 16 Demands of the nine buyers for RCC from different recycling facilities ($D_{RCC_{m,Reci}}$) and the total demand for RCC in Market 3 resulting from Figure III. 7 for Scenario 2. Figures are in metric tons.

Recycling facilities / $\boldsymbol{D_{RCC_{m,Reci}}}$**(ton)**	$\boldsymbol{D_{RCC_{1,RCCi}}}$	$\boldsymbol{D_{RCC_{2,RCCi}}}$	$\boldsymbol{D_{RCC_{3,RCCi}}}$	$\boldsymbol{D_{RCC_{4,RCCi}}}$	$\boldsymbol{D_{RCC_{5,RCCi}}}$	$\boldsymbol{D_{RCC_{6,RCCi}}}$	$\boldsymbol{D_{RCC_{7,RCCi}}}$	$\boldsymbol{D_{RCC_{8,RCCi}}}$	$\boldsymbol{D_{RCC_{9,RCCi}}}$	**Total demand for RCC from each facility**
SOCIETE DES CARRIERES CHASSE					12,319.0					12.319.0
ARC EN CIEL					12,319.0					12,319.0
LAFARGE GRANULATS FRANCE(BOUGUENAIS)					12,319.0					12,319.0
SOFERTI					12,319.0					12.319.0
Sablières de l'Atlantique				12,319.0						12.319.0
OTCM				9,380.2						9,380.2
TIMAC AGRO SAS					12,319.0					12,319.0
SAREMER					12,319.0					12,319.0
LAFARGE GRANULATS FRANCE - Secteur Ouest					12,319.0					12,319.0
GSM OUEST Pays de la Loire					12,319.0					12,319.0
2B RECYCLAGE					12,319.0					12,319.0
ALCEA					12,319.0					12,319.0
GUINGAMP	12,319.0									12,319.0
TEN (TOLERIE EMAILLERIE NANTAISE)					12,319.0					12,319.0
Total demand of each buyer for RCC ($\boldsymbol{D_{RCC_m}}$**)**	12,319.0	0.0	0.0	21,699.2	135,509.0	0.0	0.0	0.0	0.0	$\boldsymbol{D_{RCC}}$ **=169,527.2**

Legend

$D_{RCC_{m,Reci}}$	*Demand of buyer m^th for RCC from recycling facility Reci^th (ton).*
D_{RCC_m}	*Total demand of buyer m^th for RCC (ton).*
D_{RCC}	*Total demand for RCC in Market 3 (ton).*

Table IV. 17 Transportation distances between the nine buyers and different recycling facilities resulting from Figure III. 7 for Scenario 2. Distances were measured by QGIS tool. Figures are in kilometer.

Recycling facilities / $d_{m,Reci}$ (km)	$d_{1,Reci}$	$d_{2,Reci}$	$d_{3,Reci}$	$d_{4,Reci}$	$d_{5,Reci}$	$d_{6,Reci}$	$d_{7,Reci}$	$d_{8,Reci}$	$d_{9,Reci}$
SOCIETE DES CARRIERES CHASSE					14.32				
ARC EN CIEL					14.32				
LAFARGE GRANULATS FRANCE(BOUGUENAIS)					9.57				
SOFERTI					10.71				
Sablières de l'Atlantique				10.02					
OTCM				10.02					
TIMAC AGRO SAS					4.31				
SAREMER					4.31				
LAFARGE GRANULATS FRANCE - Secteur Ouest					4.31				
GSM OUEST Pays de la Loire					4.31				
2B RECYCLAGE					1.75				
ALCEA					1.75				
GUINGAMP	9.07								
TEN (TOLERIE EMAILLERIE NANTAISE)					3.77				

Legend

$d_{m,Reci}$ *Transportation distance between buyer m^{th} and recycling facility $Reci^{th}$ (km).*

4.5.3 Share of market 3 from A1 and RCC (*f1* and *f2*)

According to Table IV. 14 and Table IV. 16 resulting from Figure III. 7 and equations (III. 8) and (III. 9), the shares of A1 and RCC in Market 3 for Scenario 2 are calculated. Their values are shown in equation (IV. 9).

$$f1_{Sc2} = 90\%;\ f2_{Sc2} = 10\% \qquad \text{IV. 9}$$

Where $f1_{Sc2}$ and $f1_{Sc2}$ are the shares of A1 and RCC respectively in Market 3 for Scenario 2.

As is obvious, the shares of A1 and RCC in Market 3 resulting from Scenario 2 (equation IV. 9) are much closer to those resulting from the reference scenario (equation IV. 5) than the shares obtained from Scenario 1 (equation IV. 7). This means that a mistrust coefficient likely explains the actual market situation in *Loire-Atlantique*. The value of this coefficient has been set to 15% according to the experts' opinions (see 3.5.3) and it seems it reflects the current situation in the market where the buyers would not make choices just based on the prices of the products.

4.5.4 Environmental impact assessment results

Table IV. 18 illustrates the contributions of the territorial environmental model of CCDW management related to Scenario 2 (Figure IV. 8) to a range of environmental impacts. In addition, Table IV. 18 shows a given environmental impact translated into the number of European inhabitants which would generate the same impact, using the normalization factors in Table III. 1 and also their proportion to the total population of *Loire-Atlantique*.

Table IV. 18 Environmental impact indicator results of the territorial environmental model of CCDW management (Figure IV. 8) in Loire-Atlantique for the Scenario 2 and normalized values of the environmental impacts.

Environmental Impact Category	**Total amount**	**Unit**	**Normalized value (European inhabitant/ year)**	**Normalized value relative to Loire-Atlantique's population (%)**
Acidification potential, average European	1, 681,518.6	Kg SO_2- Eq	945,736.0	71.2
Eutrophication potential, average European	1, 021,674.6	Kg NOx- Eq	16,848.2	1.3
Resources, depletion of abiotic resources	2,598,818.9	Kg antimony-Eq	41,120,552.2	31 times of Loire-Atlantique' s population
Stratospheric ozone depletion, ODP total	245.9	Kg CFC-11- Eq	10,508.5	0.8
Climate change, GWP 100a	322,546,509.2	Kg CO_2- Eq	38,398.4	2.9
Ionizing radiation, IRP_HE	2, 118, 046,154.0	Kg U235- Eq	501,906.7	38.8
Urban land occupation, ULOP	6, 882,596.0	m^2a	501,281.6	37.8
Human health, respiratory effects, average	429,348.6	Kg PM2.5- Eq	-	-
Ecotoxicity, tota	1, 302, 202,717.9	CTU	-	-
Human toxicity, total	163.5	CTU	-	-
Fossil cumulative energy demand	4, 410, 139,038.8	MJ- Eq	67,536.6	5.1

Nuclear cumulative energy	27, 372, 474,087.6	MJ- Eq	-	-

Normalized values in Table IV. 18 show that the acidification, depletion of abiotic resource, Ionizing radiation and urban land occupation indicators are more considerable than other environmental impacts.
Figure IV. 9 shows the relative contributions of the processes included in Figure IV. 8 to 12 environmental impact categories presented in Table IV. 18 for Scenario 2.

As can be noticed from Figure IV. 9, the main contributor to the environmental impact categories is the production of D_{A3CC} for Market 2, except for “urban land occupation” to which CCDW landfilling is the main contributor (43.2%). This is mainly due to the assumption that we made, that CCDW which is not recycled is disposed into the landfill. In Scenario 2, 94% of CCDW is landfilled. The production of D_{A1} and D_{RCC} for Market 3 is the second contributor after the production of D_{A3CC} for Market 2. Stock of unused A1 contributes to 4.1-4.9% of the total environmental impacts.

According to Figure IV. 9, transportation in Markets 1, 2 and 3 does not contribute to the environmental impacts significantly compared to other processes included in the territory. The result is reasonable, as regarding to Figure IV. 8 huge amounts of natural aggregates are produced in the quarry. However, transportation distances for heavy materials, such as construction materials, are usually limited. Transportation distance in Market 1 and 2 has been considered to be 30 km, as an average distance between quarries and bituminous concrete plants/ cement concrete plants.

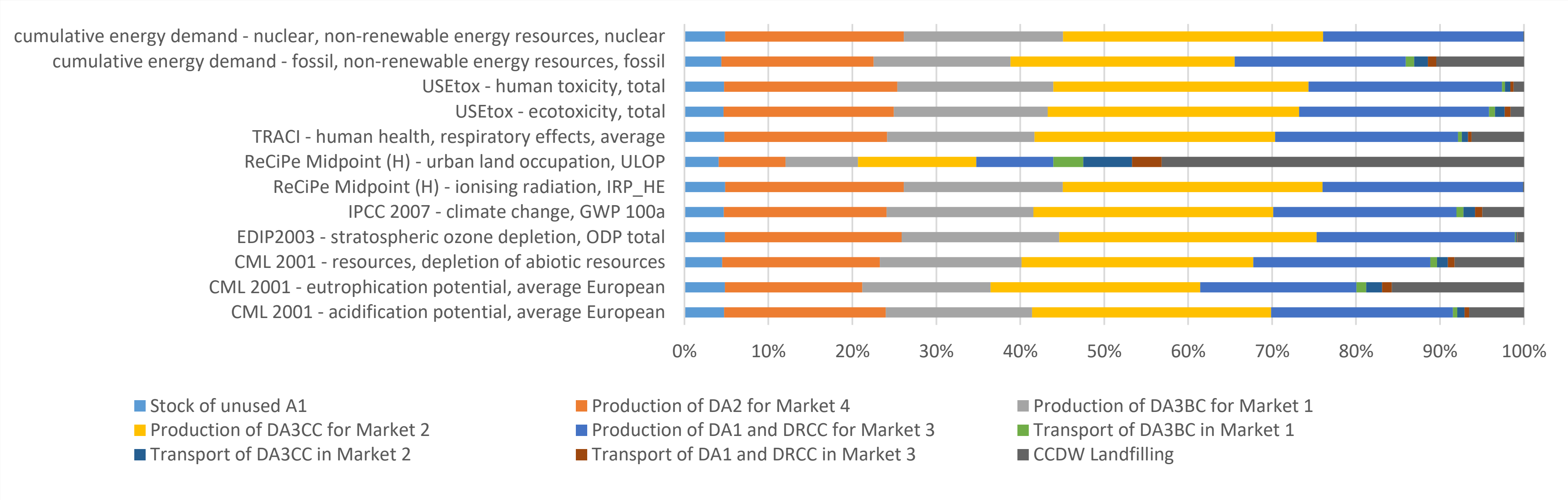


Figure IV. 9 Relative contributions of the processes included in the territorial environmental model of CCDW management (Figure IV. 8) to 12 environmental impact categories for Scenario 2. Stock of unused A1 includes the environmental impacts from production of unused A1 and stock itself, production of the demanded A2 (D_{A2}) in Market 4, production of the demanded A3BC (D_{A3BC}) in the bituminous concrete market (Market 1), production of the demanded A3CC (D_{A3CC}) in the cement concrete market (Market 2), production of the demanded RCC (D_{RCC}) and demanded A1 (D_{A1}) in the basic quality aggregate market (Market 3), transport distance between the distributers and the users of A3BC and A3CC considered 30km, Transport of D_{A1} and D_{RCC} in Market 3= transportation distances of D_{A1} and D_{RCC} from the quarries and the recycling facilities respectively to the related buyers, CCDW landfilling= landfilling of unused CCDW in the territory.

4.6 Scenario 3: price-based market mechanism model including a trust factor

This section presents the results of Scenario 3. In Scenario 3, we aimed at analyzing the sensitivity of the price-based market mechanism (Scenario 1) when the nine buyers of basic quality aggregates not only have confidence in the quality of RCC but also buy RCC for the environmental concerns, even if they have to pay a higher price (under condition Ø=1.15, see section 3.5.3).

4.6.1 MFA of CCDW management in *Loire-Atlantique*

Figure IV. 10 shows the material flows of the territorial CCDW management in *Loire-Atlantique* for Scenario 3. As can be seen from Figure IV. 10, approximately 4,908.2 kilotons of natural aggregates are produced in the territory to meet the demands of Market 1, Market 2, Market 3 and Market 4. A3 is the largest natural aggregates consumed to produce cement concrete and bituminous concrete. According to Figure IV. 10, 44% of the total A1 produced in the quarry is stored in the stock. 24% of the total CCDW generated in the territory is recycled in Scenario 3.

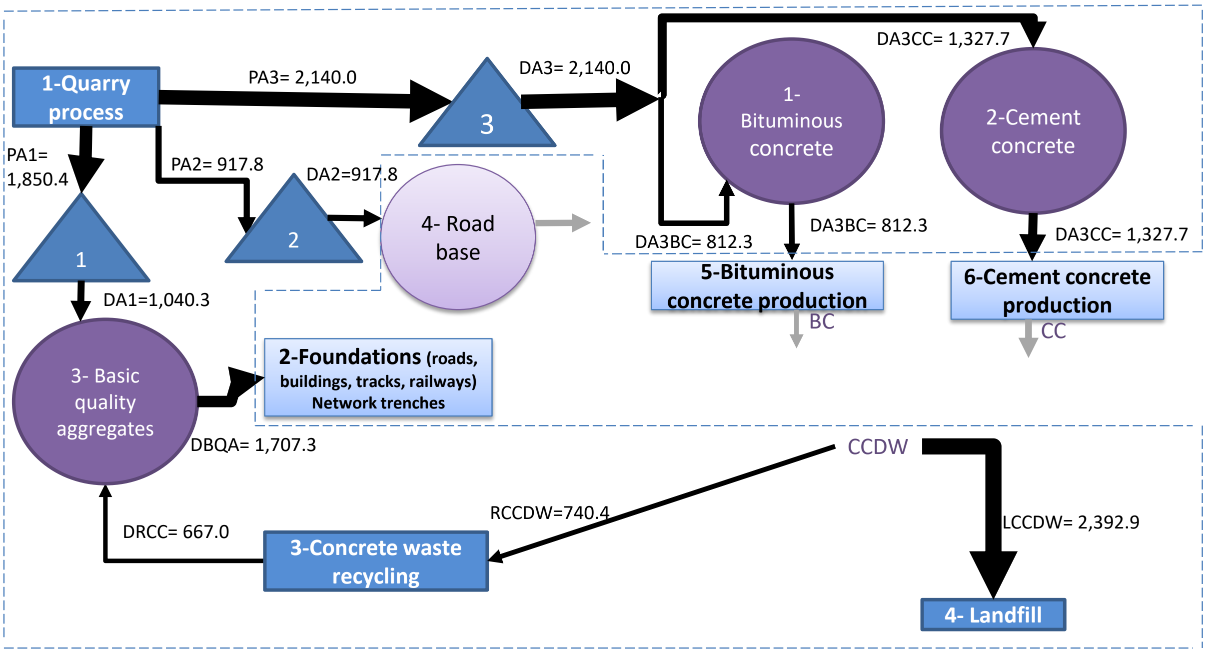


Figure IV. 10 MFA of CCDW management in Loire-Atlantique for "Scenario 3". All units are kilotons (Kt).

RCC: Recycled Cement Concrete

A1: primary category of natural aggregates

CCDW: Cement Concrete Demolition Wastes

A2: secondary category of natural aggregates

A3: tertiary category of natural aggregates

P_{A2}: produced A2

P_{A3}: produced tertiary category of natural aggregates in the quarry

Stock 3: stockpile of produced A3 in the quarry

D_{A3}: demand for tertiary category of natural aggregates

D_{A3BC}: demand for A3 in bituminous concrete market

D_{A3CC}: demand for A3 in cement concrete market

Market 2: market for cement concrete

Market 1: market for bituminous concrete	CC: cement concrete
BC: bitumenous concrete	P_{A1}: produced A1
Stock 1: stockpile of produced A1	Stock 2: stockpile of produced A2
D_{A1}: demand for A1 in basic quality aggregate market	D_{A2}: demand for A2 in road base market
Market 3: market for basic quality aggregates	Market 4: market for road base
D_{RCC}: demand for RCC	D_{BQA}: demand for basic quality aggregates
RCCDW: *fraction (R) of CCDW sent to the recycling facilities*	LCCDW: *fraction (L) of CCDW sent to the landfill*

4.6.2 Total demand for A1 and RCC and transportation distances of the demanded A1 and RCC

Table IV. 19 and Table IV. 21 resulting from Figure III. 7 for Scenario 3 show the demands of the nine buyers for A1 and RCC and the total demands for A1 and RCC in Market 3. Table IV. 20 and Table IV. 22 resulting from Figure III. 7 for Scenario 3 show travelling distances between the buyers and different quarries/recycling facilities in the territory to meet their demand for basic quality aggregates.

Distribution of the demands for basic quality aggregates between different sellers in Scenario 3 is almost similar to that obtained in Scenario 1. This is due to considering the trust factor (Ø=1.15) in the procedures in Figure III. 7 for Scenario 3 that increases the real difference between the total prices of 1 ton of A1 and the total prices of 1 ton of RCC in favor of RCC and also the limited capacity of recycling facilities in the territory (Table F. 2). Under assumption of Scenario 3 (Ø=1.15 in Figure III. 7), the nine buyers chose RCC, even if it was more expensive (up to 15% more expensive), this in turn caused traveling longer distances. For instances, buyer 5 chose the recycling facility "EDF SA" first, which is 26.69 km away from buyer 5, and then chose the quarry "Les Maraîchères", which is 9.57 km away from the buyer.

From Table IV. 19 and Table IV. 20 and equation (III. 22) the total ton-kilometer for the demanded A1 from different quarries is estimated. Likewise, from Table IV. 21 and Table IV. 22 and equation (III. 23) the total ton-kilometer for the demanded RCC from different recycling facilities is estimate. The values related to Scenario 3 are shown in equation (IV. 10).

$$D_{A1}.\,d_{Q_{Sc3}} = 17{,}123{,}679.5\,;\, D_{RCC}.\,d_{Rec_{Sc3}} = 8{,}625{,}521.4 \qquad \textit{IV. 10}$$

*Where $D_{A1}.\,d_{Q_{Sc3}}$ and $D_{RCC}.\,d_{RCC_{Sc3}}$ are the total ton-kilometer resulting from the demands of A1's buyers from different quarries and the total ton-kilometer resulting from the demands of RCC's buyers from different recycling facilities in Loire-Atlantique respectively related to Scenario 3. The values are in ton*km.*

Table IV. 19 Demands of the nine buyers for A1 from different quarries ($D_{A1_{m,Qi}}$) and the total demand for A1 in Market 3 resulting from Figure III. 7 for Scenario 3. Figures in the table are in metric tons.

Quarries / $\boldsymbol{D_{A1_{m,Qi}}}$ **(ton)**	$\boldsymbol{D_{A1_{1,Qi}}}$	$\boldsymbol{D_{A1_{2,Qi}}}$	$\boldsymbol{D_{A1_{3,Qi}}}$	$\boldsymbol{D_{A1_{4,Qi}}}$	$\boldsymbol{D_{A1_{5,Qi}}}$	$\boldsymbol{D_{A1_{6,Qi}}}$	$\boldsymbol{D_{A1_{7,Qi}}}$	$\boldsymbol{D_{A1_{8,Qi}}}$	$\boldsymbol{D_{A1_{9,Qi}}}$	**Total demand for A1 from each quarry**
La Mariais				154,065.2						154,065.2
Les Maraîchères					207,265.6					207,265.6
La Faubretière et Les Rocherons					207,350.0					207,350.0
La Coche	35,750.4									35,750.4
Le Petit Betz		35,160.3								35,160.3
La Métairie Neuve							37,373.8			37,373.8
La Bobatière	18,850.0									18,850.0
La Vallée		14,835.3								14,835.3
L'Ennerie						28,177.2				28,177.2
La Recouvrance					116,710.0					116,710.0
La Lande du Cens		14,835.3								14,835.3
La Guillonnais		15,834.2								15,834.2
La Gagnerie					60,113.0					60,113.0
La Grande Garde					93,991.0					93,991.0
Total demand of each buyer for A1 ($\boldsymbol{D_{A1_m}}$ **)**	54,600.4	80,665.1	0.0	154,065.2	685,429.6	28,177.2	37,373.8	0.0	0.0	$\boldsymbol{D_{A1} = 1,040{,}311.3}$

Legend

$D_{A1_{m,Qi}}$ *Demand of buyer m^{th} for A1 from quarry Qi^{th} (ton).*

D_{A1_m} *Total demand of buyer m^{th} for A1 (ton)*

D_{A1} *Total demand for A1 in Market 3 (ton)*

Table IV. 20 Transportation distances between the nine buyers of A1 and different quarries ($d_{m,Qi}$) resulting from Figure III. 7 for Scenario 3. Distances were measured by QGIS tool. Figures in the table are in kilometer.

Quarries / $d_{m,Qi}$**(km)**	$d_{1,Qi}$	$d_{2,Qi}$	$d_{3,Qi}$	$d_{4,Qi}$	$d_{5,Qi}$	$d_{6,Qi}$	$d_{7,Qi}$	$d_{8,Qi}$	$d_{9,Qi}$
La Mariais				18.93					
Les Maraîchères					9.57				
La Faubretière et Les Rocherons					16.56				
La Coche	13.29								
Le Petit Betz		25.91							
La Métairie Neuve							10.76		
La Bobatière	9.07								
La Vallée		17.07							
L'Ennerie						2.74			
La Recouvrance					23.23				
La Lande du Cens		1.95							
La Guillonnais		1.95							
La Gagnerie					24.2				
La Grande Garde					24.2				

Legend

$d_{m,Qi}$ *Transportation distance between buyer m^th^ and quarry Qi^th^ (km).*

Table IV. 21 Demands of the nine buyers for RCC from different recycling facilities ($D_{RCC_{m,Reci}}$) and the total demand for RCC in Market 3 resulting from Figure III. 7 for Scenario 3. Figures are in metric tons.

Recycling facilities / $D_{RCC_{m,Reci}}$**(ton)**	$D_{RCC_{1},RCCi}$	$D_{RCC_{2},RCCi}$	$D_{RCC_{3},RCCi}$	$D_{RCC_{4},RCCi}$	$D_{RCC_{5},RCCi}$	$D_{RCC_{6},RCCi}$	$D_{RCC_{7},RCCi}$	$D_{RCC_{8},RCCi}$	$D_{RCC_{9},RCCi}$	**Total demand for RCC from each facility**
FOCAST CHATEAUBRIANT			12,319.0							12,319.0
CHARIER CM - CARRIERES ET MATERIAUX							12,319.0			12,319.0
SOCIETE DES CARRIERES CHASSE					12,319.0					12,319.0
ARC EN CIEL					12,319.0					12,319.0
BAGLIONE SA					12,319.0					12,319.0
LAFARGE GRANULATS FRANCE(BOUGUENAIS)					12,319.0					12,319.0
EDF SA					12,319.0					12,319.0
SOFERTI					12,319.0					12,319.0
Pf Le Bréhet				7,601.0						7,601.0
Sablières de l'Atlantique				12,319.0						12,319.0
OTCM				12,319.0						12,319.0
IMERYS Metalcasting France				12,319.0						12,319.0
EQIOM				12,319.0						12,319.0
CHARIER TP				12,319.0						12,319.0
CETRA GRANULATS				12,319.0						12,319.0
SOCACHEM						12,319.0				12,319.0
CHARIER CM - CARRIERES ET MATERIAUX (LA HAIE FOUASSIERE)								12,319.0		12,319.0
CHARIER CM - CARRIERES ET MATERIAUX (Herbignac)				12,319.0						12,319.0
LAFARGE GRANULATS FRANCE (CHAUMES EN RETZ)						12,319.0				12,319.0
GAUTIER VALORISATION								12,319.0		12,319.0
CARRIERE BLANLOEIL								12,319.0		12,319.0
AGERA									12,319.0	12,319.0

CARRIERES GSM(ST PAZANNE)	12,319.0									12,319.0
CARRIERS ET MATERIAUX DU GRAND OUEST	1,442.6							10,876.4		12,318.6
CARRIERE AUBRON ET MECHINEAU								12,319.0		12,319.0
CARRIERES GSM (ROUANS)						12,319.0				12,319.0
CARRIERES GSM (TEILLE)									12,319.0	12,319.0
SOCIETE DRAGAGES D'ANCENIS			2,703.2						9,615.8	12,319.0
SOCAC - STE DES CARRIERES DE CAMPBON							12,319.0			12,319.0
SOCAC							12,319.0			12,319.0
LAFARGE GRANULATS FRANCE (CAMBON)							12,319.0			12,319.0
ORBELLO GRANULATS LOIRE		8,826.7							3,492.3	12,319.0
BOUYER LEROUX Structure SAS								12,319.0		12,319.0
TIMAC AGRO SAS					12,319.0					12,319.0
SAREMER					12,319.0					12,319.0
LAFARGE GRANULATS FRANCE - Secteur Ouest					12,319.0					12,319.0
GSM OUEST Pays de la Loire					12,319.0					12,319.0
2B RECYCLAGE					12,319.0					12,319.0
ALCEA					12,319.0					12,319.0
SYNDICAT MIXTE CENTRE NORD ATLANTIQUE		12,319.0								12,319.0
PHILVALOR									12,319.0	12,319.0
ECOTERRE DU CELLIER									6,500.0	6,500.0
BARBAZANGES TRI OUEST			12,319.0							12,319.0
GUINGAMP	12,319.0									12,319.0
DEDIENNE AUTOMOTIVE								12,319.0		12,319.0
BLANCHARD TP ECOCENTRE								12,319.0		12,319.0
TEN (TOLERIE EMAILLERIE NANTAISE)					12 319,00					12,319.0
ACTIPLAST									12,319.0	12,319.0
GROUPE MEAC SAS			12,319.0							12,319.0
TECHNA FRANCE NUTRITION							12,319.0			12,319.0

LAFARGE GRANULATS FRANCE			12,319.0							12,319.0
CARRIERES CHASSE (PETIT MARS)									12,319.0	12,319.0
LAFARGE GRANULATS FRANCE (ST COLOMBAN)								12,319.0		12,319.0
CARRIERES GSM (ST COLOMBAN)								12,319.0		12,319.0
CARRIERES CHASSE (ST VIAUD)						12,319.0				12,319.0
Total demand of each buyer for RCC ($\boldsymbol{D_{RCC_m}}$)	26,080.6	21,145.7	51,979.2	93,834.0	160,147.0	49,276.0	61,595.0	121,747.4	81,203.1	$\boldsymbol{D_{RCC}}$ = **667,008.0**

Legend

$D_{RCC_{m,Reci}}$ *Demand of buyer m^th^ for RCC from recycling facility Reci^th^ (ton).*

D_{RCC_m} *Total demand of buyer m^th^ for RCC (ton).*

D_{RCC} *Total demand for RCC in Market 3 (ton).*

Table IV. 22 Transportation distances between the nine buyers and different recycling facilities resulting from Figure III. 7 for Scenario 3. Distances were measured by QGIS tool. Figures in the table are in kilometer.

Recycling facilities / $d_{m,Reci}$ **(km)**	$d_{1,Reci}$	$d_{2,Reci}$	$d_{3,Reci}$	$d_{4,Reci}$	$d_{5,Reci}$	$d_{6,Reci}$	$d_{7,Reci}$	$d_{8,Reci}$	$d_{9,Reci}$
FOCAST CHATEAUBRIANT			3.53						
CHARIER CM - CARRIERES ET MATERIAUX							15.85		
SOCIETE DES CARRIERES CHASSE					14.32				
ARC EN CIEL					14.32				
BAGLIONE SA					23.45				
LAFARGE GRANULATS FRANCE(BOUGUENAIS)					9.57				
EDF SA					26.69				
SOFERTI					10.71				
Pf Le Bréhet				21.71					
Sablières de l'Atlantique				10.02					
OTCM				10.02					
IMERYS Metalcasting France				10.02					
EQIOM				10.02					
CHARIER TP				10.02					
CETRA GRANULATS				10.02					
SOCACHEM						8.97			
CHARIER CM - CARRIERES ET MATERIAUX (LA HAIE FOUASSIERE)								6.21	
CHARIER CM - CARRIERES ET MATERIAUX (Herbignac)				20.93					
LAFARGE GRANULATS FRANCE (CHAUMES EN RETZ)						5.96			
GAUTIER VALORISATION								9.74	
CARRIERE BLANLOEIL								9.74	
AGERA									20.67

CARRIERES GSM(ST PAZANNE)	13.29								
CARRIERS ET MATERIAUX DU GRAND OUEST	29.53							22.03	
CARRIERE AUBRON ET MECHINEAU								5	
CARRIERES GSM (ROUANS)						15.01			
CARRIERES GSM (TEILLE)									12.59
SOCIETE DRAGAGES D'ANCENIS			23.97						24.95
SOCAC - STE DES CARRIERES DE CAMPBON							10.94		
SOCAC							10.94		
LAFARGE GRANULATS FRANCE (CAMBON)							10.94		
ORBELLO GRANULATS LOIRE		49.53							31.05
BOUYER LEROUX Structure SAS								18.67	
TIMAC AGRO SAS					4.31				
SAREMER					4.31				
LAFARGE GRANULATS FRANCE - Secteur Ouest					4.31				
GSM OUEST Pays de la Loire					4.31				
2B RECYCLAGE					1.75				
ALCEA					1.75				
SYNDICAT MIXTE CENTRE NORD ATLANTIQUE		16.39							
PHILVALOR									15.94
ECOTERRE DU CELLIER									15.94
BARBAZANGES TRI OUEST			4.37						
GUINGAMP	9.07								
DEDIENNE AUTOMOTIVE								11.98	
BLANCHARD TP ECOCENTRE								13.83	
TEN (TOLERIE EMAILLERIE NANTAISE)					3.77				
ACTIPLAST									17.86
GROUPE MEAC SAS			9.85						
TECHNA FRANCE NUTRITION							21.32		

LAFARGE GRANULATS FRANCE			13.84						
CARRIERES CHASSE (PETIT MARS)									19.36
LAFARGE GRANULATS FRANCE (ST COLOMBAN)								20.04	
CARRIERES GSM (ST COLOMBAN)								20.04	
CARRIERES CHASSE (ST VIAUD)						9.88			

Legend

$d_{m,Reci}$ *Transportation distance between buyer m^{th} and recycling facility $Reci^{th}$ (km).*

4.6.3 Share of Market 3 from A1 and RCC (*f1* and *f2*)

According to Table IV. 19 and Table IV. 21 resulting from Figure III. 7 and equations (III. 8) and (III. 9), the shares of A1 and RCC in Market 3 for Scenario 3 are calculated. Their values are shown in equation (III. 11)

$$f1_{Sc3} = 61\%;\ f2_{Sc3} = 39\% \qquad \text{IV. 11}$$

Where $f1_{Sc3}$ and $f1_{Sc3}$ are the shares of A1 and RCC respectively in Market 3 for Scenario 3.

As can be noticed from equation (III. 11), the shares of A1 and RCC in Market 3 for Scenario 3 are almost the same as those obtained in Scenario 1 (equation IV. 7). According to the results, there is a potential to increase the current share of RCC in Market 3 from 6% to 39%. The 39% RCC in Market 3 corresponds to the total production of the recycling facilities in *Loire-Atlantique* in 2012 (Table F. 2).

4.6.4 Environmental impact assessment results

Table IV. 23 illustrates the contributions of the territorial environmental model of CCDW management related to Scenario 3 (Figure IV. 10) to a range of environmental impacts. In addition, Table IV. 23 shows a given environmental impact translated into the number of European inhabitants which would generate the same impact, using the normalization factors in Table III. 1 and also their proportion to the total population of *Loire-Atlantique*.

Table IV. 23 Environmental impact indicator results of the territorial environmental model of CCDW management (Figure IV. 10) in Loire-Atlantique for the Scenario 3 and normalized values of the environmental impacts.

Environmental Impact Category	**Total amount**	**Unit**	**Normalized value (European inhabitant/ year)**	**Normalized value relative to Loire-Atlantique's population (%)**
Acidification potential, average European	1, 677,291.6	Kg SO_2- Eq	943,358.6	71.1
Eutrophication potential, average European	1, 019,745.6	Kg NOx- Eq	16,816.4	1.3
Resources, depletion of abiotic resources	2, 576,391.2	Kg antimony- Eq	40,765,683.5	30.7 times of Loire-Atlantique's population
Stratospheric ozone depletion, ODP total	246.1	Kg CFC-11- Eq	10,517.1	0.8
Climate change, GWP 100a	322,101,853.5	Kg CO_2- Eq	38,345.5	2.9
Ionizing radiation, IRP_HE	2, 121, 467,131.3	Kg U235- Eq	502,717.3	37.9
Urban land occupation, ULOP	6, 617,822.8	m^2a	481,997.3	36.3
Human health, respiratory effects, average	428,616.6	Kg PM2.5- Eq	-	-
Ecotoxicity, tota	1, 301, 999,535.8	CTU	-	-
Human toxicity, total	163.6	CTU	-	-
Fossil cumulative energy demand	4, 360, 184,686.5	MJ- Eq	66,771.6	5

Nuclear cumulative energy	27, 418, 684,744.4	MJ- Eq	-	-

Normalized values in Table IV. 23 show that the acidification, depletion of abiotic resource, Ionizing radiation and urban land occupation indicators are more considerable than other environmental impacts.
Figure IV. 11 shows the relative contributions of the processes included in Figure IV. 10 to 12 environmental impact categories presented in Table IV. 23 for Scenario 3.

As can be noticed from Figure IV. 11, the main contributor to the environmental impact categories is the production of D_{A3CC} for Market 2, except for “urban land occupation” to which CCDW landfilling is the main contributor (36.3%). This is mainly due to the assumption that we made, that CCDW which is not recycled is disposed into the landfill. In Scenario 3, 76% of CCDW is landfilled. The production of D_{A2} for Market 4 is the second contributor after the production of D_{A3CC} for Market 2. Stock of unused A1 contributes to 10.9-12.5% of the total environmental impacts.

According to Figure IV. 11, transportation in Markets 1, 2 and 3 does not contribute to the environmental impacts significantly compared to other processes included in the territory. The result is reasonable, as regarding to Figure IV. 10 huge amounts of natural aggregates are produced in the quarry. However, transportation distances for heavy materials, such as construction materials, are usually limited. Transportation distance in Market 1 and 2 has been considered to be 30 km, as an average distance between quarries and bituminous concrete plants/ cement concrete plants.

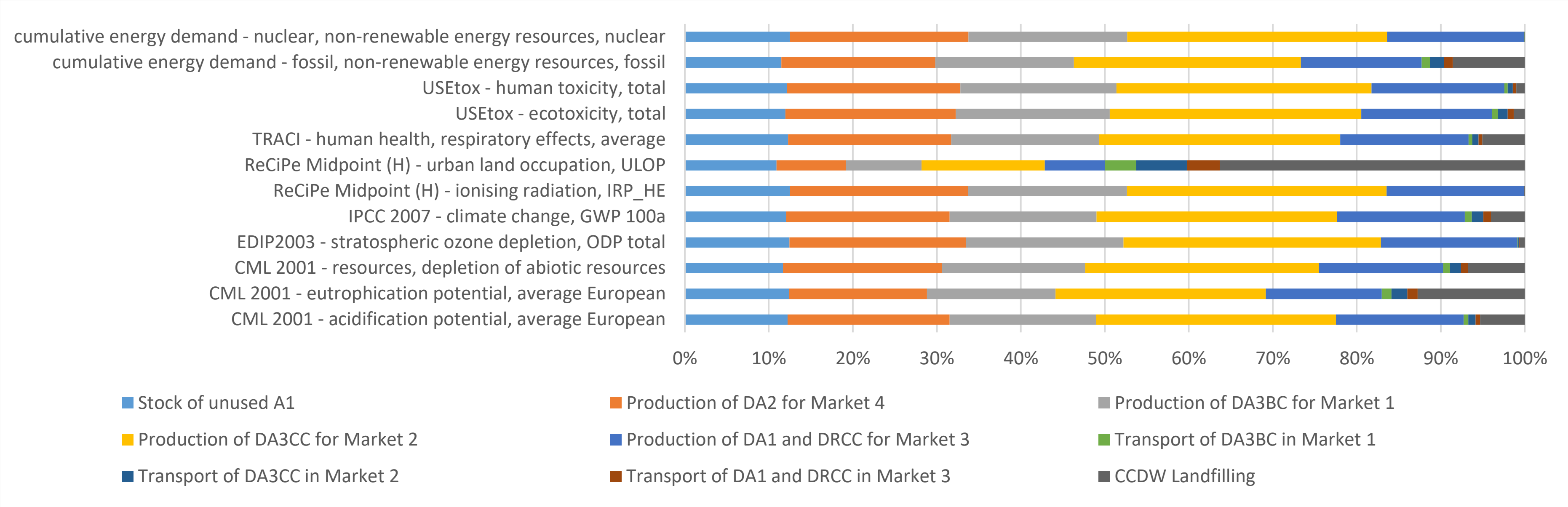


Figure IV. 11 Relative contributions of the processes included in the territorial environmental model of CCDW management (Figure IV. 10) to 12 environmental impact categories for Scenario 3. Stock of unused A1 includes the environmental impacts from production of unused A1 and stock itself, production of the demanded A2 (D_{A2}) in Market 4, production of the demanded A3BC (D_{A3BC}) in the bituminous concrete market (Market 1), production of the demanded A3CC (D_{A3CC}) in the cement concrete market (Market 2), production of the demanded RCC (D_{RCC}) and demanded A1 (D_{A1}) in the basic quality aggregate market (Market 3), transport distance between the distributers and the users of A3BC and A3CC considered 30km, Transport of D_{A1} and D_{RCC} in Market 3= transportation distances of D_{A1} and D_{RCC} from the quarries and the recycling facilities respectively to the related buyers, CCDW landfilling= landfilling of unused CCDW in the territory.

4.7 Scenario 4: legal obligation to use RCC (100% RCC in Market 3_ *f2*= 100%)

This section presents results of Scenario 4. In Scenario 4, we have assumed an enforcement of law in Market 3 to use only RCC as basic quality aggregates in the foundations (discussed in section 3.5.4). To fulfill this assumption, an increase of the production capacity of the recycling facilities in *Loire-Atlantique* was required, based on equation (III. 27). This is due to the reason that the production volumes of the recycling facilities in *Loire-Atlantique* (Table F. 2) are not sufficient to meet the total demand for basic quality aggregates in Market 3 in *Loire-Atlantique*, although there is an adequate supply of CCDW in the territory.

4.7.1 MFA of CCDW management in *Loire-Atlantique*

Figure IV. 12 shows the material flows of the territorial CCDW management in *Loire-Atlantique* for Scenario 4. As can be seen from Figure IV. 12, approximately 4,908.2 kilotons of natural aggregates are produced in the territory to meet the demands of Market 1, Market 2, Market 3 and Market 4. A3 is the largest natural aggregates consumed to produce cement concrete and bituminous concrete. According to our assumption in Scenario 4, 100% of the total A1 produced in the quarry is stored in the stock. 60% of the total CCDW generated in the territory is recycled in Scenario 4.

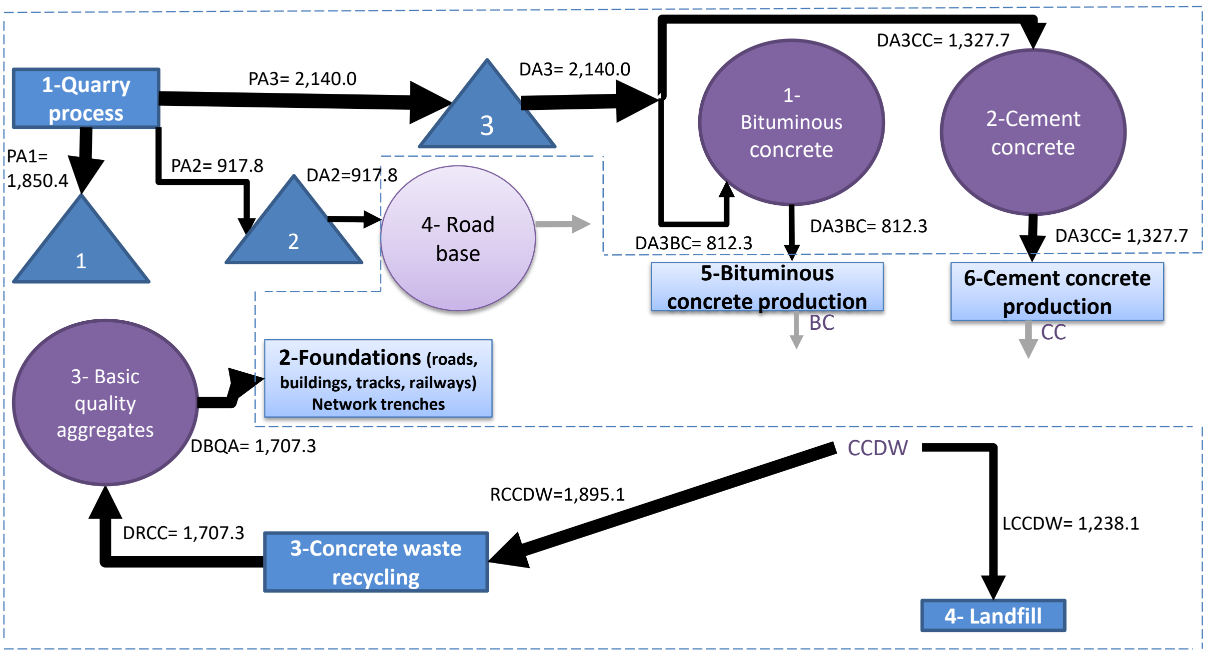


Figure IV. 12 MFA of CCDW management in Loire-Atlantique for "Scenario 4". All units are kilotons (Kt).

Legend

RCC: Recycled Cement Concrete

CCDW: Cement Concrete Demolition Wastes

A3: tertiary category of natural aggregates

P_{A3}: produced tertiary category of natural aggregates in the quarry

A1: primary category of natural aggregates

A2: secondary category of natural aggregates

P_{A2}: produced A2

Stock 3: stockpile of produced A3 in the quarry

D_{A3}: demand for tertiary category of natural aggregates

D_{A3BC}: demand for A3 in bituminous concrete market

D_{A3CC}: demand for A3 in cement concrete market

Market 2: market for cement concrete

Market 1: market for bituminous concrete

CC: cement concrete

BC: bitumenous concrete

P_{A1}: produced A1

Stock 1: stockpile of produced A1

Stock 2: stockpile of produced A2

D_{A1}: demand for A1 in basic quality aggregate market

D_{A2}: demand for A2 in road base market

Market 3: market for basic quality aggregates

Market 4: market for road base

D_{RCC}: demand for RCC

D_{BQA}: demand for basic quality aggregates

RCCDW: *fraction (R) of CCDW sent to the recycling facilities*

LCCDW: *fraction (L) of CCDW sent to the landfill*

4.7.2 Total demand for A1 and RCC and transportations distances of the demanded A1 and RCC

According to the assumption considered in Scenario 4, the total demand for RCC equals the total demand for basic quality aggregates in Market 3 in the territory. In order to investigate the distribution of the demand between different recycling facilities Figure III. 9 was used. Table IV. 24 resulting from Figure III. 9 shows the demands of the nine buyers for RCC from different recycling facilities. As can be seen in Table IV. 24, in order to meet the total demand for basic quality aggregates in the territory, all recycling facilities in the territory sell RCC as much as they produce. This is due to the assumptions made in (III. 27). Table IV. 25 resulting from Figure III. 9 shows traveling distances between the nine buyers and different recycling facilities in the territory to meet their demands for basic quality aggregates. Based on the procedures defined in Figure III. 9, the recycling facilities which are the closest to the buyers are chosen. However, not all the closest recycling facilities to the nine buyers are able to meet the demands of the nine buyers for basic quality aggregates. Therefore, in Scenario 4 some buyers required to traveling long distances to buy RCC. For instance, buyer 5 in segment 5 (as the biggest buyer) not only buys from 11 recycling facilities in segment 5 (see Figure IV. 3), which are the facilities closer to buyer 5 than other buyers, but also has to buy from other facilities in other segments. This is due to the reason that, 11 recycling facilities in segment 5 can meet 40% of its demand for basic quality aggregates. As a result, buyer 5 has to travel a range of distances between 23.45 km and 83.59 km to other segments (3, 4, 6, 8 and 9) to meet his demand for basic quality aggregates. Accordingly, traveling distances in Scenario 4 in Market 3 between the nine buyers and the sellers are longer compared to those in the reference scenario.

Table IV. 24 Demands of the nine buyers for RCC from different recycling facilities ($D_{RCC_{m,Reci}}$) resulting from Figure III. 9 and the total demand for RCC in Market 3 for Scenario 4. Figures are in metric tons.

Recycling facilities / $D_{RCC_{m,Reci}}$**(ton)**	$D_{RCC_{1,RCCi}}$	$D_{RCC_{2,RCCi}}$	$D_{RCC_{3,RCCi}}$	$D_{RCC_{4,RCCi}}$	$D_{RCC_{5,RCCi}}$	$D_{RCC_{6,RCCi}}$	$D_{RCC_{7,RCCi}}$	$D_{RCC_{8,RCCi}}$	$D_{RCC_{9,RCCi}}$	**Total demand for RCC from each facility**
FOCAST CHATEAUBRIANT			31,042.2							31,042.2
CHARIER CM - CARRIERES ET MATERIAUX				25,200.0			5,842.2			31,042.2
SOCIETE DES CARRIERES CHASSE					31,042.2					31,042.2
ARC EN CIEL					31,042.2					31,042.2
BAGLIONE SA					31,042.2					31,042.2
LAFARGE GRANULATS FRANCE(BOUGUENAIS)					31,042.2					31,042.2
EDF SA					31,042.2					31,042.2
SOFERTI					31,042.2					31,042.2
Pf Le Bréhet				5,404.2	25,638.0					31,042.2
Sablières de l'Atlantique				31,042.2						31,042.2
OTCM				31,042.2						31,042.2
IMERYS Metalcasting France				31,042.2						31,042.2
EQIOM				31,042.2						31,042.2
CHARIER TP				31,042.2						31,042.2
CETRA GRANULATS				31,042.0						31,042.0
SOCACHEM						31,042.0				31,042.0
CHARIER CM - CARRIERES ET MATERIAUX (LA HAIE FOUASSIERE)								31,042.2		31,042.2
CHARIER CM - CARRIERES ET MATERIAUX (Herbignac)				31,042.0						31,042.0
LAFARGE GRANULATS FRANCE (CHAUMES EN RETZ)						31,042.2				31,042.2
GAUTIER VALORISATION								31,042.2		31,042.2
CARRIERE BLANLOEIL					2,421.3			28,621.0		31,042.3
AGERA					31,042.0					31,042.0

CARRIERES GSM(ST PAZANNE)	31,042.0									31,042.0
CARRIERS ET MATERIAUX DU GRAND OUEST					31,042.0					31,042.0
CARRIERE AUBRON ET MECHINEAU								31,042.0		31,042.0
CARRIERES GSM (ROUANS)					31,042.2					31,042.2
CARRIERES GSM (TEILLE)									31,042.0	31,042.0
SOCIETE DRAGAGES D'ANCENIS					31,042.2					31,042.2
SOCAC - STE DES CARRIERES DE CAMPBON							31,042.2			31,042.2
SOCAC							31,042.2			31,042.2
LAFARGE GRANULATS FRANCE (CAMBON)							31,042.2			31,042.2
ORBELLO GRANULATS LOIRE					31,042.2					31,042.2
BOUYER LEROUX Structure SAS					31,042.2					31,042.2
TIMAC AGRO SAS					31,042.2					31,042.2
SAREMER					31,042.2					31,042.2
LAFARGE GRANULATS FRANCE - Secteur Ouest					31,042.2					31,042.2
GSM OUEST Pays de la Loire					31,042.2					31,042.2
2B RECYCLAGE					31,042.2					31,042.2
ALCEA					31,042.2					31,042.2
SYNDICAT MIXTE CENTRE NORD ATLANTIQUE		31,042.2								31,042.2
PHILVALOR									31,042.0	31,042.0
ECOTERRE DU CELLIER					11,923.0				19,119.0	31,042.0
BARBAZANGES TRI OUEST		8,684.3	20,937.0		1,420.7					31,042.0
GUINGAMP	31,042.0									31,042.0
DEDIENNE AUTOMOTIVE					31,042.2					31,042.2
BLANCHARD TP ECOCENTRE					31,042.2					31,042.2
TEN (TOLERIE EMAILLERIE NANTAISE)					31,042.2					31,042.2
ACTIPLAST					31,042.2					31,042.2
GROUPE MEAC SAS		31,042.2								31,042.2

TECHNA FRANCE NUTRITION		31,042.2								31,042.2
LAFARGE GRANULATS FRANCE					31,042.2					31,042.2
CARRIERES CHASSE (PETIT MARS)					31,042.2					31,042.2
LAFARGE GRANULATS FRANCE (ST COLOMBAN)	18,597.0				12,446.0					31,043.0
CARRIERES GSM (ST COLOMBAN)					31,042.2					31,042.2
CARRIERES CHASSE (ST VIAUD)					15,673.0	15,369.0				31,042.0
Total demand of each buyer for RCC (D_{RCC_m})	80,681.0	101,810.9	51,979.2	247,899.2	845,576.6	77,453.2	98,968.8	121,747.4	81,203.0	$\boldsymbol{D_{RCC}} =$ **1 ,707,319.3**

Legend

$D_{RCC_{m,Reci}}$ *Demand of buyer m^th^ for RCC from recycling facility Reci^th^ (ton).*

D_{RCC_m} *Total demand of buyer m^th^ for RCC (ton).*

D_{RCC} *Total demand for RCC in Market 3 (ton).*

Table IV. 25 Transportation distances between the nine buyers and different recycling facilities resulting from Figure III. 9 for Scenario 4. Distances were measured by QGIS tool. Figures are in kilometer.

Recycling facilities / $\boldsymbol{d_{m,Reci}}$ **(km)**	$\boldsymbol{d_{1,Reci}}$	$\boldsymbol{d_{2,Reci}}$	$\boldsymbol{d_{3,Reci}}$	$\boldsymbol{d_{4,Reci}}$	$\boldsymbol{d_{5,Reci}}$	$\boldsymbol{d_{6,Reci}}$	$\boldsymbol{d_{7,Reci}}$	$\boldsymbol{d_{8,Reci}}$	$\boldsymbol{d_{9,Reci}}$
FOCAST CHATEAUBRIANT			3.53						
CHARIER CM - CARRIERES ET MATERIAUX				18.93			15.85		
SOCIETE DES CARRIERES CHASSE					14.32				
ARC EN CIEL					14.32				
BAGLIONE SA					23.45				
LAFARGE GRANULATS FRANCE(BOUGUENAIS)					9.57				
EDF SA					26.69				
SOFERTI					10.71				
Pf Le Bréhet				21.71	83.59				

Sablières de l'Atlantique				10.02					
OTCM				10.02					
IMERYS Metalcasting France				10.02					
EQIOM				10.02					
CHARIER TP				10.02					
CETRA GRANULATS				10.02					
SOCACHEM						8.97			
CHARIER CM - CARRIERES ET MATERIAUX (LA HAIE FOUASSIERE)								6.21	
CHARIER CM - CARRIERES ET MATERIAUX (Herbignac)				20.93					
LAFARGE GRANULATS FRANCE (CHAUMES EN RETZ)						5.96			
GAUTIER VALORISATION								9.74	
CARRIERE BLANLOEIL					27.16			9.74	
AGERA					50.71				
CARRIERES GSM(ST PAZANNE)	13.29								
CARRIERS ET MATERIAUX DU GRAND OUEST					33.61				
CARRIERE AUBRON ET MECHINEAU								5.00	
CARRIERES GSM (ROUANS)					28.15				
CARRIERES GSM (TEILLE)									12.59
SOCIETE DRAGAGES D'ANCENIS					54.93				
SOCAC - STE DES CARRIERES DE CAMPBON							10.94		
SOCAC							10.94		

LAFARGE GRANULATS FRANCE (CAMBON)							10.94		
ORBELLO GRANULATS LOIRE					61.56				
BOUYER LEROUX Structure SAS					32.57				
TIMAC AGRO SAS					4.31				
SAREMER					4.31				
LAFARGE GRANULATS FRANCE - Secteur Ouest					4.31				
GSM OUEST Pays de la Loire					4.31				
2B RECYCLAGE					1.75				
ALCEA					1.75				
SYNDICAT MIXTE CENTRE NORD ATLANTIQUE		16.39							
PHILVALOR									15.94
ECOTERRE DU CELLIER					23.14				15.94
BARBAZANGES TRI OUEST		35.35	4.37		63.35				
GUINGAMP	9.07								
DEDIENNE AUTOMOTIVE					33.76				
BLANCHARD TP ECOCENTRE					21.41				
TEN (TOLERIE EMAILLERIE NANTAISE)					3.77				
ACTIPLAST					50.78				
GROUPE MEAC SAS		35.25							
TECHNA FRANCE NUTRITION		28.77							
LAFARGE GRANULATS FRANCE					72.81				
CARRIERES CHASSE (PETIT MARS)					25.14				
LAFARGE GRANULATS FRANCE (ST COLOMBAN)	22.23				24.20				

CARRIERES GSM (ST COLOMBAN)					24.20				
CARRIERES CHASSE (ST VIAUD)					45.07	9.88			

Legend

$d_{m,Reci}$ *Transportation distance between buyer m^th^ and recycling facility Reci^th^ (km).*

From Table IV. 24 and Table IV. 25 and equation (III. 23) the total ton-kilometer for the demanded RCC from different recycling facilities is estimate. This value related to Scenario 4 is shown in equation (IV. 12).

$$D_{RCC}.\,d_{Rec_{Sc4}} = 33{,}685{,}575.3 \quad \text{IV. 12}$$

Where $D_{RCC}.\,d_{RCC_{Sc4}}$ *is the total ton-kilometer resulting from the demands of RCC's buyers from different recycling facilities in Loire-Atlantique related to Scenario 4. The value is in ton*km.*

4.7.3 Share of Market 3 from A1 and RCC (*f1* and *f2*)

According to the assumption made in Scenario 4 that the demand for basic quality aggregates in Market 3 is only met by the recycling facilities, the shares of A1 and RCC in Market 3 for Scenario 4 are as follow:

$$f1_{Sc4} = 0\%;\ f2_{Sc4} = 100\% \quad \text{IV. 13}$$

Where $f1_{Sc4}$ *and* $f2_{Sc4}$ *are shares of A1 and RCC in Market 3 respectively, according to the assumption of Scenario 4.*

4.7.4 Environmental impact assessment results

Table IV. 26 illustrates the contributions of the territorial environmental model of CCDW management related to Scenario 4 (Figure IV. 12) to a range of environmental impacts. In addition, Table IV. 26 shows a given environmental impact translated into the number of European inhabitants which would generate the same impact, using the normalization factors in Table III. 1 and also their proportion to the total population of *Loire-Atlantique*.

Table IV. 26 Environmental impact indicator results of the territorial environmental model of CCDW management (Figure IV. 12) in Loire-Atlantique for the Scenario 4 and normalized values of the environmental impacts.

Environmental Impact Category	**Total amount**	**Unit**	**Normalized value (European inhabitant/ year)**	**Normalized value relative to Loire-Atlantique's population (%)**
Acidification potential, average European	1, 670, 719.2	Kg SO_2- Eq	939,662.1	70.8
Eutrophication potential, average European	1, 018,734.0	Kg NOx- Eq	16,799.7	1.3
Resources, depletion of abiotic resources	2,534,672.3	Kg antimony-Eq	40,105,574.4	30.2 times of Loire-Atlantique's population
Stratospheric ozone depletion, ODP total	246.5	Kg CFC-11-Eq	10,534.2	0.8
Climate change, GWP 100a	321,884,059.2	Kg CO_2- Eq	38,319.5	2.9
Ionizing radiation, IRP_HE	2, 128, 685,775.6	Kg U235-Eq	504,428.0	38
Urban land occupation, ULOP	6, 133,056.9	m^2a	446,690.2	33.6
Human health, respiratory effects, average	427,564.9	Kg PM2.5-Eq	-	-
Ecotoxicity, tota	1, 304, 044,505.3	CTU	-	-

Human toxicity, total	163.8	CTU	-	-
Fossil cumulative energy demand	4, 266, 728,626.6	MJ- Eq	65,340.4	4.9
Nuclear cumulative energy	27, 515, 686,689.2	MJ- Eq	-	-

Normalized values in Table IV. 26 show that the acidification, depletion of abiotic resource, Ionizing radiation and urban land occupation indicators are more considerable than other environmental impacts.
Figure IV. 13 shows the relative contributions of the processes included in Figure IV. 12 to 12 environmental impact categories presented in Table IV. 26 for Scenario 4.

As can be noticed from Figure IV. 13, both the stock of unused A1 and the production of D_{A3CC} for Market 2 are the main contributors to the environmental impact categories. Their contributions are almost similar, except for "urban land occupation" to which the stock of unused A1 contributes the most (26.9%). This is due to the reason that under assumption of Scenario 4 all A1 produced in the quarry is stored in the stock. The production of D_{A1} and D_{RCC} for Market 3 with 100% RCC and 0% A1 contributes to 0.6-2.6% of the total environmental impacts. This implies that recycling of CCDW does not have significant environmental impacts compared to other processes.

According to Figure IV. 13, transportation in Markets 1, 2 and 3 does not contribute to the environmental impacts significantly compared to other processes included in the territory. The result is reasonable, as regarding to Figure IV. 12 huge amounts of natural aggregates are produced in the quarry. However, transportation distances for heavy materials, such as construction materials, are usually limited. Transportation distance in Market 1 and 2 has been considered to be 30 km, as an average distance between quarries and bituminous concrete plants/ cement concrete plants.

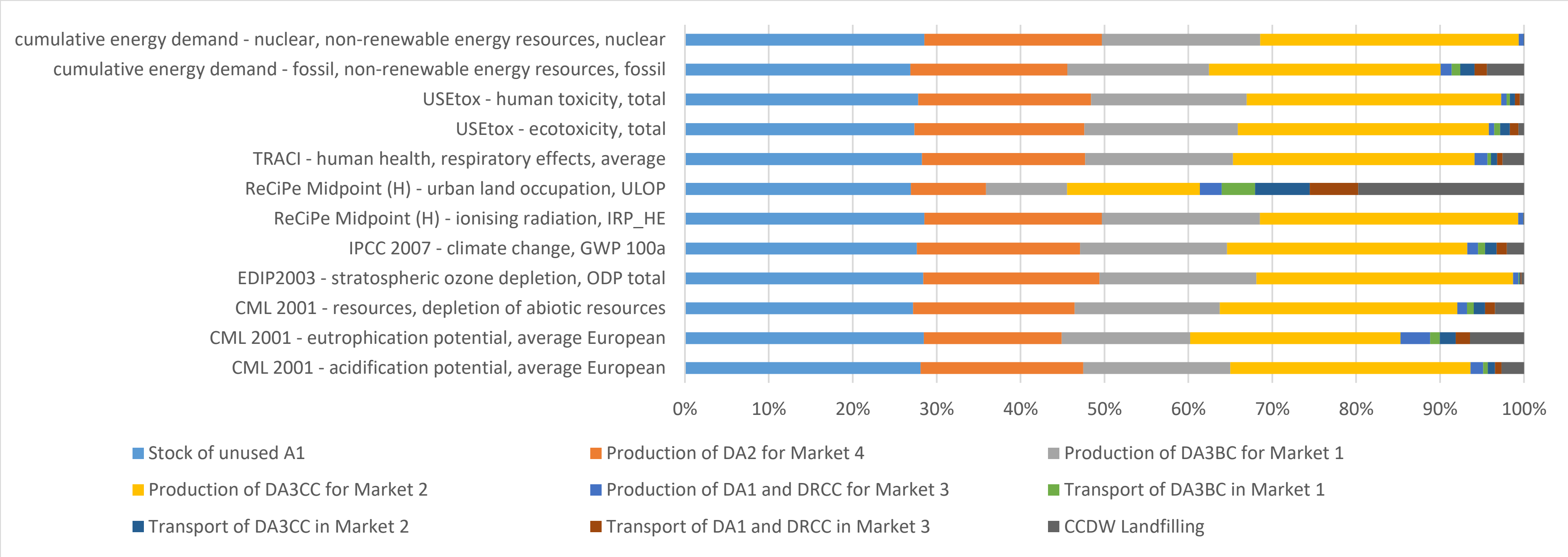


Figure IV. 13 Relative contributions of the processes included in the territorial environmental model of CCDW management (Figure IV. 12) to 12 environmental impact categories for Scenario 4. Stock of unused A1 includes the environmental impacts from production of unused A1 and stock itself, production of the demanded A2 (D_{A2}) in Market 4, production of the demanded A3BC (D_{A3BC}) in the bituminous concrete market (Market 1), production of the demanded A3CC (D_{A3CC}) in the cement concrete market (Market 2), production of the demanded RCC (D_{RCC}) and demanded A1 (D_{A1}) in the basic quality aggregate market (Market 3), transport distance between the distributers and the users of A3BC and A3CC considered 30km, Transport of D_{A1} and D_{RCC} in Market 3= transportation distances of D_{A1} and D_{RCC} from the quarries and the recycling facilities respectively to the related buyers, CCDW landfilling= landfilling of unused CCDW in the territory.

4.8 Scenario 5: legal obligation to use A1 (100% A1 in Market 3_ *f1*= 100%)

This section presents the results of Scenario 5. In Scenario 5, unlike Scenario 4, we have assumed an enforcement of law in Market 3 based on which just A1 is used in the foundations (as discussed in section 3.5.5).

4.8.1 MFA of CCDW management in *Loire-Atlantique*

Figure IV. 14 shows the material flows of the territorial CCDW management in *Loire-Atlantique* for Scenario 4. As can be seen from Figure IV. 14, approximately 4,908.2 kilotons of natural aggregates are produced in the territory to meet the demands of Market 1, Market 2, Market 3 and Market 4. A3 is the largest natural aggregates consumed to produce cement concrete and bituminous concrete. According to Figure IV. 14, 8% of the total A1 is produced in the quarry is stored in the stock. Based on the assumption made in Scenario 5, the total CCDW generated in the territory is disposed in the landfill.

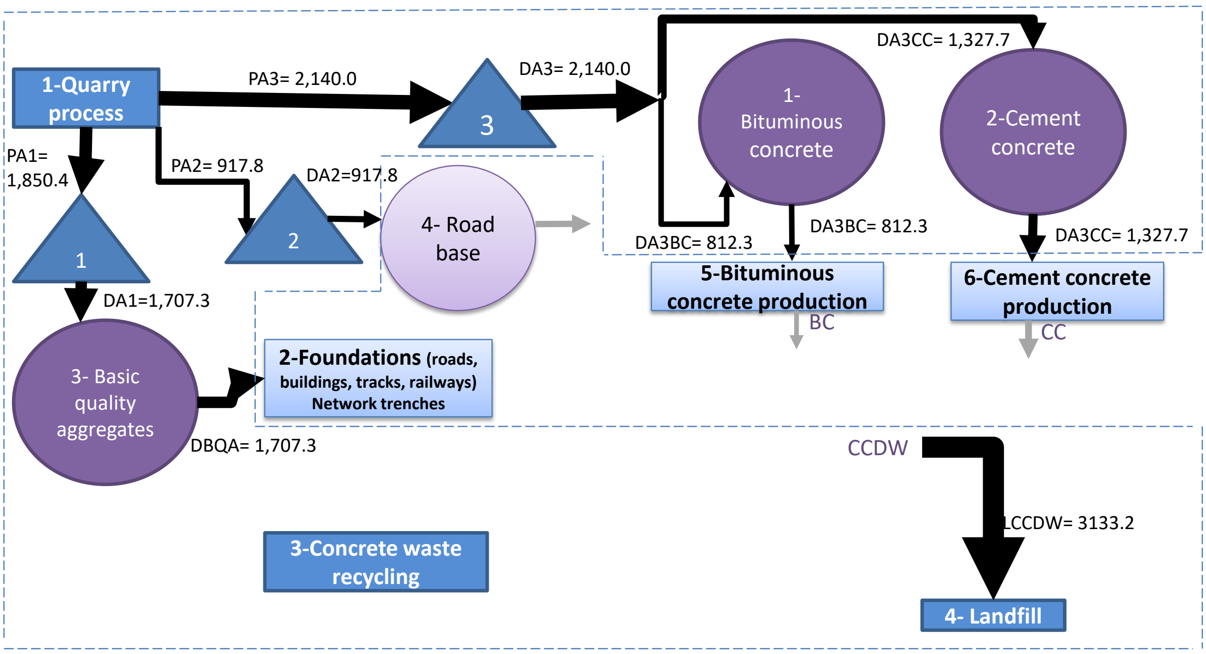


Figure IV. 14 MFA of CCDW management in Loire-Atlantique for "Scenario 5". All units are kilotons (Kt).

Legend

Process

Stock

Flow

Market

RCC: Recycled Cement Concrete

A1: primary category of natural aggregates

CCDW: Cement Concrete Demolition Wastes

A2: secondary category of natural aggregates

A3: tertiary category of natural aggregates

P_{A2}: produced A2

P_{A3}: produced tertiary category of natural aggregates in the quarry

Stock 3: stockpile of produced A3 in the quarry

D_{A3}: demand for tertiary category of natural aggregates

D_{A3BC}: demand for A3 in bituminous concrete market

D_{A3CC}: demand for A3 in cement concrete market

Market 2: market for cement concrete

Market 1: market for bituminous concrete	CC: cement concrete
BC: bitumenous concrete	P_{A1}: produced A1
Stock 1: stockpile of produced A1	Stock 2: stockpile of produced A2
D_{A1}: demand for A1 in basic quality aggregate market	D_{A2}: demand for A2 in road base market
Market 3: market for basic quality aggregates	Market 4: market for road base
D_{RCC}: demand for RCC	D_{BQA}: demand for basic quality aggregates
RCCDW: *fraction (R) of CCDW sent to the recycling facilities*	LCCDW: *fraction (L) of CCDW sent to the landfill*

4.8.2 **Total demand for A1 and RCC and transportation distances of the demanded A1 and RCC**

According to the assumption considered in Scenario 5, the total demand for A1 in Market 3 equals the total demand for basic quality aggregates. In order to investigate the distribution of the total demand between different quarries, Figure III. 8 was used.

Table IV. 27 resulting from Figure III. 8 shows the demands of the nine buyers for A1 from different quarries in the territory. Table IV. 28 resulting from Figure III. 8 shows traveling distances between the nine buyers and different quarries in the territory to meet their demands for basic quality aggregates.

Based on the procedures defined in Figure III. 8, the quarries which are the closest to the buyers are chosen. As the quarries which are the closest to the nine buyers have higher production volumes than the recycling facilities, traveling distances in Scenario 5 are shorter than those in Scenario 4. For instance, buyer 5 in segment 5, as the biggest buyer that drives traveling distances, travelled a range of distances between 9.57 km and 25.14 km to meet his demand for basic quality aggregates. The closest quarry to buyer 5 (9.57 km away from buyer 5) located in segment 5 can meet 25% of his total demand for basic quality aggregates. The furthest quarry to buyer 5 is located in segment 9.

Table IV. 27 Demands of the nine buyers for A1 from different quarries ($D_{A1_{m,Qi}}$) resulting from Figure III. 8 and the total demand for A1 in Market 3 for Scenario 5. Figures in the table are in metric tons.

Quarries / $D_{A1_{m,Qi}}$**(ton)**	$D_{A1_{1,Qi}}$	$D_{A1_{2,Qi}}$	$D_{A1_{3,Qi}}$	$D_{A1_{4,Qi}}$	$D_{A1_{5,Qi}}$	$D_{A1_{6,Qi}}$	$D_{A1_{7,Qi}}$	$D_{A1_{8,Qi}}$	$D_{A1_{9,Qi}}$	**Total demand for A1 from each quarry**
La Mariais				226,200.0						226,200.0
Les Maraîchères					207,265.6					207,265.6
La Faubretière et Les Rocherons					207,350.0					207,350.0
La Margerie								121,747.4		121,747.4
La Clarté				21,699.2						21,699.2
La Coche	48,794.0									48,794.0
La Guibourgère									37,474.0	37,474.0
Le Bois de la Roche			51,979.2							51,979.2
Le Petit Betz							37,700.0			37,700.0
Landes Coeffard		4,624.2					12,475.0			17,099.2
Bel Air		23,775.0								23,775.0
La Métairie Neuve							48,793.8			48,793.8
La Bobatière	18,850.0									18,850.0
La Vallée		14,835.3							26 ,55.0	40,990.3
L'Ennerie						77,453.2				77,453.2
La Recouvrance					116,710.1					116,710.1
La Lande du Cens		14,835.3								14,835.3
La Guillonnais		15,834.0								15,834.0
La Pommeraie		27,907.0			161,784.2				17,574.0	207,265.2
La Gagnerie	13,037.0				47,076.0					60,113.0
La Grande Garde					105,390.7					105,390.7
Total demand of each buyer for A1 (D_{A1_m}**)**	80,681.0	101,810.9	51,979.2	247,899.2	845,576.6	77,453.2	98,968.8	121,747.4	81,203.0	D_{A1} **= 1, 707,319.30**

Legend

$D_{A1_{m,Qi}}$ *Demand of buyer m*[th] *for A1 from quarry Qi*[th] *(ton).*

D_{A1_m}	*Total demand of buyer m^th^ for A1 (ton)*
D_{A1}	*Total demand for A1 in Market 3 (ton)*

Table IV. 28 Transportation distances between the nine buyers of A1 and different quarries ($d_{m,Qi}$) resulting from Figure III. 8 for Scenario 5. Distances were measured by QGIS tool. Figures in the table are in kilometer.

Quarries / $d_{m,Qi}$**(km)**	$d_{1,Qi}$	$d_{2,Qi}$	$d_{3,Qi}$	$d_{4,Qi}$	$d_{5,Qi}$	$d_{6,Qi}$	$d_{7,Qi}$	$d_{8,Qi}$	$d_{9,Qi}$
La Mariais				18.93					
Les Maraîchères					9.57				
La Faubretière et Les Rocherons					16.56				
La Margerie								5.57	
La Clarté				20.93					
La Coche	13.29								
La Guibourgère									12.59
Le Bois de la Roche			11.95						
Le Petit Betz							10.94		
Landes Coeffard		25.91					10.94		
Bel Air		27.64							
La Métairie Neuve							10.76		
La Bobatière	9.07								
La Vallée		17.07							12.59
L'Ennerie						2.74			
La Recouvrance					23.23				
La Lande du Cens		1.95							
La Guillonnais		1.95							
La Pommeraie		26.67			25.14				19.36
La Gagnerie	22.23				24.2				
La Grande Garde					24.2				

Legend

$d_{m,Qi}$ *Transportation distance between buyer m^{th} and quarry Qi^{th} (km).*

From Table IV. 27 and Table IV. 28 and equation (III. 22) the total ton-kilometer for the demanded A1 from different quarries is estimated. This value related to Scenario 5 is shown in equation (IV. 14).

$$D_{A1}.\,d_{Q_{Sc5}} = 27{,}291{,}798.6 \qquad \text{IV. 14}$$

Where $D_{A1}.\,d_{Q_{Sc5}}$ *is the total ton-kilometer resulting from the demands of A1's buyers from different quarries in Loire-Atlantique related to Scenario 5.The value is in ton*km.*

4.8.3 Share of Market 3 from A1 and RCC (*f1* and *f2*)

According to the assumption made in Scenario 5, that the total demand for basic quality aggregates in Market 3 is only met by the quarries in the territory, the shares of A1 and RCC in Market 3 are as follow.

$$f1_{Sc5} = 100\%;\ f2_{Sc5} = 0\% \qquad \text{IV. 15}$$

Where $f1_{Sc5}$ and $f2_{Sc5}$ are the shares of A1 and RCC in Market 3 respectively, according to the assumption of Scenario 5.

4.8.4 Environmental impact assessment results

Table IV. 29 illustrates the contributions of the territorial environmental model of CCDW management related to Scenario 5 (Figure IV. 14) to a range of environmental impacts. In addition, Table IV. 29 shows a given environmental impact translated into the number of European inhabitants which would generate the same impact, using the normalization factors in Table III. 1 and also their proportion to the total population of *Loire-Atlantique*.

Table IV. 29 Environmental impact indicator results of the territorial environmental model of CCDW management (Figure IV. 14) in Loire-Atlantique for the Scenario 5 and normalized values of the environmental impacts.

Environmental Impact Category	Total amount	Unit	Normalized value (European inhabitant/ year)	Normalized value relative to Loire-Atlantique's population (%)
Acidification potential, average European	1,684,272.7	Kg SO_2- Eq	947,285.0	71.4
Eutrophication potential, average European	1,024,059.0	Kg NOx- Eq	16,887.5	1.3
Resources, depletion of abiotic resources	2,609,526.9	Kg antimony-Eq	41,289,982.4	31.1 times of Loire-Atlantique's population
Stratospheric ozone depletion, ODP total	245.9	Kg CFC-11- Eq	10,506.8	0.8
Climate change, GWP 100a	323,091,164.5	Kg CO_2- Eq	38,463.2	2.9
Ionizing radiation, IRP_HE	2,116,917,307.9	Kg U235- Eq	501,639.2	37.8
Urban land occupation, ULOP	7,005,078.4	m^2a	510,202.4	38.4
Human health, respiratory effects, average	429,876.7	Kg PM2.5- Eq	-	-
Ecotoxicity, tota	1,303,579,334.8	CTU	-	
Human toxicity, total	163.6	CTU	-	
Fossil cumulative energy demand	4,433,684,469.7	MJ- Eq	67,897.2	5.1
Nuclear cumulative energy	27,356,929,969.9	MJ- Eq	-	-

Normalized values in Table IV. 29 show that the acidification, depletion of abiotic resource, Ionizing radiation and urban land occupation indicators are more considerable than other environmental impacts.

Figure IV. 15 shows the relative contributions of the processes included in Figure IV. 14 to 12 environmental impact categories presented in Table IV. 29 for Scenario 5.

As can be noticed from Figure IV. 15, the production of D_{A3CC} for Market 2 is the main contributor to the environmental impact categories, except for “urban land occupation” to which CCDW landfilling is the main contributor (45.2%). This is due to the assumption we made in Scenario 5, that all CCDW generated in the territory is disposed in the landfill and the total demand for basic quality aggregate is met only by the quarries. The production of D_{A1} and D_{RCC} for Market 3 is the second contributor after the production of D_{A3CC} for Market 2. This process in Scenario 5 includes only production of the demanded A1. The stock of unused A1 contributes to 1.8-2.2% of the total environmental impacts. This is not very significant compared to other process, since 8% of the total A1 produced is stored in the stock.

According to Figure IV. 15, transportation in Markets 1, 2 and 3 does not contribute to the environmental impacts significantly compared to other processes included in the territory. The result is reasonable, as regarding to Figure IV. 14 huge amounts of natural aggregates are produced in the quarry. However, transportation distances for heavy materials, such as construction materials, are usually limited. Transportation distance in Market 1 and 2 has been considered 30 km as an average distance between quarries and bituminous concrete plants/ cement concrete plants.

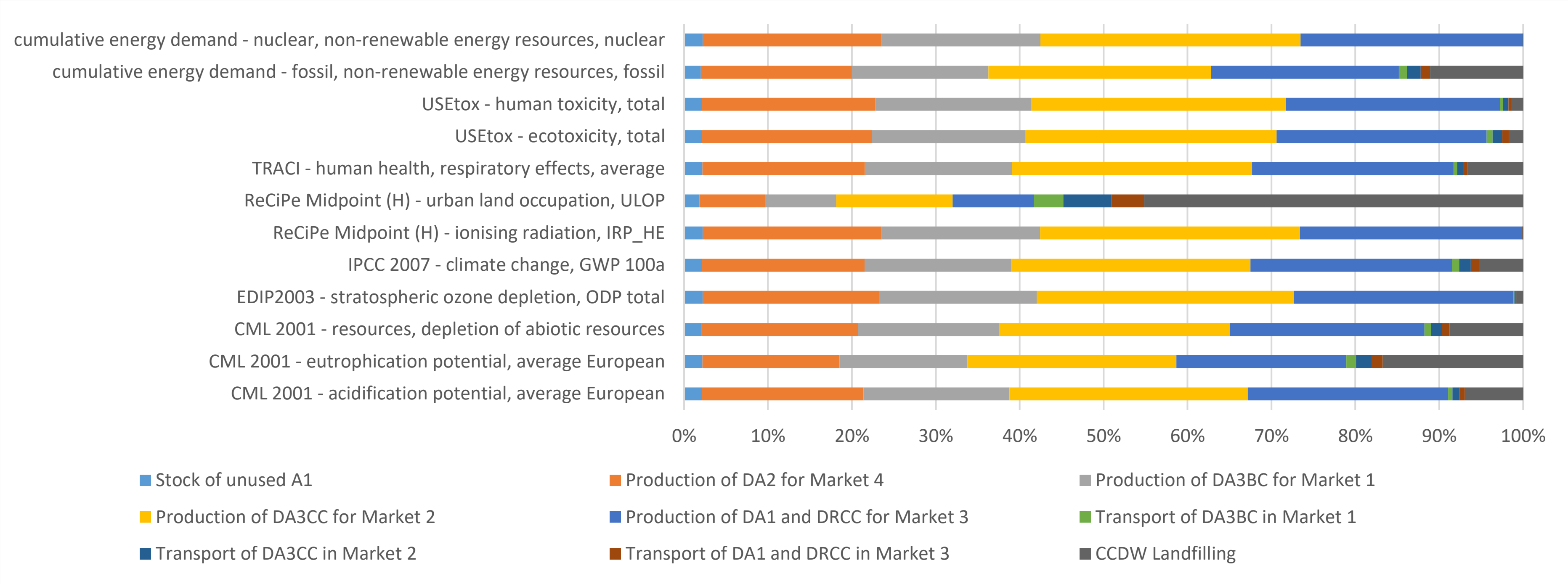


Figure IV. 15 Relative contributions of the processes included in the territorial environmental model of CCDW management (Figure IV. 14) to 12 environmental impact categories for Scenario 5. Stock of unused A1 includes the environmental impacts from production of unused A1 and stock itself, production of the demanded A2 (D_{A2}) in Market 4, production of the demanded A3BC (D_{A3BC}) in the bituminous concrete market (Market 1), production of the demanded A3CC (D_{A3CC}) in the cement concrete market (Market 2), production of the demanded RCC (D_{RCC}) and demanded A1 (D_{A1}) in the basic quality aggregate market (Market 3), transport distance between the distributers and the users of A3BC and A3CC considered 30km, Transport of D_{A1} and D_{RCC} in Market 3= transportation distances of D_{A1} and D_{RCC} from the quarries and the recycling facilities respectively to the related buyers, CCDW landfilling= landfilling of unused CCDW in the territory.

4.9 Comparison of scenarios

The goal of this section is to determine whether the environmental impacts caused by the reference scenario (Figure IV. 4) are significantly affected when the shares of A1 and RCC in Market 3 are changed in different scenarios (Scenario 1, Scenario 2, Scenario 3, Scenario 4 and Scenario 5).

In this study, only parts of the conceptual model in Figure II. 34 that are different (in terms of process type or magnitude) when the shares of A1 and RCC (*f1 and f2*) vary in different scenarios, have been selected for the environmental performance comparison. The environmental impacts caused by production of the demanded A2 and A3 remain unchanged, even when the shares of A1 and RCC in Market 3 are changed.

Figure IV. 16 shows the system boundary considered to compare the LCIA results of the reference scenario with those resulting from different scenarios.

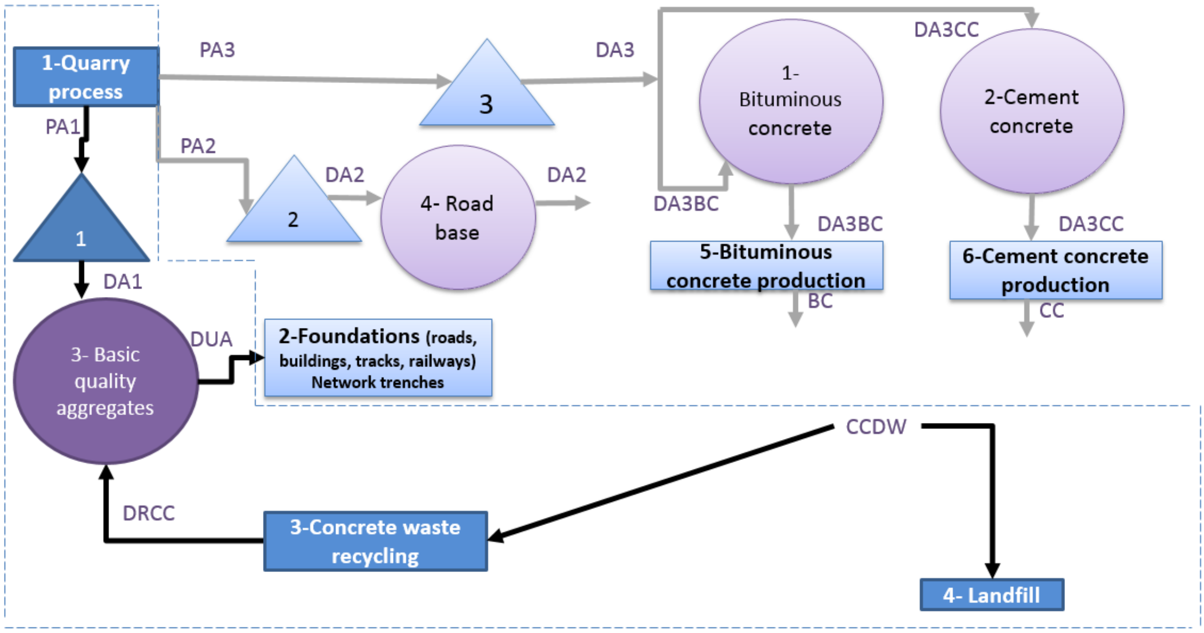


Figure IV. 16 System boundary considered to compare the environmental performance of the territorial environmental model of CCDW management caused by different shares of A1 and RCC in Market 3 (the dashed lines show the system boundary).

Legend

Process

Flow

Stock

Market

RCC: Recycled Cement Concrete

A1: primary category of natural aggregates

CCDW: Cement Concrete Demolition Wastes

A2: secondary category of natural aggregates

A3: tertiary category of natural aggregates

P_{A2}: produced A2

P_{A3}: produced tertiary category of natural aggregates in the quarry

Stock 3: stockpile of produced A3 in the quarry

D_{A3}: demand for tertiary category of natural aggregates

D_{A3BC}: demand for A3 in bituminous concrete market

D_{A3CC}: demand for A3 in cement concrete market

Market 2: market for cement concrete

Market 1: market for bituminous concrete

CC: cement concrete

BC: bitumenous concrete	P_{A1}: produced A1
Stock 1: stockpile of produced A1	Stock 2: stockpile of produced A2
D_{A1}: demand for A1 in basic quality aggregate market	D_{A2}: demand for A2 in road base market
Market 3: market for basic quality aggregates	Market 4: market for road base
D_{RCC}: demand for RCC	D_{BQA}: demand for basic quality aggregates
RCCDW: *fraction (R) of CCDW sent to the recycling facilities*	LCCDW: *fraction (L) of CCDW sent to the landfill*

4.9.1 **Comparison of markets, material flows and their transport**

Table IV. 30 presents a comparison between scenarios discussed in this chapter in terms of shares of A1 and RCC in Market 3.

When we introduced a 15% mistrust factor for RCC in Scenario 2, the market share in Scenario 2 was found to be the closest to that of the reference scenario. On the contrary, market share in Scenario 1 and Scenario 3, which was based on prices and confidence in the quality of RCC, was very different from that of the reference scenario.

Table IV. 30 Shares of A1 and RCC in Market 3 according to the studies scenarios.

Compared scenarios	**Share of A1 in Market 3 (%)**	**Share of RCC in Market 3 (%)**
Reference scenario: current situation in the territory in 2012	94	6
Scenario 1: Price-based market mechanism model	62	38
Scenario 2: Price-based market mechanism model with mistrust factor for RCC	90	10
Scenario 3: Price-based market mechanism model with trust factor for RCC	61	39
Scenario 4: legal obligation to use RCC	0	100
Scenario 5: legal obligation to use A1	100	0

Table IV. 31 provides main material flows in the territory for the reference scenario and different studied scenarios in this chapter.

Materials flows in Scenario 2 are close to those of the reference scenario, since the market mechanisms are similar. Scenario 1 and Scenario 3 in which the share of RCC in Market 3 increased compared to that of the reference, the stock of A1 increased and CCDW landfilling decreased.

Table IV. 31 Material flows in the territory according to the discussed scenarios. Figures in the table are in kilotons (Kt).

Compared scenarios	**D_{BQA}**	**D_{A1}**	**D_{RCC}**	**Stock of unused A1**	**CCDW**	**RCCDW**	**LCCDW**
Reference scenario: current situation in the territory in 2012	1,707.3	1,607.3	100.0	243.1	3,133.2	111.0	3,022.2
Scenario 1: Price-based market mechanism model	1,707.3	1,052.6	654.7	797.8	3,133.2	726.7	2,406.5
Scenario 2: Price-based market mechanism model with mistrust factor for RCC	1,707.3	1,537.8	169.5	312.6	3,133.2	188.2	2,945.1
Scenario 3: Price-based market mechanism model with trust factor for RCC	1,707.3	1,040.3	667.0	810.1	3,133.2	740.4	2,392.9

Scenario 4: legal obligation to use RCC	1,707.3	0.0	1,707.3	1850.4	3,133.2	1,895.1	1,238.1
Scenario 5: legal obligation to use A1	1,707.3	1,707.3	0.0	143.1	3,133.2	0.0	3,133.2

Legend

D_{BQA} : demand for basic quality aggregates *D_{A1}: demand for A1 in Market 3*

D_{RCC}: demand for RCC in Market 3 *CCDW: Cement Concrete Demolition Waste*

RCCDW: fraction (R) of CCDW sent to the recycling facilities *LCCDW: fraction (L) of CCDW sent to the landfills*

Table IV. 32 presents a comparison between the studied scenarios in terms of the total ton-kilometers for A1 and RCC in Market 3.

As it is evident in Table IV. 32, total ton-kilometers in these scenarios are similar. Therefore, it is expected that environmental impact results will not be sensitive to the changes in transport. However, as the total ton-kilometers in Scenario 2 are fewer than those of the reference scenario and Scenarios 1 and 3, the environmental performance of Scenario 2 in terms of transport should be slightly better. As discussed in section 4.7.2, the nine buyers in Scenario 4 needed to travel longer distances to meet their demands for basic quality aggregates. Therefore, the environmental impacts of the transport in Scenario 4 is expected to be higher than those of the reference scenario and Scenario 5.

Table IV. 32 total ton-kilometers, $D_{A1}.d_Q$ and $D_{RCC}.d_{Rec}$ respectively for A1 and RCC, according to the studies scenarios

Compared scenarios	**$D_{A1}.d_Q$ (km.ton)**	**$D_{RCC}.d_{Rec}$ (ton.km)**
Reference scenario: current situation in the territory in 2012	25,202,782.9	626,556.0
Scenario 1: Price-based market mechanism model	16,987,784.1	8,290,328.8
Scenario 2: Price-based market mechanism model with mistrust factor for RCC	23,108,506.7	1,233,743.5
Scenario 3: Price-based market mechanism model with trust factor for RCC	17,123,679.5	8,625,521.4
Scenario 4: legal obligation to use RCC	33,685,575.3	0.0
Scenario 5: legal obligation to use A1	0.0	27,291,798.6

4.9.2 Comparing the environmental impacts of the reference scenario with those of Scenario 1, Scenario 2 and Scenario 3

In this section the environmental impacts of the reference scenario presented in section 4.3.4, are compared with those of Scenario 1, Scenario 2 and Scenario 3 presented in sections 4.4.3, 4.5.4 and 4.6.4 respectively, with respect to the system boundary illustrated in Figure IV. 16.

In Figure IV. 17, we can see immediately that there are no substantial differences in the 12 environmental impact indicators related to four different conditions in Market 3. There is a similar pattern for almost all the environmental impact indicators, to which the reference scenario contributes the most and Scenario 1 and Scenario 3 contribute the least, except to the nuclear cumulative energy demand, ionizing radiation and stratospheric ozone depletion indicators they contribute the most. Their greater contribution to the nuclear cumulative energy demand indicator is because in Scenario 1 and Scenario 3, more CCDW has been crushed and more unused A1 has been stocked. This in turn leads to consuming more electricity for which the main energy source in France is nuclear power. The ionizing radiation and stratospheric ozone depletion indicators are related to the consumption of nuclear power in the processes.

The biggest differences in Figure IV. 17 are for the fossil cumulative energy demand, urban land occupation and depletion of abiotic resource indicators, where the contribution of Scenario 3 is respectively about 0.96, 0.92 and 0.97 times of the contribution of the reference scenario. These differences are because in the extraction of raw materials and disposal of wastes, fossil fuels, such as diesel, have been used. In the reference scenario more CCDW is landfilled compared to other scenarios (1, 2 and 3). Therefore, the fossil cumulative energy demand indicator is higher and subsequently higher depletion of the abiotic resource indicator is caused. In the reference scenario, more lands are occupied owing to landfilling more CCDW instead of recycling. As a result, the urban land occupation indicator in the reference scenario is higher.

Not surprisingly, environmental impacts caused by the reference scenario and Scenario 1 are almost the same as those of Scenario 2 and Scenario 3 respectively. The environmental impact results of the reference scenario and Scenario 1 are 0.99-1 times of those of Scenario 2 and Scenario 3 respectively. These similarities are because the market shares in the reference scenario and Scenario 2 (equations IV. 5 and IV. 9) are similar and market shares in Scenario 1 and Scenario 3 are similar too (equations IV. 7 and IV. 11).

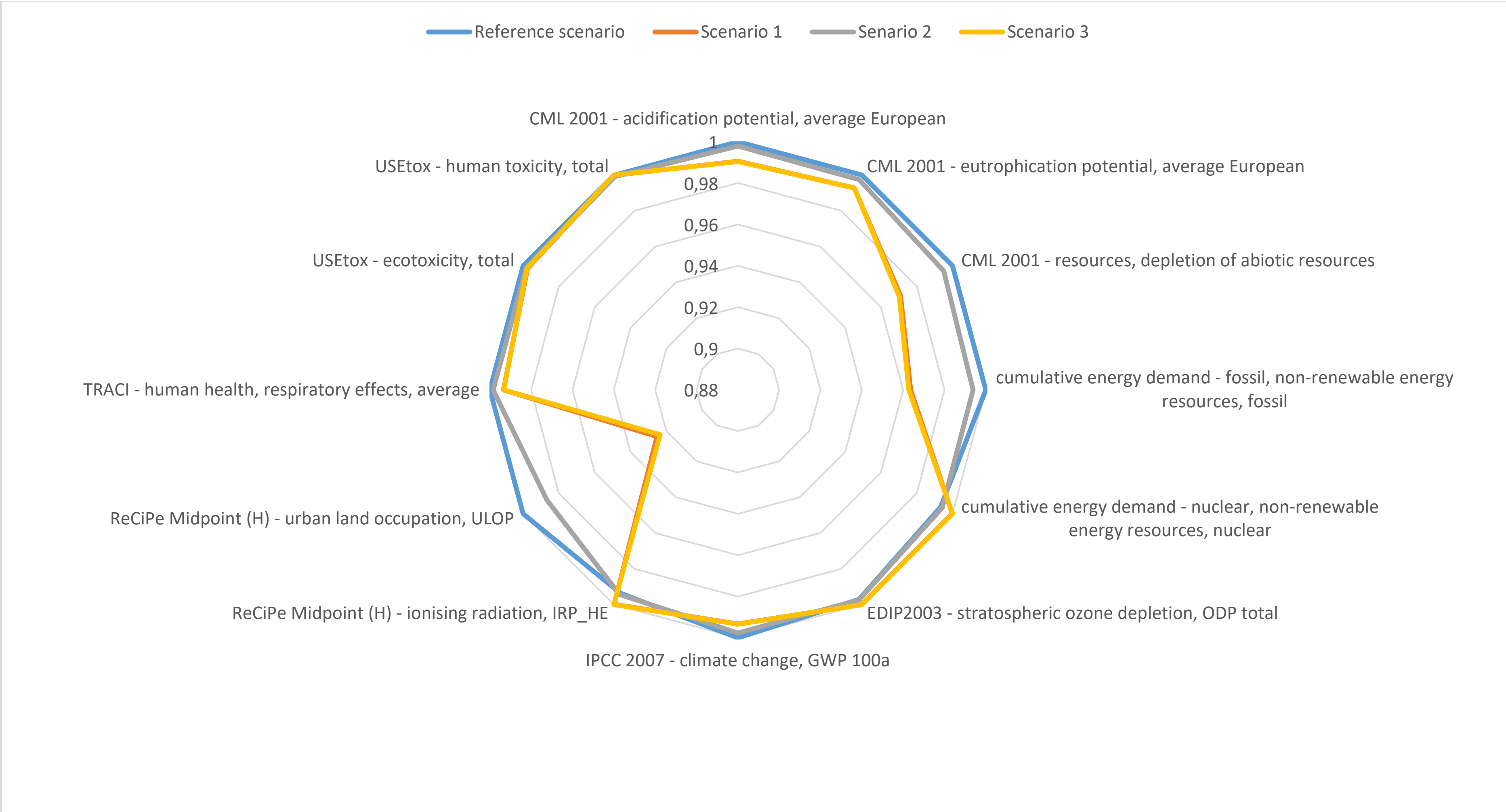


Figure IV. 17 Comparing the environmental impact indicators measured for the territorial environmental model of CCDW management in Loire-Atlantique with four different conditions in Market 3, considering the system boundary in Figure IV. 16. Four different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 1: 62% A1 and 38% RCC in Market 3, Scenario 2: 90% A1 and 10% RCC in Market 3 and Scenario 3: 61% A1 and 39% RCC in Market 3".

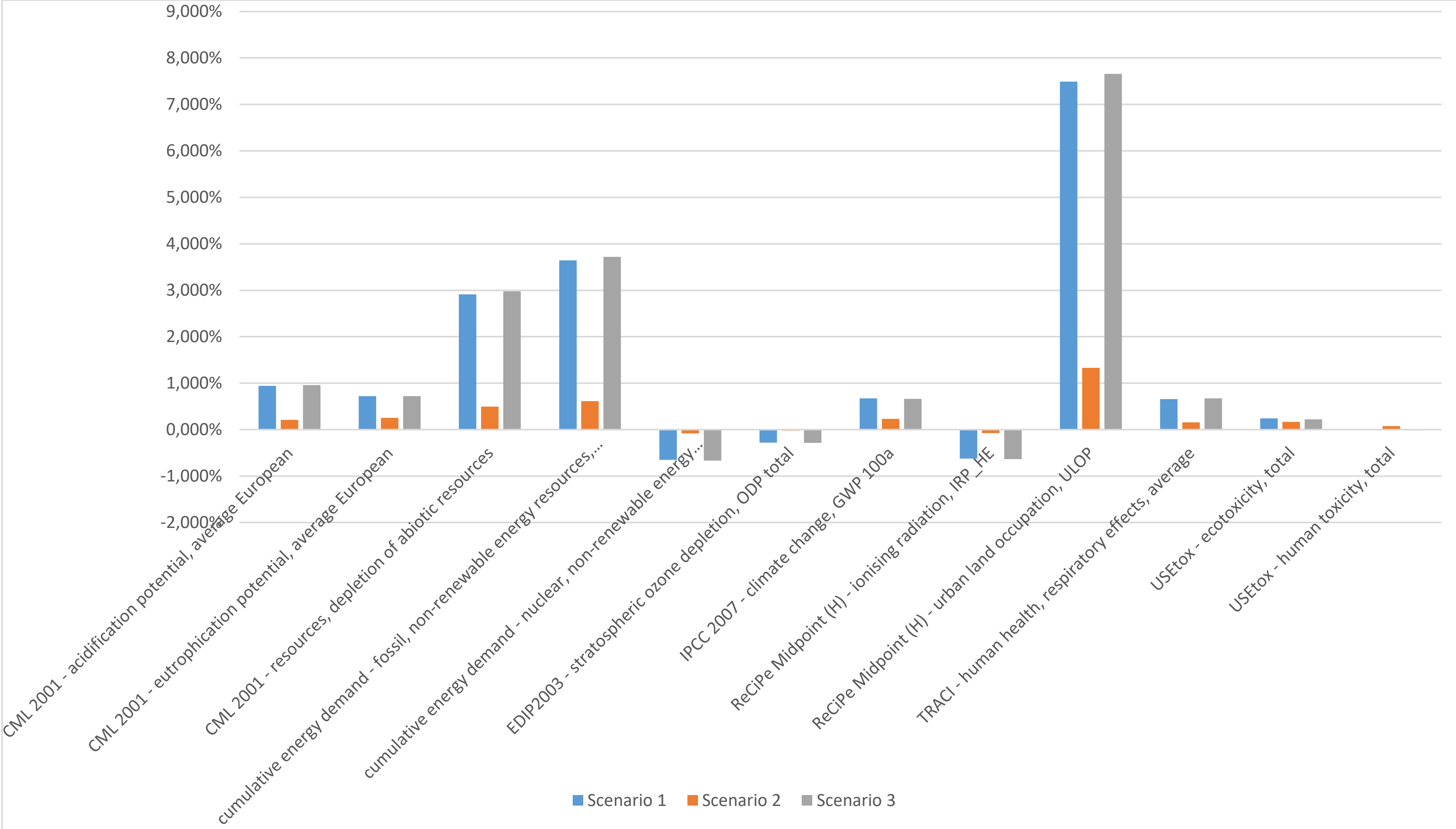


Figure IV. 18 Environmental improvements gained from different shares of A1 and RCC in Market 3 compared to the reference scenario. Negative values show that there is no environmental improvements compared to the reference scenario. Scenario 1: 62% A1 and 38% RCC in Market 3, Scenario 2: 90% A1 and 10% RCC in Market 3, Scenario 3: 61% A1 and 39% RCC in Market 3.

Table IV. 33 Magnitude of the environmental improvements gained in Scenario 3 compared to the reference scenario and the normalized values of the environmental impact improvements and their proportion to Loire-Atlantique's population.

Environmental impact category	**Acidification**	**Eutrophication**	**Depletion of abiotic resources**	**Climate change**	**Urban land occupation**	**Human health, respiratory effects**	**Ecotoxicity**	***Fossil CED**
Environmental impact improvements	5,402.9 Kg SO_2- Eq.	2,978.2 Kg NOx-Eq	26,912.8 Kg antimony- Eq.	688,862.1 Kg CO_2- Eq.	320,230.0 m^2a	957.5 Kg PM2.5- Eq.	845,521.0 CTU	59,808,300.0 MJ Eq.
Normalized value (European people/year)	3,038.7	49.1	425,835.1	82.0	23,323.4	-	-	915.9
Normalized value relative to Loire-Atlantique's population (%)	0.23	0.004	32.1	0.01	1.76	-	-	0.07

*cumulative energy demand

Overall, Figure IV. 17 illustrates that using more RCC in Market 3 (Scenario 3) has resulted in improving the environmental performance of CCDW management in *Loire-Atlantique*, compared to the reference Scenario. These environmental improvements (from 0.001-0.07% to 1.3-7.7%) are shown in Figure IV. 18, while deterioration has occurred in terms of nuclear cumulative energy demand, ionizing radiation and stratospheric ozone depletion indicators (as discussed above), 0.08-0.67%, 0.08-0.64% and 0.02- 0.29% respectively.

According to Figure IV. 18, the environmental improvements resulting from Scenario 3 (where the share of RCC in Market 3 is 39%), compared to the reference scenario (where the share of RCC in Market 3 is 6%) are from 0.22% to 7.7% for the ecotoxicity and urban land occupation indicators respectively. Table IV. 33 shows the magnitude of some of the environmental improvements resulting from increasing the share of RCC in Market 3 from 6% to 39%. In addition, the table shows a reduction in an environmental impact which has been translated into the number of European inhabitants that would generate the same impact, using the normalization factors in Table III. 1.

According to Table IV. 33, the improvement in the depletion of abiotic resource indicator almost corresponds to the sum of populations in segments 1, 2, 3, 4 and 6 in Figure IV. 3, which is considerable. The improvement in the land occupation indicator almost corresponds to half of the population in segment 3 in Figure IV. 3. Improvements in the acidification and fossil cumulative energy indicators represent the population of a small commune in *Loire-Atlantique*.

Figure IV. 19 - Figure IV. 30 depict the contribution of different processes included in the considered system boundary (Figure IV. 16) to 12 environmental impact categories when rising the share of RCC in Market 3 from 6% to 10%, 38% and 39% in Scenario 1, Scenario 2 and Scenario 3 respectively. The aim is to discover the reason why there is a slight difference between the LCIA results caused by four different conditions in Market 3 (reference scenario, Scenario 1, Scenario 2 and Scenario 3).

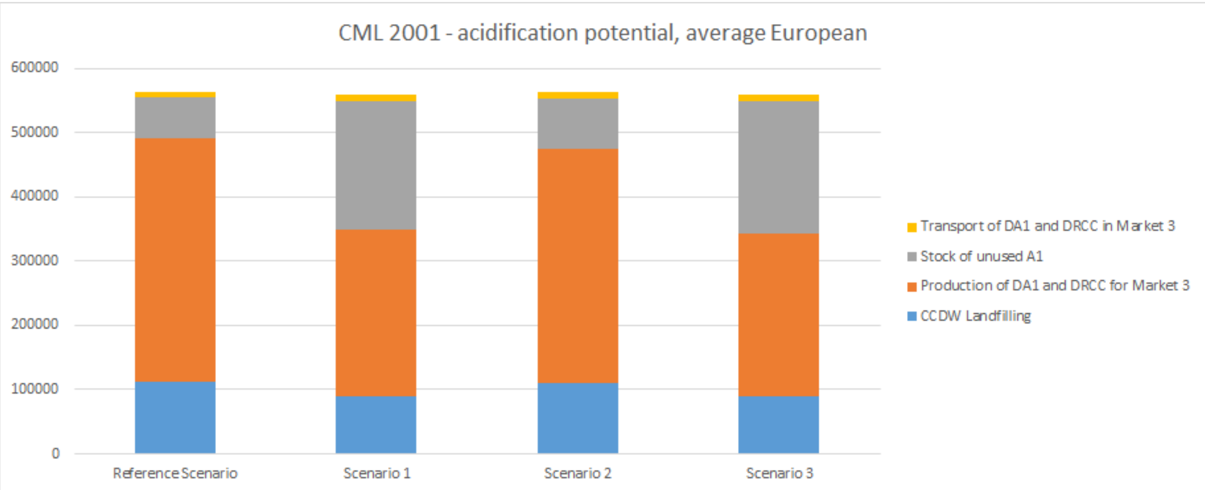


Figure IV. 19 The effects of four different conditions in Market 3 on total acidification potential, average European indicator (kg SO_2 eq.) resulting from different processes included in Figure IV. 16. Four different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 1: 62% A1 and 38% RCC in Market 3, Scenario 2: 90% A1 and 10% RCC in Market 3 and Scenario 3: 61% A1 and 39% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1=

includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

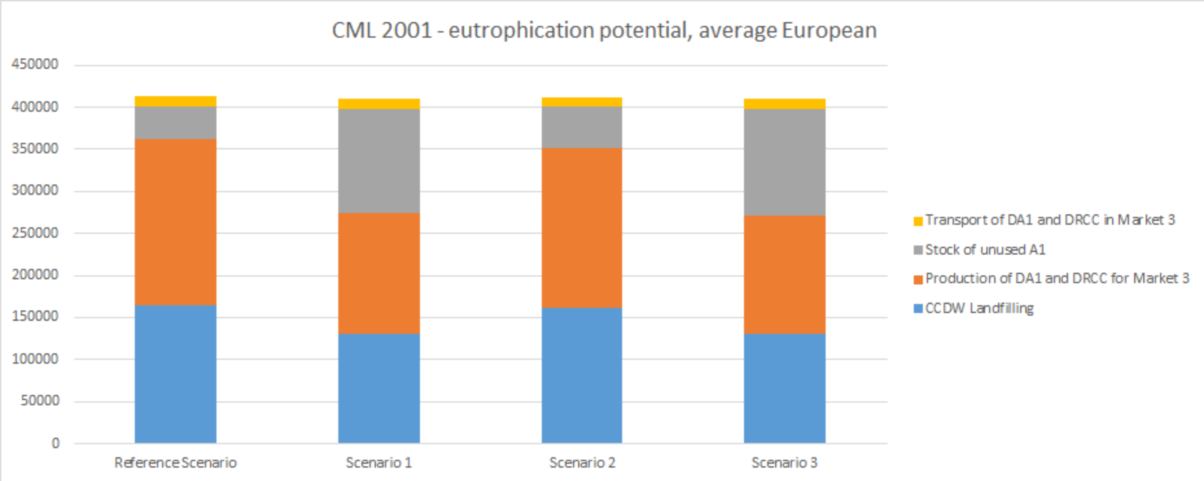


Figure IV. 20 The effects of four different conditions in Market 3 on eutrophication potential, average European indicator (kg NOx eq.) resulting from different processes included in Figure IV. 16. Four different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 1: 62% A1 and 38% RCC in Market 3, Scenario 2: 90% A1 and 10% RCC in Market 3 and Scenario 3: 61% A1 and 39% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

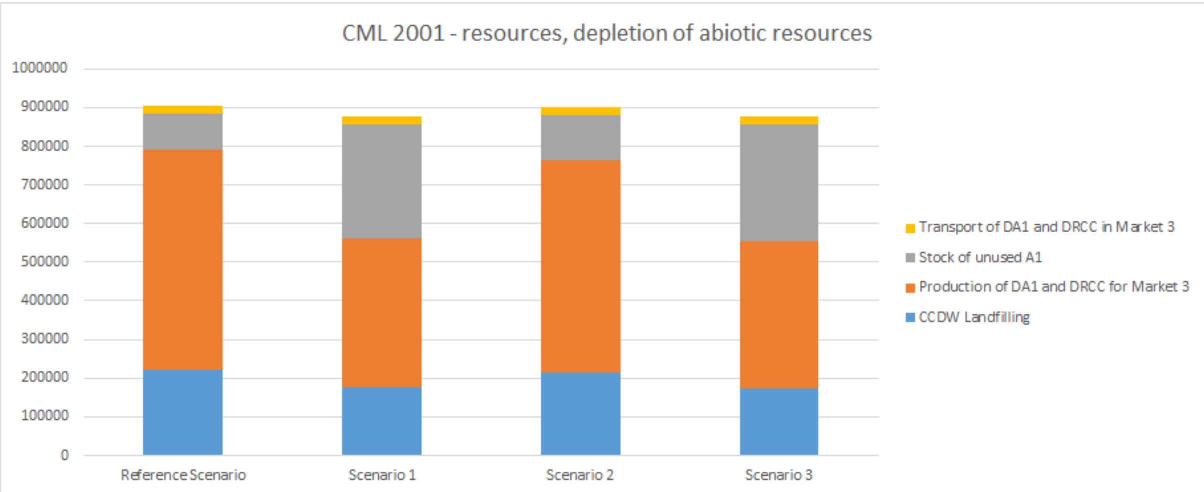


Figure IV. 21 The effects of four different conditions in Market 3 on total resources, depletion of abiotic resources indicator (Kg antimony eq.) resulting from different processes included in Figure IV. 16. Four different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 1: 62% A1 and 38% RCC in Market 3, Scenario 2: 90% A1 and 10% RCC in Market 3 and Scenario 3: 61% A1 and 39% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

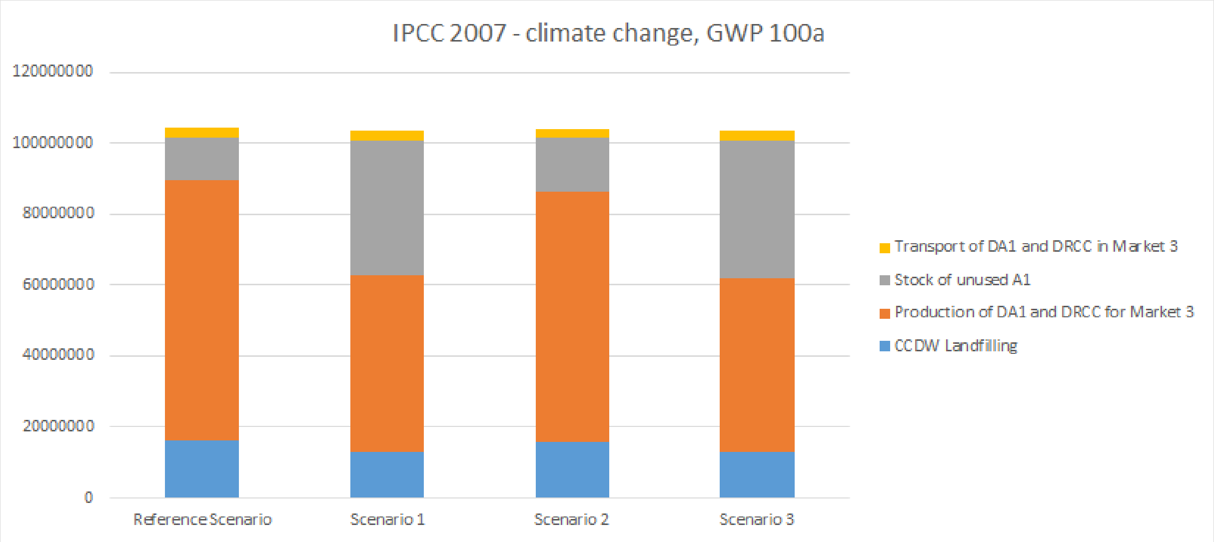


Figure IV. 22 The effects of four different conditions in Market 3 on total climate change potential indicator (Kg CO_2 eq.) resulting from different processes included in Figure IV. 16. Four different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 1: 62% A1 and 38% RCC in Market 3, Scenario 2: 90% A1 and 10% RCC in Market 3 and Scenario 3: 61% A1 and 39% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

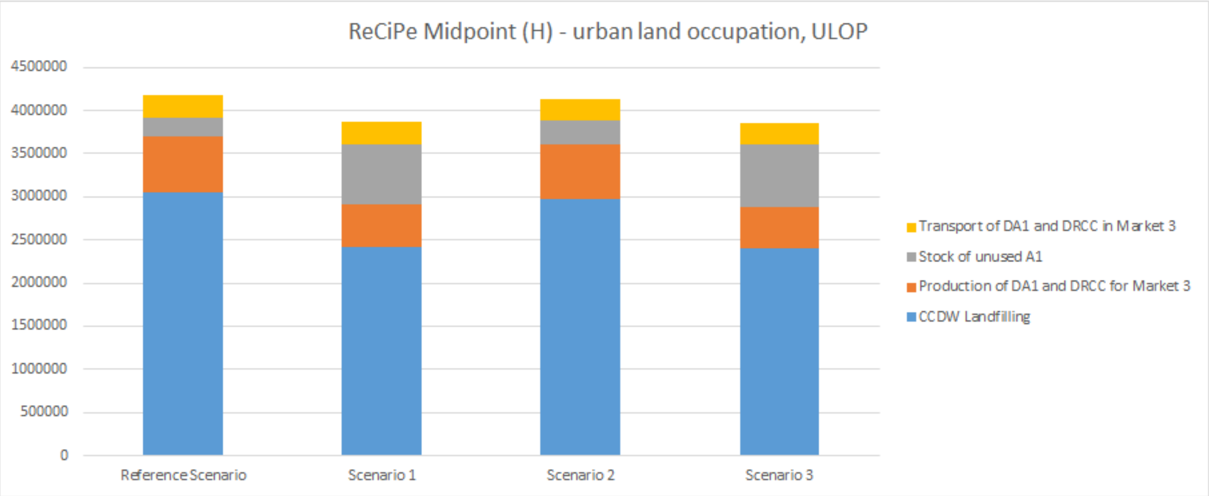


Figure IV. 23 The effects of four different conditions in Market 3 on total urban land occupation indicator (Kg m^2a eq.) resulting from different processes included in Figure IV. 16. Four different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 1: 62% A1 and 38% RCC in Market 3, Scenario 2: 90% A1 and 10% RCC in Market 3 and Scenario 3: 61% A1 and 39% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

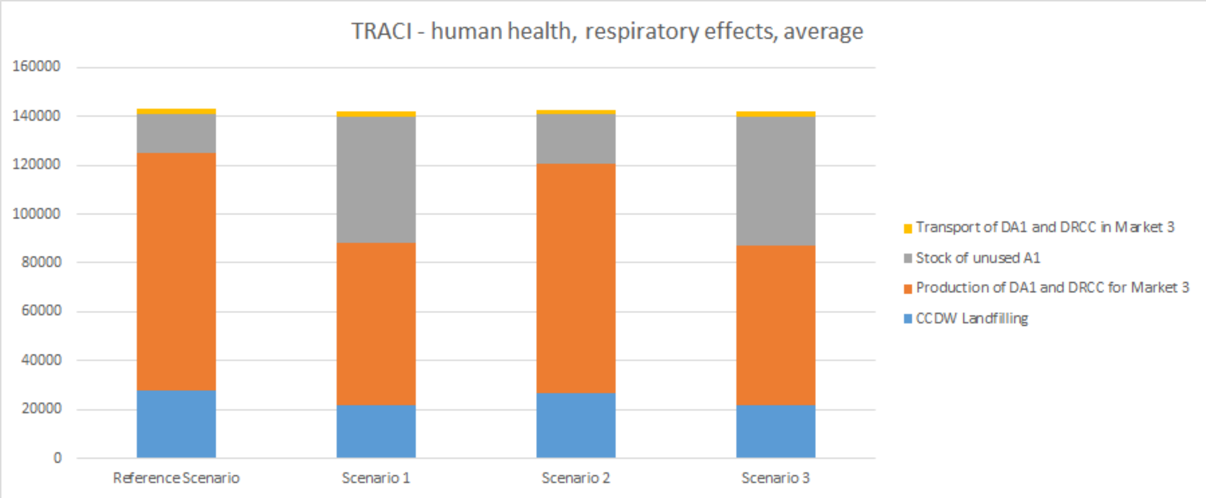


Figure IV. 24 The effects of four different conditions in Market 3 on total Human health respiratory effect indicator (Kg PM2.5 eq.) resulting from different processes included in Figure IV. 16. Four different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 1: 62% A1 and 38% RCC in Market 3, Scenario 2: 90% A1 and 10% RCC in Market 3 and Scenario 3: 61% A1 and 39% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

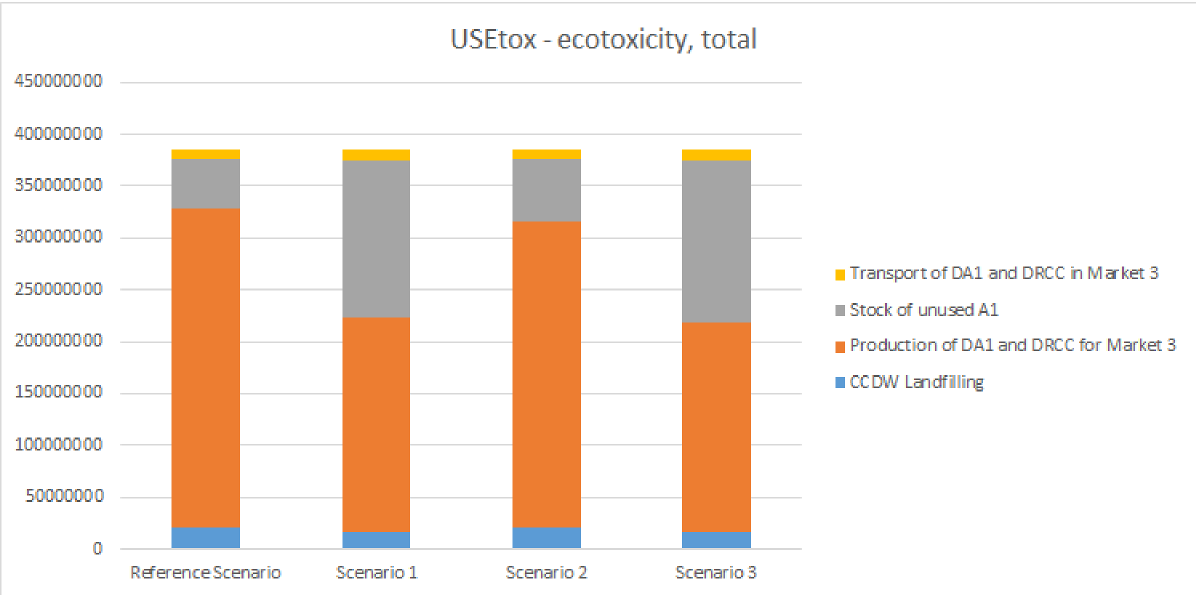


Figure IV. 25 The effects of four different conditions in Market 3 on total ecotoxicity indicator (CTU) resulting from different processes included in Figure IV. 16. Four different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 1: 62% A1 and 38% RCC in Market 3, Scenario 2: 90% A1 and 10% RCC in Market 3 and Scenario 3: 61% A1 and 39% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

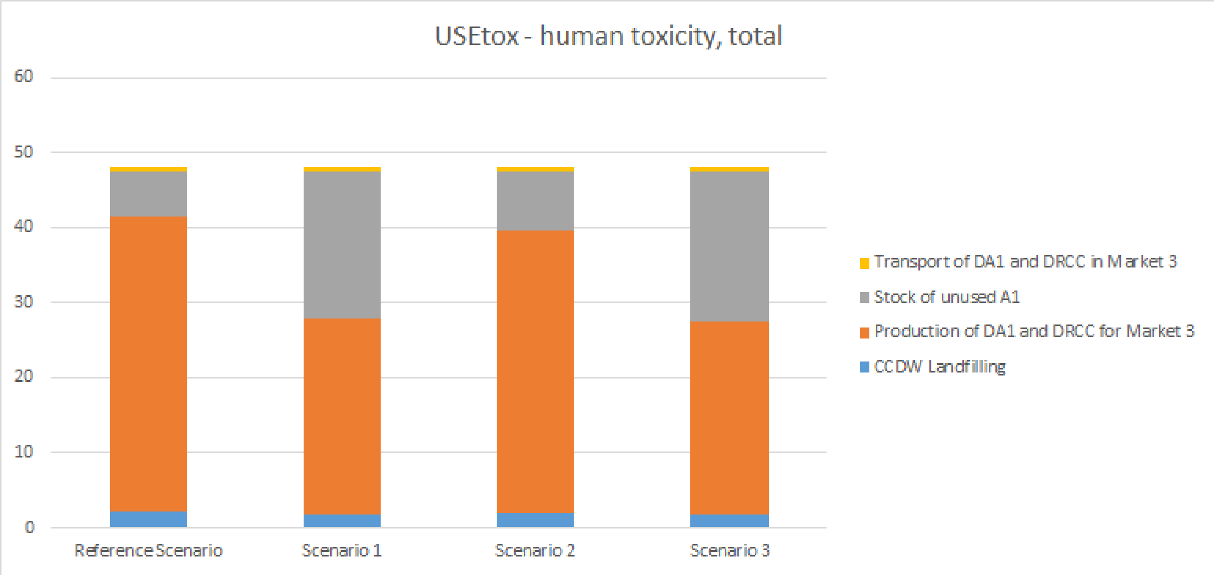


Figure IV. 26 The effects of four different conditions in Market 3 on total human toxicity indicator (CTU) resulting from different processes included in Figure IV. 16. Four different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 1: 62% A1 and 38% RCC in Market 3, Scenario 2: 90% A1 and 10% RCC in Market 3 and Scenario 3: 61% A1 and 39% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

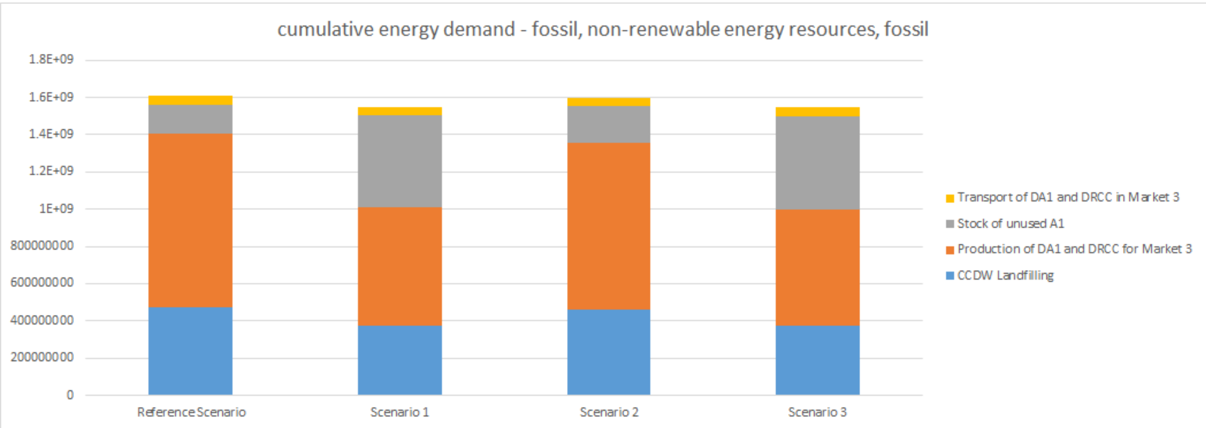


Figure IV. 27 The effects of four different conditions in Market 3 on total fossil cumulative energy demand indicator (MJ eq.) resulting from different processes included in Figure IV. 16. Four different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 1: 62% A1 and 38% RCC in Market 3, Scenario 2: 90% A1 and 10% RCC in Market 3 and Scenario 3: 61% A1 and 39% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

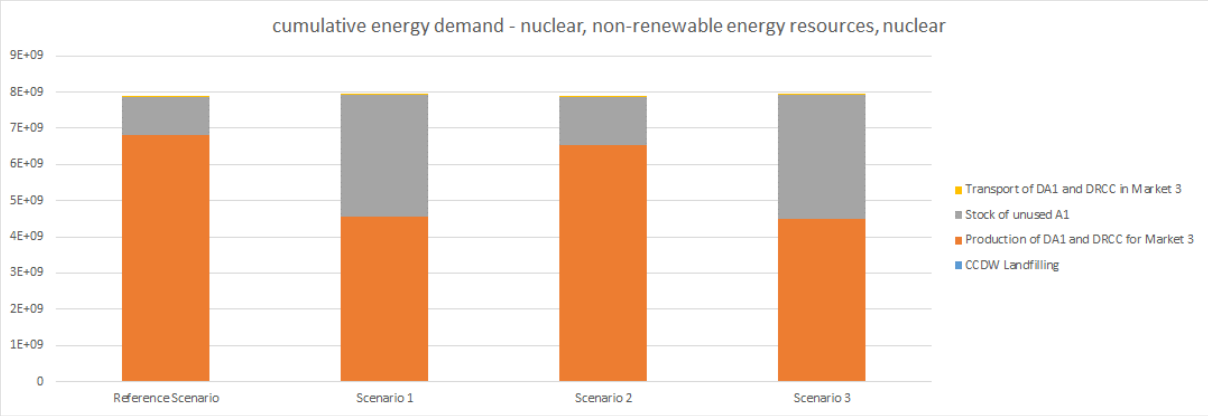


Figure IV. 28 The effects of four different conditions in Market 3 on total nuclear cumulative energy demand indicator (MJ eq.) resulting from different processes included in Figure IV. 16. Four different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 1: 62% A1 and 38% RCC in Market 3, Scenario 2: 90% A1 and 10% RCC in Market 3 and Scenario 3: 61% A1 and 39% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

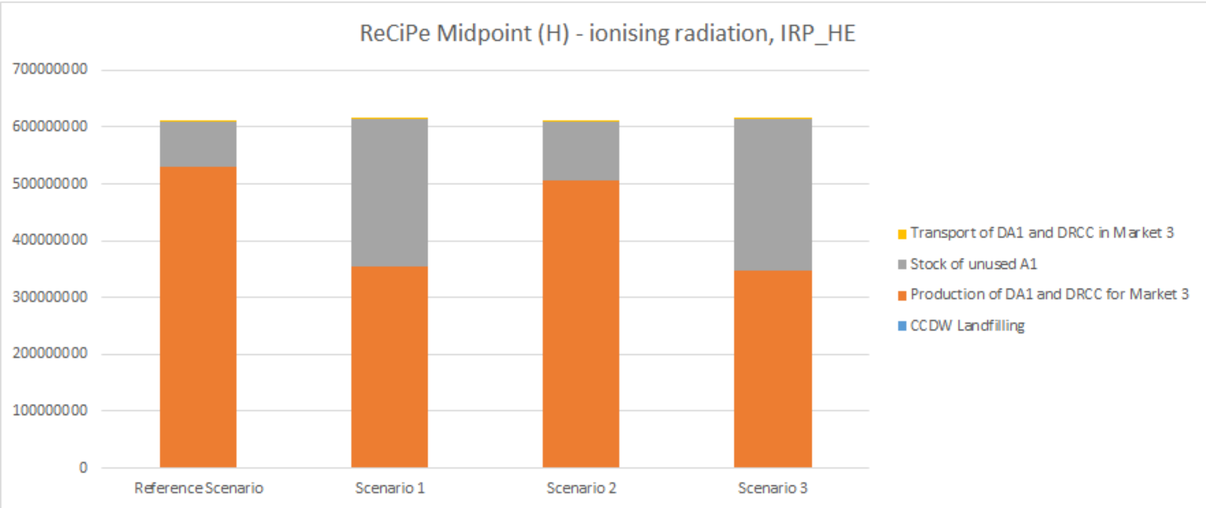


Figure IV. 29 The effects of four different conditions in Market 3 on total Ionising radiation indicator (Kg U235 eq.) resulting from different processes included in Figure IV. 16. Four different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 1: 62% A1 and 38% RCC in Market 3, Scenario 2: 90% A1 and 10% RCC in Market 3 and Scenario 3: 61% A1 and 39% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

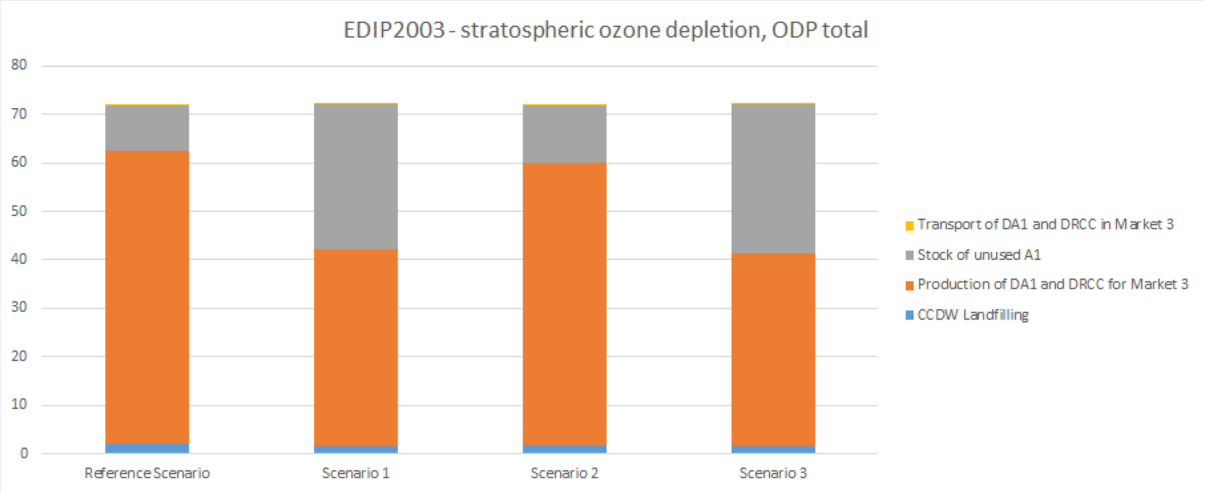


Figure IV. 30 The effects of four different conditions in Market 3 on total Stratospheric ozone depletion indicator (Kg CFC-11 eq.) resulting from different processes included in Figure IV. 16. Four different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 1: 62% A1 and 38% RCC in Market 3, Scenario 2: 90% A1 and 10% RCC in Market 3 and Scenario 3: 61% A1 and 39% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} in the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW for the territory.

As shown in Figure IV. 17 and Figure IV. 18, the environmental performance of CCDW management in *Loire-Atlantique* has been slightly improved in Scenario 1, Scenario 2 and Scenario 3 when the share of RCC in Market3 increased compared to the reference scenario. This slight improvement is evident from Figure IV. 19 - Figure IV. 27. According to the charts (Figure IV. 19 - Figure IV. 27), the reduction in the environmental impacts due to increasing the share of RCC in Market 3 or lowering CCDW landfilling has been offset by the increase in the environmental impacts caused by the stock of unused A1 (Scenario 1 and Scenario 3).

In Figure IV. 28 - Figure IV. 30, the environmental burdens are more than the environmental benefits in the case of increasing the share of RCC in Market 3 compared to the reference scenario. Therefore, the environmental deterioration in terms of nuclear cumulative energy demand, ionizing radiation and stratospheric ozone depletion has happened.

As can be noticed from Figure IV. 19 - Figure IV. 30, the environmental impacts are not significantly sensitive to the transportation of D_{A1} and D_{RCC} between sellers and the nine buyers of basic quality aggregates. This is because the shorter traveling distances between different quarries and the buyers in the reference scenario and Scenario 2 compared to Scenario 1 and Scenario 3 have been offset by the larger amount of A1 that has been hauled in the reference scenario and Scenario 2 (this issue is clear in equations IV. 4, IV. 6, IV. 8 and IV. 10). However, Scenario 2 has performed slightly better in terms of transport (see Figure IV. 31). This is due to the reason that, in Scenario 2 the choices of the nine buyers of basic quality aggregates are based on not only the total prices of the products, but also buyers' confidence in the quality of RCC. Therefore, they bought RCC when a shorter traveling distance to reach a recycling facility compensated the lower confidence of buyers in the quality of RCC. As mentioned earlier, in Scenario 1, the nine buyers make a choice between A1 and RCC based on the total prices of the products. Therefore, in some cases, the cheaper price of one ton of RCC at the recycling facilities compared to that of A1 at quarries (RCC is 0.5 €/ton cheaper) is enough to choose RCC in the market instead of A1. For instance, according to the results of Scenario 1, buyer 5 in segment 5 with the highest demand for basic quality aggregates, travelled up to 23.45 km to buy RCC, prior to buying A1 from the quarry, which is 9.57 km away. However, higher environmental impacts of transporting D_{RCC} in Scenario 1 have been compensated for by the lower amount of D_{A1}, which has been transported. Therefore, Scenario 1 resulted in fewer environmental impacts caused by transportation compared to the reference scenario.

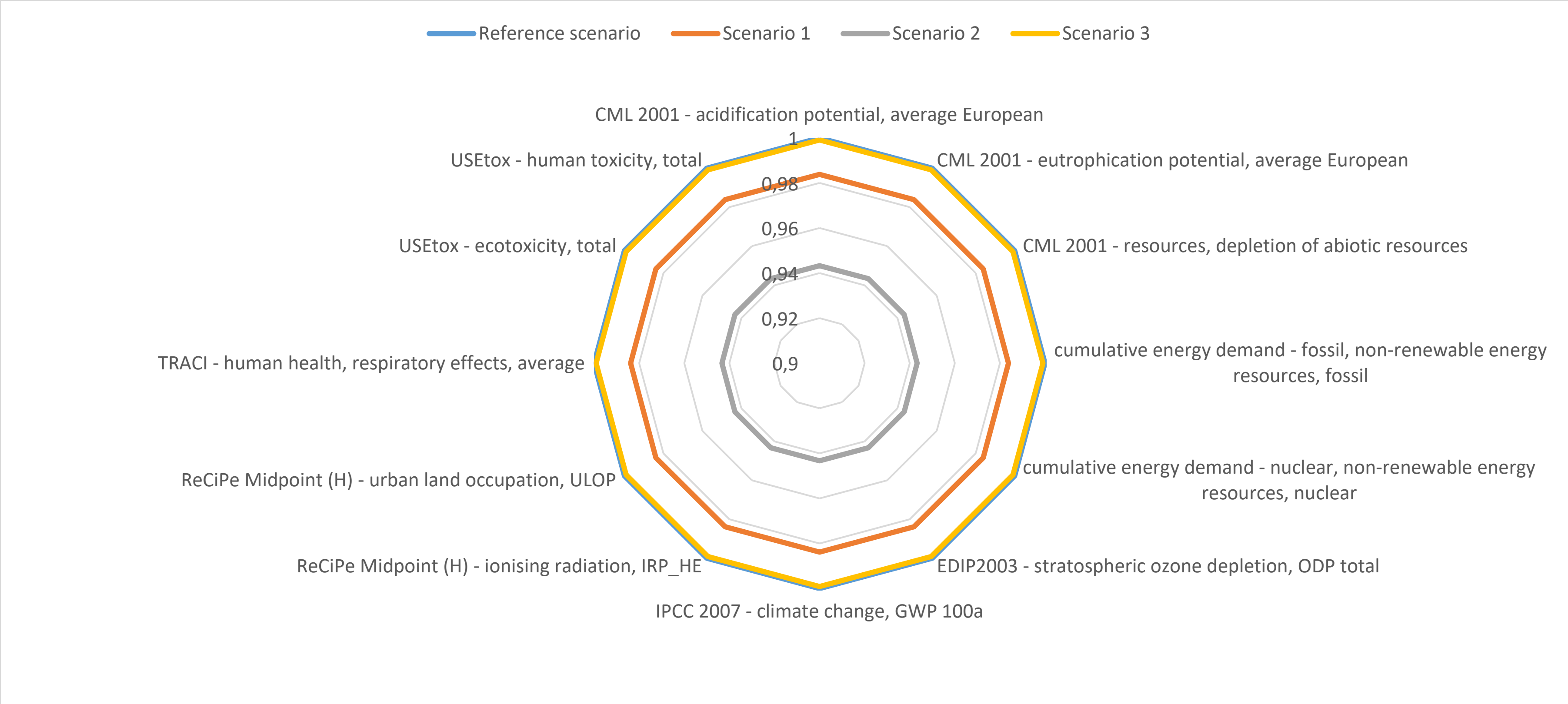


Figure IV. 31 Comparing the environmental impact indicators measured for transporting D_{A1} and D_{RCC} in Market 3 related to four different conditions in Market 3. Four different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 1: 62% A1 and 38% RCC in Market 3, Scenario 2: 90% A1 and 10% RCC in Market 3 and Scenario 3: 61% A1 and 39% RCC in Market 3".

4.9.3 Comparing the environmental impacts of the reference scenario with those of two defined obligatory scenarios (Scenario 4 and Scenario 5) in Market 3

In this section the environmental impacts of the reference scenario presented in section 4.3.4, are compared with those of Scenario 4 and Scenario 5 presented in sections 4.7.4 and 4.8.4. Scenario 5 refers to an obligatory use of RCC instead of A1 in the foundations, therefore shares of A1 and RCC are as equation (IV. 13). On the contrary, Scenario 5 refers to an obligatory use of A1 in the foundations instead of RCC, thus the shares of A1 and RCC are as equation (IV. 15).

In Figure IV. 32, we can see immediately that there are no considerable differences in 12 environmental impact indicators caused by the reference scenario, Scenario 4 and Scenario 5 (three different conditions in Market 3). There is a similar pattern for almost all the environmental impact indicators, to which Scenario 5 and the reference scenario respectively contribute the most and Scenario 4 contributes the least, except for the nuclear cumulative energy demand, ionizing radiation and stratospheric ozone depletion indicators Scenario 4 contributes the most. Greater contribution of Scenario 4 to the nuclear energy demand is because crushing CCDW to produce RCC and stock of unused A1 require electricity and the main energy source in France is nuclear power. Subsequently, the magnitude of the ionizing radiation and stratospheric ozone depletion indicators are related to the consumption of nuclear power in the processes.

The biggest differences in Figure IV. 32 are for the fossil cumulative energy demand, urban land occupation and depletion of abiotic resource indicators, where the contributions of Scenario 4 are respectively about 0.9, 0.8 and 0.92 times of the contributions of the reference scenario. These differences are because in the extractions of raw material and disposal of wastes, fossil fuels, such as diesel, have been used. In Scenario 4 less CCDW is landfilled compared to the reference scenario. Therefore, the fossil cumulative energy demand indicator is lower, which in turn has lowered the depletion of abiotic resource indicator. In Scenario 4, less land is occupied owing to more recycling of CCDW instead of landfilling. Therefore, the urban land occupation indicator in Scenario 4 is less than the reference scenario.

Not surprisingly, environmental impacts caused by the reference scenario are almost the same as those caused by Scenario 5. The environmental impact results of Scenario 5 are 0.99-1 times of those of the reference scenario. These similarities are due to the similar market shares for A1 and RCC, in Market 3, in the reference scenario and Scenario 5 (see equations IV. 5 and IV. 15).

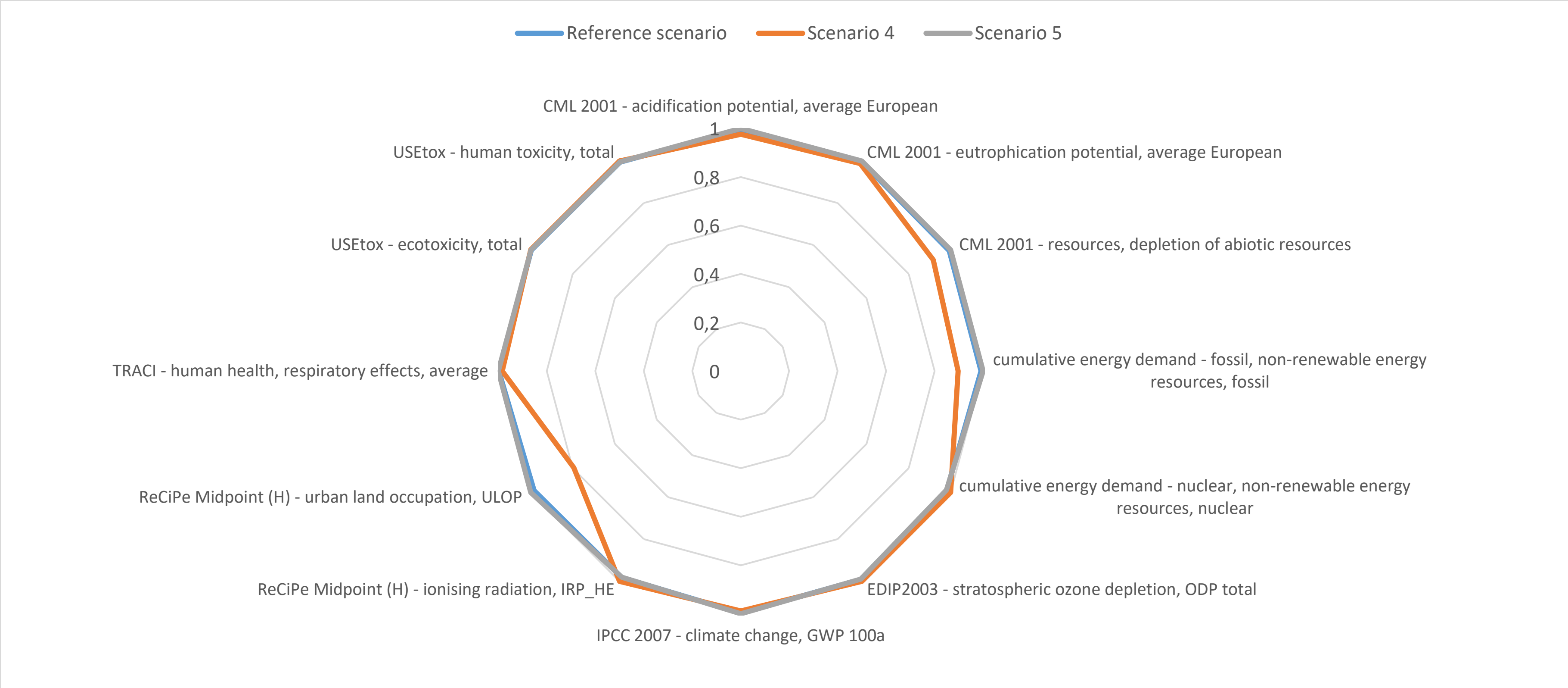


Figure IV. 32 Comparing the environmental impact indicators measured for the territorial environmental model of CCDW management in Loire-Atlantique with three different conditions in Market 3, considering the system boundary in Figure IV. 16. Three different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 4: 0% A1 and 100% RCC in Market 3, Scenario 5= 100% A1 and 0% RCC in Market 3.

Overall, Figure IV. 32 illustrates that, using more RCC in Market 3 (in Scenario 4), compared to the reference scenario, has resulted in improving the environmental performance of CCDW management in *Loire-Atlantique*. These environmental improvements (from 0.9% to 23.9%) are shown in Figure IV. 33, while deterioration has occurred in terms of nuclear cumulative energy demand, ionizing radiation and stratospheric ozone depletion indicators (as discussed above), 1.9%, 1.8% and 0.9% respectively. On the other hand, using more A1 in Market 3 (Scenario 5), compared to the reference scenario, has resulted in the deterioration of the environmental performance of CCDW management in *Loire-Atlantique* (from 0.08% to 1.6%); see Figure IV. 33. By contrast, environmental improvements in terms of nuclear cumulative energy demand, ionizing radiation and stratospheric ozone depletion indicators, 0.12%, 0.11% and 0.03% respectively, have resulted from using more A1 in Market 3 (in Scenario 5), compared to the reference scenario; see Figure IV. 33. This is due to the fact that, in Scenario 5 CCDW has not been recycled, thus no energy has been used for recycling. In addition, less A1 has been stocked, which this in turn has minimized electricity consumption.

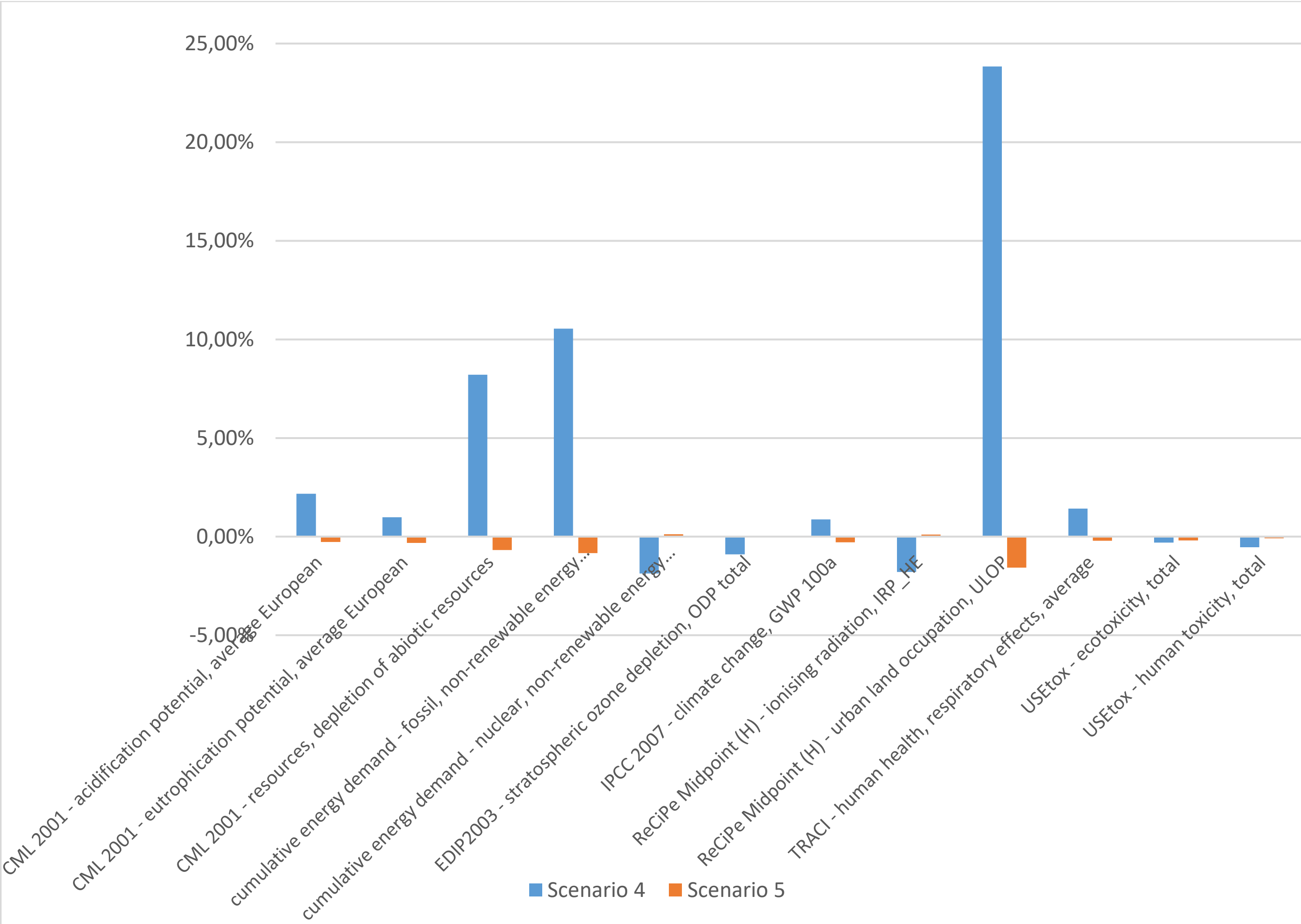


Figure IV. 33 Environmental improvements gained from different shares of A1 and RCC in Market 3 compared to the reference scenario. Negative values show that there is no environmental improvements compared to the reference scenario. Scenario 4: 0% A1 and 100% RCC in Market 3, Scenario 5: 100% A1 and 0% RCC in Market 3.

Table IV. 34 shows the magnitude of some of the environmental improvements resulting from increasing the share of RCC in Market 3 from 6% to 100%. Moreover, Table IV. 34 shows a reduction in an environmental impact which has been translated into the number of European inhabitants that would generate the same impact, using normalization factors in Table III. 1.

Table IV. 34 Magnitude of the environmental improvements gained in Scenario 4 compared to the reference scenario and the normalized values of the impact improvements and their proportion to Loire-Atlantique's populations.

Environmental impact category	**Acidification**	**Eutrophication**	**Depletion of abiotic resources**	**Climate change**	**Urban land occupation**	**Human health, respiratory effects**	***Fossil CED**
Environmental impact improvements	11,975.3 Kg SO_2- Eq.	3,989.9 Kg NOx- Eq.	68,631.7 Kg antimony- Eq.	688,862.1 Kg CO_2- Eq.	804,995.9 m^2a	2 009.3 Kg PM2.5- Eq.	153 264 359.9 MJ Eq.
Normalized value (European people/year)	6,735.3	65.8	1,085 944.3	82.0	58,630.4	-	2,347.1
Normalized value relative to Loire-Atlantique's population (%)	0.51	0.005	81.8	0.01	4.4	-	0.18

*Fossil cumulative energy demand

According to Table IV. 34, the improvement in the depletion of abiotic resource indicator is significant and representative of the sum of populations in segments 1, 2, 3, 4, 5 and 6 in Figure IV. 3. Improvement in the urban land occupation indicator is almost equal to the population of segment 1 in Figure IV. 3. Improvements in the acidification and fossil cumulative energy indicators represent the population of a small commune in *Loire-Atlantique*.

Figure IV. 34 - Figure IV. 45 depict the contribution of different processes included in the considered system boundary (Figure IV. 16) to 12 environmental impact categories, when rising the share of RCC in Market 3 (from 6% to 100%) and lowering the share of RCC in Market 3 (from 6% to 0%). The aim is to discover the reason why there is a slight difference between the LCIA results obtained from three different conditions in Market 3 (reference scenario, Scenario 4 and Scenario 5).

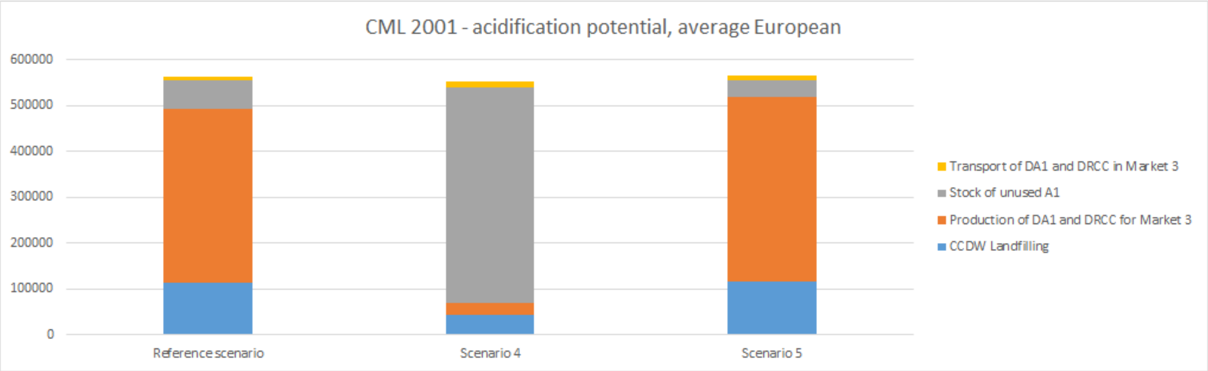


Figure IV. 34 The effects of three different conditions in Market 3 on total acidification potential, average European indicator (kg SO_2 eq.) resulting from different processes included in Figure IV. 16. Three different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 4: 0% A1 and 100% RCC in Market 3 and Scenario 5: 100% A1 and 0% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

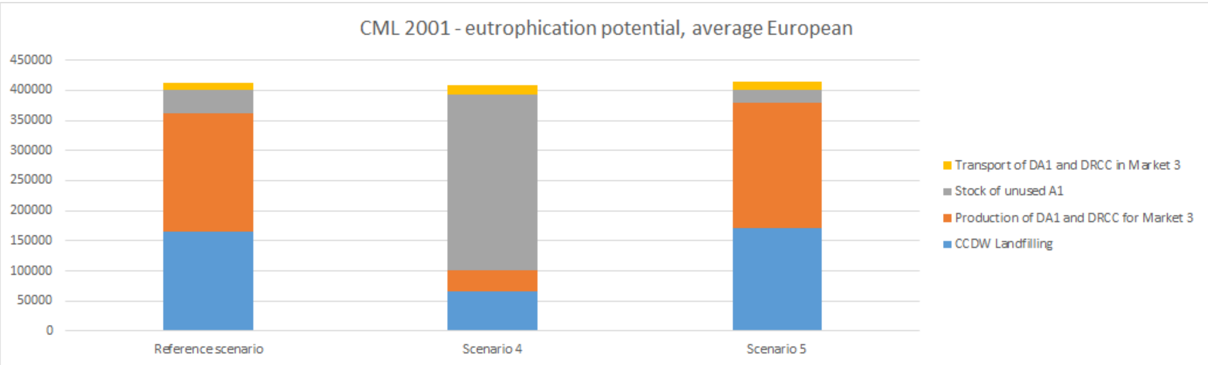


Figure IV. 35 The effects of three different conditions in Market 3 on eutrophication potential, average European indicator (kg NOx eq.) resulting from different processes included in Figure IV. 16. Three different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 4: 0% A1 and 100% RCC in Market 3 and Scenario 5: 100% A1 and 0% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

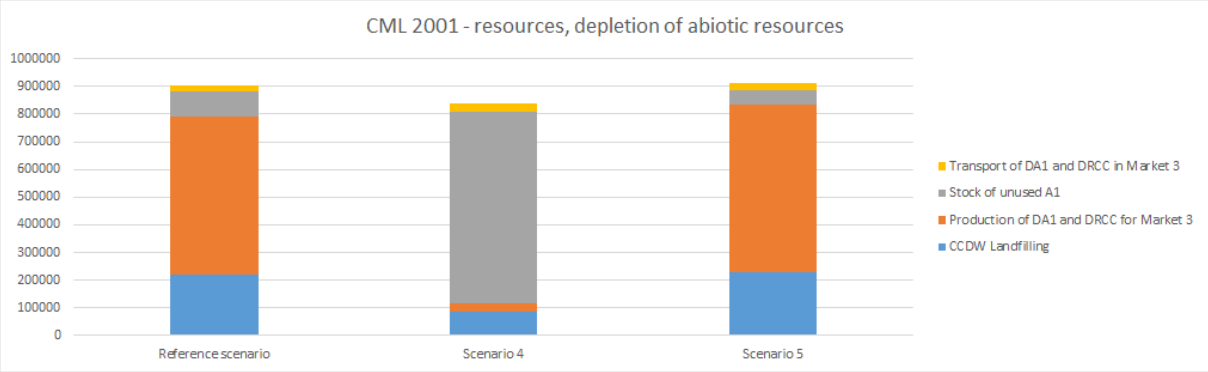


Figure IV. 36 The effects of three different conditions in Market 3 on total resources, depletion of abiotic resources indicator (Kg antimony eq.) resulting from different processes included in Figure IV. 16. Three different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 4: 0% A1 and 100% RCC in Market 3 and Scenario 5: 100% A1 and 0% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

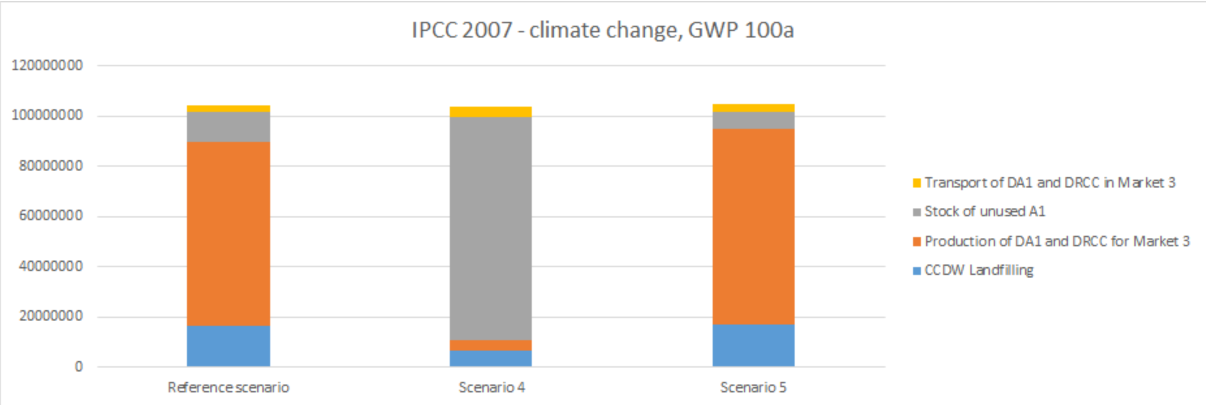


Figure IV. 37 The effects of three different conditions in Market 3 on total climate change potential indicator (Kg CO_2 eq.) resulting from different processes included in Figure IV. 16. Three different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 4: 0% A1 and 100% RCC in Market 3 and Scenario 5: 100% A1 and 0% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

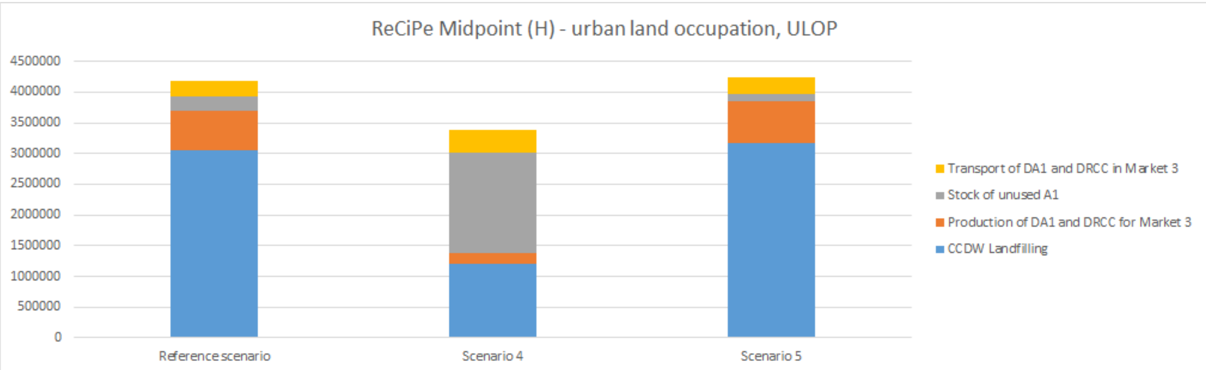


Figure IV. 38 The effects of three different conditions in Market 3 on total urban land occupation indicator (Kg m^2a eq.) resulting from different processes included in Figure IV. 16. Three different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 4: 0% A1 and 100% RCC in Market 3 and Scenario 5: 100% A1 and 0% RCC in Market 3". Transport of

D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

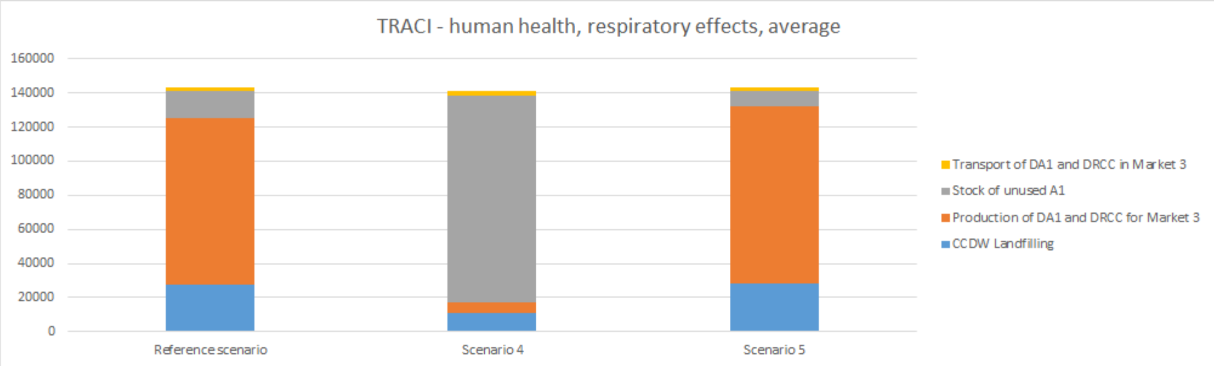


Figure IV. 39 The effects of three different conditions in Market 3 on total Human health respiratory effect indicator (Kg PM2.5 eq) resulting from different processes included in Figure IV. 16. Three different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 4: 0% A1 and 100% RCC in Market 3 and Scenario 5: 100% A1 and 0% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

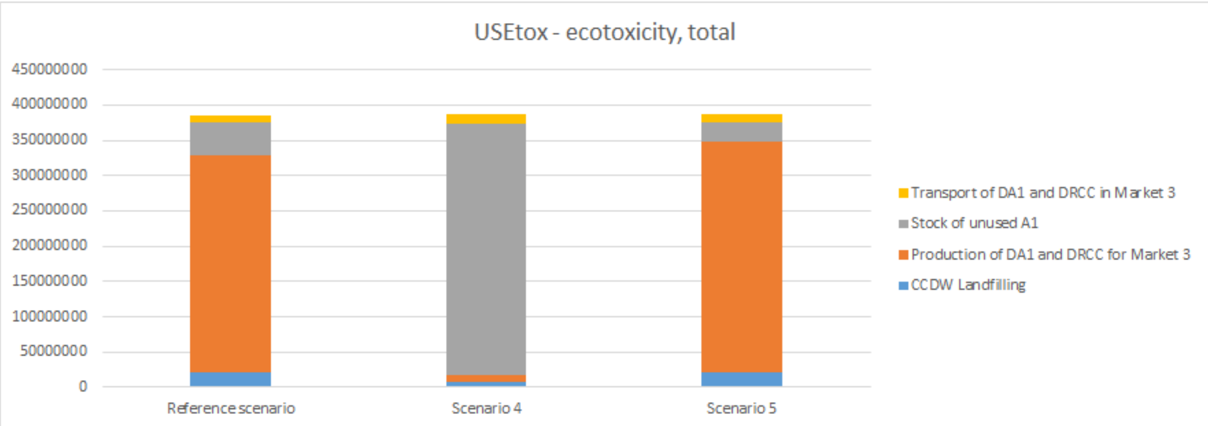


Figure IV. 40 The effects of three different conditions in Market 3 on total ecotoxicity indicator (CTU) resulting from different processes included in Figure IV. 16. Three different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 4: 0% A1 and 100% RCC in Market 3 and Scenario 5: 100% A1 and 0% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

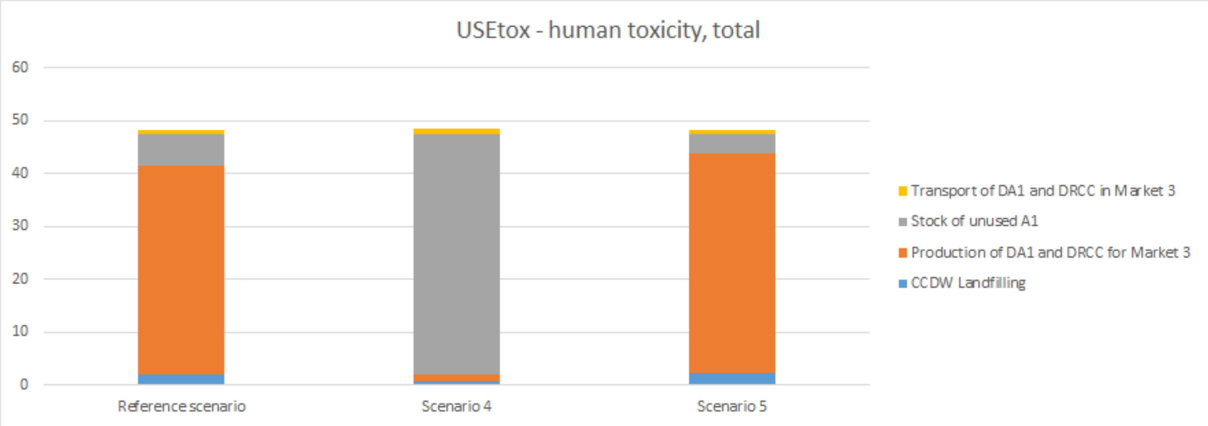


Figure IV. 41 The effects of three different conditions in Market 3 on total human toxicity indicator (CTU) resulting from different processes included in Figure IV. 16. Three different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 4: 0% A1 and 100% RCC in Market 3 and Scenario 5: 100% A1 and 0% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

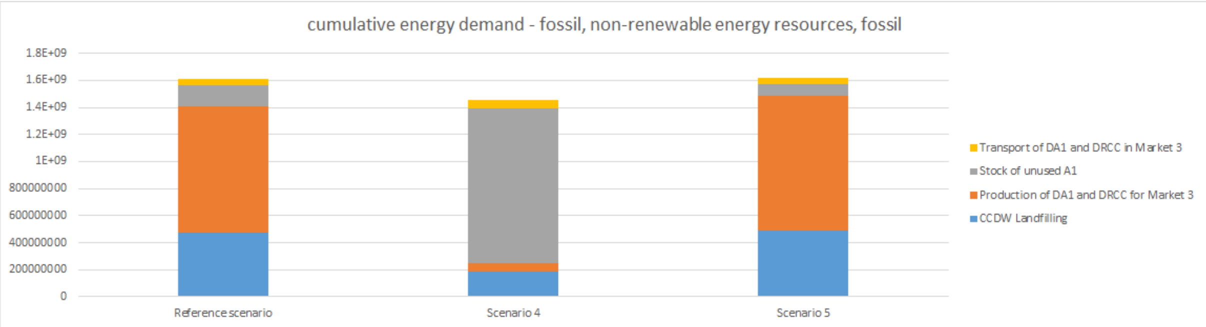


Figure IV. 42 The effects of four different conditions in Market 3 on total fossil cumulative energy demand indicator (MJ eq.) resulting from different processes included in Figure IV. 16. Three different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 4: 0% A1 and 100% RCC in Market 3 and Scenario 5: 100% A1 and 0% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

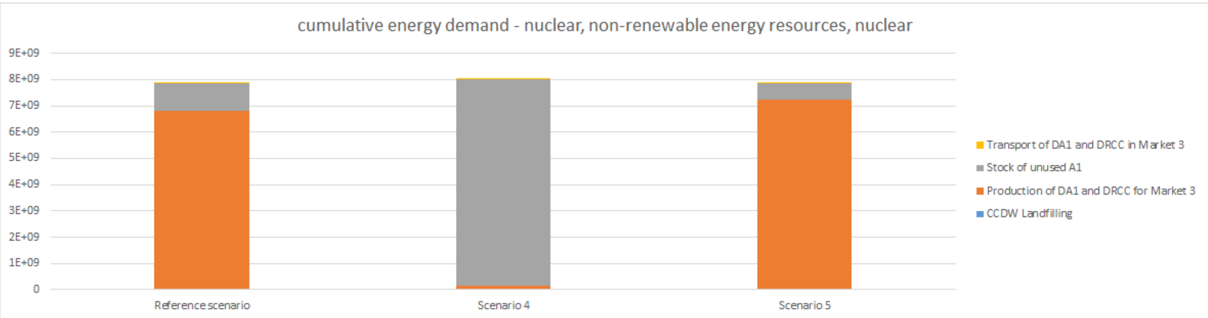


Figure IV. 43 The effects of four different conditions in Market 3 on total nuclear cumulative energy demand indicator (MJ eq.) resulting from different processes included in Figure IV. 16. Three different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 4: 0% A1 and 100% RCC in Market 3 and Scenario 5: 100% A1 and 0% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

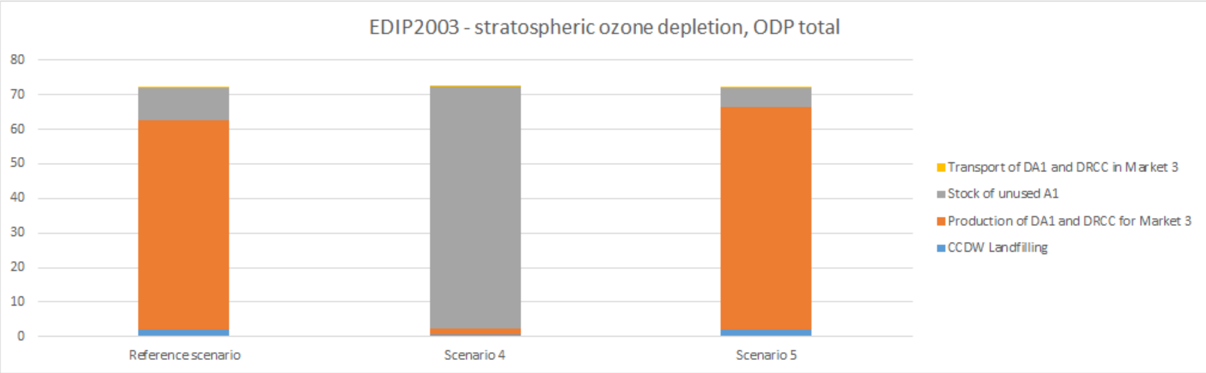


Figure IV. 44 The effects of three different conditions in Market 3 on total Stratospheric ozone depletion indicator (Kg CFC-11 eq) resulting from different processes included in Figure IV. 16. Three different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 4: 0% A1 and 100% RCC in Market 3 and Scenario 5: 100% A1 and 0% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

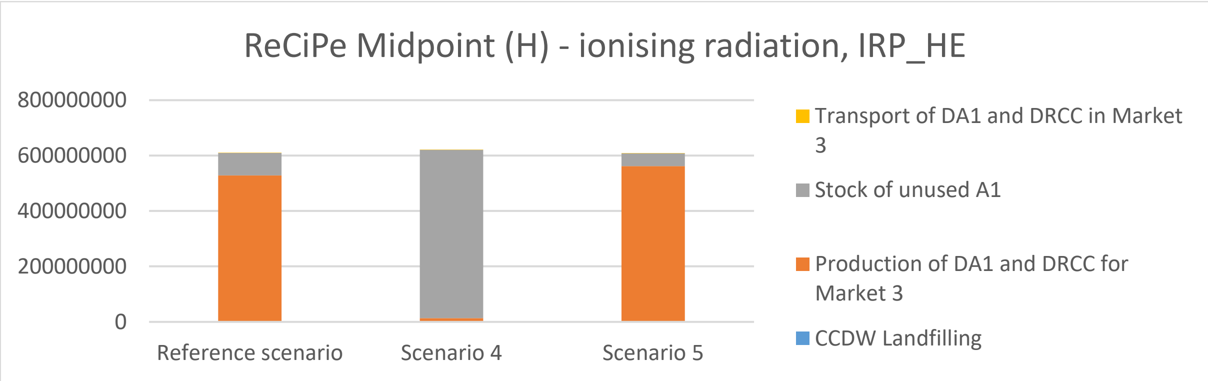


Figure IV. 45 The effects of three different conditions in Market 3 on total Ionising radiation indicator (Kg U235 eq.) resulting from different processes included in Figure IV. 16. Three different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 4: 0% A1 and 100% RCC in Market 3 and Scenario 5: 100% A1 and 0% RCC in Market 3". Transport of D_{A1} and D_{RCC} in Market 3= transport of demanded A1 (D_{A1}) and demanded RCC (D_{RCC}) from the quarries and the recycling facilities respectively to the related buyers, Stock of unused A1= includes production of unused A1 and stock itself, production of D_{RCC} and D_{A1} for the basic quality aggregate market (Market 3), CCDW landfilling= landfilling of unused CCDW in the territory.

According to Figure IV. 34 - Figure IV. 45, the environmental impacts caused by the production D_{A1} and D_{RCC} for Market 3 in Scenario 4 are significantly lower than those in the reference scenario and Scenario 5. As assumed in Scenario 4, Market 3 in Scenario 4 includes only RCC. Knowing this, the lower environmental impacts implied that, recycling CCDW does not have so many impacts on the environment compared to the impacts of the raw material extraction and A1 production. Likewise, the environmental impacts of CCDW landfilling in Scenario 4 are lower than those in the reference scenario and Scenario 5, since lower amount of CCDW has been landfilled in Scenario 4. On the other hand, a lot of A1 has been produced in Scenario 4 but not consumed (due to the assumption of Scenario 4). As a result, the impacts of producing D_{A1} in the reference scenario and Scenario 5 have been compensated for by the lower environmental impacts of stock of unused A1 in the reference scenario and Scenario 5.

As a result, the environmental performance has been slightly improved in the case of Scenario 4 compared to the reference scenario and Scenario 5. Environmental deterioration happens when the environmental burdens are more than the environmental benefits. For instance, in

Figure IV. 43-Figure IV. 45 deterioration in environmental performance of CCDW management in *Loire-Atlantique* in terms of the nuclear cumulative energy demand, ionizing radiation and stratospheric ozone depletion indicators has happened in Scenario 4 compared to the reference scenario and Scenario 5.

According to Figure IV. 34 - Figure IV. 45, the environmental impacts are not significantly sensitive to the transportation of D_{A1} and D_{RCC} between sellers and the nine buyers of basic quality aggregates. Because the total number of ton-kilometers is similar in the reference scenario and Scenario 5 (equations IV. 12 and IV. 14), while it is a bit higher in Scenario 4 (equation IV. 12). Because, traveling distances in Scenario 4 are longer compared to the reference scenario and Scenario 5 (as discussed in section 4.7.2). Accordingly, the environmental impacts caused by transportation in Scenario 4 are slightly higher than those caused by the reference scenario and Scenario 5. This issue has been illustrated in Figure IV. 46.

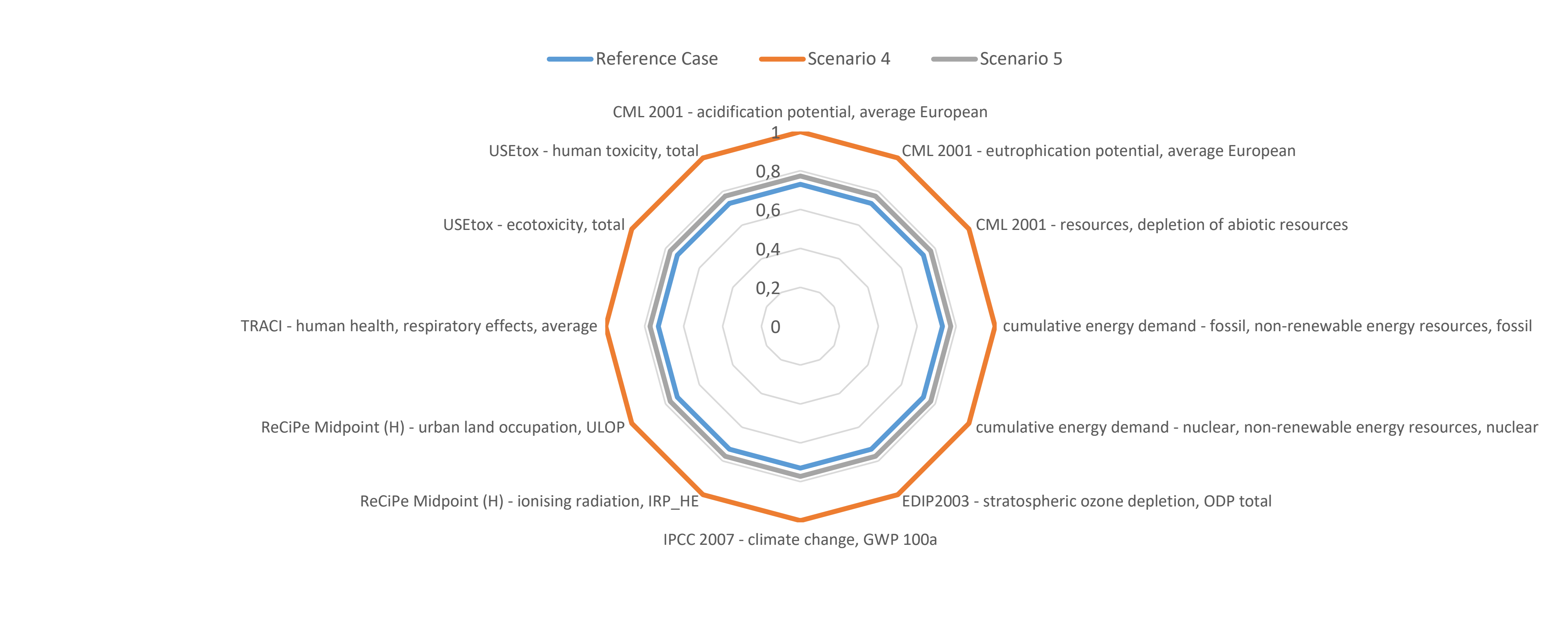


Figure IV. 46 Comparing the environmental impact indicators measured for transporting D_{A1} and D_{RCC} in Market 3 related to three different conditions in Market 3. Three different conditions: "Reference scenario: 94% A1, 6% RCC in Market 3, Scenario 4: 0% A1 and 100% RCC in Market 3 and Scenario 5: 100% A1 and 0% RCC in Market 3".

4.10 **Conclusion**

This chapter introduced *Loire-Atlantique* on the west coast of France as the territory understudy in this PhD. Literature, statistics and facilities were used as the main source to collect data on input and output flows of the territorial environmental model of CCDW management in Figure II. 34. Some assumptions had to be made to provide the required data for the model. Collected data were mainly related to year 2012.

Results of the reference scenario, which reflected the situation in the territory in 2012, and different scenarios defined in chapter 3 including the total demand respectively for A1 and RCC in Market 3, shares of A1 and RCC in Market 3, transportation distances between the buyers and sellers in Market 3 and total environmental impacts were presented in this chapter. The shares of A1 and RCC in Market 3 resulting from the price-based market mechanism model (Scenario 1) were very different from those of the reference scenario (as it was expected). This implied that, the mechanisms in Market 3 included other parameters besides the total prices of the product in the market, which affected the choices of buyers of basic quality aggregates in the market. One of those parameters considered in this PhD was the buyers' confidence in the quality of RCC.

Scenario 2 and Scenario 3 set to analyze the sensitivity of the price-based market mechanism model (Scenario 1) to the confidence of buyers, represented by nine aggregate buyers, in the quality of RCC. Results showed that when the buyers had lower confidence in the quality of RCC (Scenario 2), the shares of A1 and RCC in Market 3 were close to those of the reference scenario unlike when they had higher confidence in the quality of RCC (Scenario 3). Scenario 2 showed that, not the buyers were not affected just by the respective prices of A1 and RCC in Market 3, but also by their confidence in the quality of RCC. Results of Scenario 1 and Scenario 3 showed that, if the buyers made choices based on the total prices of the products or if the taxes on A1 increased, there would be a potential to increase the share of RCC in Market 3, up to 38-39%.

However, according to the LCIA results, the buyers' confidence in the quality of RCC did not significantly affect the environmental performance of the territorial environmental model of CCDW management in *Loire-Atlantique*, although it did affect the shares of A1 and RCC in Market 3. This was mainly due to the fact that, a compensation usually happened between the lower impacts of the CCDW recycling and the impacts of A1 production and the stock of unused A1 in the territory. Accordingly, increasing the share of RCC in Market 3 slightly improved the environmental performance of the CCDW management compared to the reference scenario. The main environmental improvement was in terms of the depletion of the abiotic resource indicator. The reduction in this indicator corresponded to 32.1% of *Loire-Atlantique*'s population, when the impact indicator was normalized.

The LCIA results of two scenarios regarding the enforcement of law in Market 3 (Scenario 4: 100% RCC in Market 3 and Scenario 5: 100% A1 in Market 3) revealed the fact that the environmental impacts of recycling CCDW were considerably lower than those of A1 production. However, in Scenario 4 on one hand, there was a circular economy for RCC; but on the other hand, a lot of A1 was produced for nothing. Therefore, the significantly lower impacts of recycling CCDW compared to producing A1 were offset by the impacts of the stock of unused A1 in the territory. As a result, the environmental performance of CCDW management in *Loire-Atlantique* was slightly improved, when increasing the share of RCC in Market 3 to 100%. The main environmental improvement was in terms of the depletion of abiotic resource indicator. The reduction in this indicator corresponded to 82% of *Loire-Atlantique*'s population, when the impact indicator was normalized.

To sum up, results of the comparisons showed that increasing the share of RCC in Market 3 compared to the reference scenario would improve the environmental performance of CCDW management in *Loire-Atlantique*, but not significantly. The main cause of this slight improvement is that the lower impacts of recycling CCDW were offset by the impacts of the stock of unused A1, which had to be produced since it is a dependent co-product of the quarry process. Therefore, in order to improve the environmental performance of CCDW management in *Loire-Atlantique* considerably, the inevitable production of A1 should be avoided by replacing A2 and A3 with an alternative. For instance, replacing A3 in cement concrete mix by RCC.

However, prior to an environmental analysis, it is required to investigate whether certain types of technologies needed to produce RCC are adequate for cement concrete mixes. Furthermore, it is required to perform specific analyses to determine in which types of construction projects RCC will lead to the maximum environmental benefits, as either cement concrete aggregates or basic quality aggregates.

CHAPTER V DISCUSSION

5.1 Introduction

In this chapter, we discuss whether the methodology proposed in this PhD did reach the main aim of this PhD and provide answers to the main research questions. We also discuss the limits of our work.

5.2 Discussion

In this PhD we aimed at evaluating the environmental performance of CCDW management in *Loire-Atlantique* for current situation and prospective scenarios based on actual practices to answer the following research questions:

- Would promoting recycling in the construction sector lead to minimizing the dependence on primary materials?
- Would replacing natural aggregates by Recycled Cement Concrete (RCC) improve the environmental performance?
- Could RCC be considered as a proper alternative to natural aggregates?

Based on the actual practices in France RCC mainly replaces basic quality natural aggregates (A1) produced in the quarries. Knowing this, a conceptual model was developed for the territorial environmental model of CCDW management in Figure II. 34. A combination of different methodologies was proposed to evaluate the environmental performance of CCDW management in the territory: LCA, MFA and a market mechanism model. The methodology could be adapted to any territory by using local MFA and local economic data, since construction materials are handled and managed locally.

5.2.1 MFA model

One of the most challenging parts of this PhD was data collection for the MFA model. The most recent data associated to CCDW management in *Loire-Atlantique* was from year 2012. Some assumptions needed to make to extrapolate the required information for some missing data, such as:

- Actual production of the quarries in *Loire-Atlantique*; using the relation between the actual production and authorized production of the Charier Company's quarries to estimate the actual productions of other quarries in *Loire-Atlantique* was a reasonable assumption. Because Charier Company's quarries represent one thirds of the total production in the region of *Pays de la Loire* in France. Furthermore, this relation would show the economic situation in the territory in 2012 that quarries produced less than their authorized production capacity.
- Estimating the production of each category of natural aggregates (A1, A2 and A3) from the total production in the quarries in *Loire-Atlantique*; this required knowing the production proportions of A1, A2 and A3 in each quarry. They could have been estimated through the Los Angeles (LA) values obtained from crushing of natural rocks

in each quarry, but we did not have an access to these values. Therefore, the average mass ratios of the products in Charier Company's quarries were used as the mass ratios in the quarries in *Loire-Atlantique*.

- Estimating the demands for A1 and A2 in the territory; there were no precise data concerning the consumption of A1 and A2 in *Loire-Atlantique*. Therefore, the demand proportions for A1, A2, and A3 in Charier Company's quarries were calculated and used to estimate the total demands for A1 and A2 in *Loire-Atlantique* in 2012, given that the total demand for A3 in *Loire-Atlantique* in 2012 was known. We assumed that these proportions were representative of all quarries in *Loire-Atlantique*.
- Production volumes of recycling facilities in *Loire-Atlantique* were not available. As a matter of fact, knowing these missing data could have changed the market share obtained in Scenarios 1, 2 and 3. However, based on personal communications with the recycling facilities, there is no limit for a recycling facility to produce RCC as long as it has an adequate supply of CCDW. Therefore, assumptions made in section 4.2.1.3 were quite acceptable.
- Creating the list of recycling facilities; the list of recycling facilities in *Loire-Atlantique* resulted from different sources and assumptions. However, more precise information concerning the type of the recycling facilities in *Loire-Atlantique* may be needed in the future.
- CCDW generated in Loire-Atlantique; CCDW was considered to be 40% of the total construction and demolition waste generated in France. We assumed that total construction and demolition waste produced per inhabitant in France was valid for Loire-Atlantique. According to this assumption, total CCDW generated in Loire-Atlantique was estimated. In order to calculate more precisely the total environmental impacts that each scenario produces, we need specific figures for Loire-Atlantique. Alternative figures found during this PhD thesis were also literature-based. Any changes in the amount of CCDW would affect the environmental impacts generated from CCDW landfilling and subsequently the total environmental impacts of the system. However, a change in this figure would not affect the results of comparisons between different scenarios studied in this thesis, since this change would make the same proportion of changes to every scenario. It should be noticed that, if ever the amount of CCDW considered in this PhD were lower in reality, we might not be able to define a scenario such as Scenario 4 in which the share of RCC in the market is 100%, due to an insufficient supply of waste. As a development of this work, due to new insights made available to us as this PhD thesis was being completed, new calculations with a lower figure for the total CCDW generated in *Loire-Atlantique* will be carried out by the author as a perspective for publication in forthcoming articles.
- CCDW disposed in the landfill; in our model we considered that CCDW that was not recycled was disposed into the landfill (some quarries which have reached the end of their life are used as landfills and are similar to them from an environmental points of view). This value was estimated from the difference between CCDW generated in *Loire-Atlantique* and CCDW required to produce RCC demanded in the market (CERC provided this value). However, there are recycling activities inside companies that own the entire production chain from demolition to road construction. Therefore,

demolished materials are internally recycled without going through a market. We needed data related to internal recycling to account for in our model, but they were not available. Therefore, our model reflected only the mechanism concerning the products that went through the market.

5.2.2 **Market mechanism model**

The reallocation routines in the procedures of the market mechanism model in Figure III. 7 provided enough complexity to spread the demand for basic quality aggregates in the territory between different sellers (quarries and recycling facilities). This detailed degree of routines would compensate the small, if any, numbers of buyers.

The market mechanism model enabled us to reach the results in terms of market share, while we did not have the representation of the market itself, since we did not have the physical locations of the buyers in *Loire-Atlantique*. The model enabled us to understand the impacts of some parameters including confidence factor on market share. Even if it did not represent reality, it was good enough to question reality. For instance, if in reality the market mechanisms were just based on the prices of the products, there would be a potential to increase the share of RCC in the market to 38%. This indicates a need to work on consumer's confidence in the quality of RCC or on the necessity to impose taxes on natural aggregates in order to make their price less attractive.

However, we know that in reality several parameters may be involved such as:

- Selling prices of A1 and RCC at quarries and recycling facilities respectively may not be the same all over the territory.
- If a seller has stock of a resource, he may sell it for a cheaper price than the going price. This is mostly true for the quarries.
- There may be a competition between the buyers for having a resource that a buyer may offer a higher price to have the resource.

We did not consider the above-mentioned parameters, mainly because the physical locations of the buyers were not known. A buyer in the territory represented the consolidated buyers located in the center of gravity of a segment on the map (Figure IV. 3). Therefore, we were not able to model a price for each buyer. As a result, considering a set, predetermined selling price or average selling price in the territory was the best possible option.

5.2.3 **LCA model**

The model developed in this PhD thesis to evaluate the environmental performance of CCDW management in a given territory is an expanded system including multitude of reference flows, while a classical LCA focuses on one functional unit. In a classical LCA used for an environmental assessment of waste management, the system understudy is usually expanded to include avoided burdens through recycling (such as impacts of a waste material that could have been landfilled but has been recycled) to isolate the functional unit and avoid the multi-functionality problems of recycling. But we considered both the flow of waste that was recycled and the rest of waste that was landfilled in the scope of the study.

In the classical LCA, the potential environmental impacts of a product or a service through its life cycle are related to the elementary flows associated with producing a specific amount of a product that is going to be used and not be stored (e.g. due to an inevitable extra production). In our model we accounted for the extra production (stock of materials in the territory that were demand constrained).

One of the main concepts in a consequential LCA is to estimate the environmental consequences of increasing or decreasing the demand for a product in a market. It assumes that when the demand for a product in a market decreases, its production decreases, and vice versa. While, we showed not only the environmental consequences of increasing/decreasing the demand for a product in the market, but also the environmental impacts from producing the unused products due to the inevitable production.

5.2.4 **Border effects of the territory**

On the map of *Loire-Atlantique* in Figure IV. 3 the border effect was not taken into account. In other words, in this study the interactions of the territory understudy with other territories were not considered, mainly due to a lack of data. This implies that, if a seller is located close to the border of a department (another territory) with *Loire-Atlantique*, a buyer in *Loire-Atlantique* close to the border may prefer to buy from that seller due to the distance. Expanding the scale of the territory, e.g. from departmental scale to a regional scale might better reflect the reality concerning the trading between different territories with the same borders.

According to the environmental impacts resulting from different scenarios, normalization of the depletion of the abiotic resources exceeded *Loire-Atlantique'*s population. This issue might be related to the border effect and export and import activities taking place in the territory as well as large numbers of quarries in the territory.

5.2.5 **Perspectives scenario for waste management**

The methodology proposed in this PhD enabled us to assess the environmental performance of CCDW management in *Loire-Atlantique* for current situation in the territory and different scenarios as well as answer the research questions.

As a result, using RCC instead of natural aggregates in the low-grade application (foundations) would not minimize the dependence on primary materials, as A1 was inevitably produced in the territory, even if it was not utilized. Moreover, quarries were still needed to produce natural aggregates (A2 and A3) for higher-grade applications (e.g. bituminous concrete and cement concrete). Replacing A1 with RCC would improve the overall environmental performance, but not significantly. This was mainly due to the stock of unused A1 in the quarries. RCC could be considered as a proper alternative to natural aggregates. Because they are technically equivalent, RCC is more economically beneficial and producing RCC has much lower environmental impacts than producing the same amount of A1 in the quarries.

However, in this study we considered RCC to be technically equivalent to basic quality aggregates. If the quality of RCC is improved to be used as aggregates in high-grade applications (e.g. cement concrete), the conceptual model will be changed as follows:

- There would not be the stock of unused A1 due to the lack of demand in the market or inevitable production because of the demand for A3
- The cement concrete market (Market 2) would have two suppliers: A3CC (A3 for cement concrete) and RCC. Therefore, a market mechanism model would have to be developed for Market 2 to investigate the shares of A3CC and RCC in the market.

CHAPTER VI CONCLUSIONS AND PERSPECTIVES

6.1 Conclusions

The main objective of this PhD thesis was to evaluate the environmental performance of Cement Concrete Demolition Waste (CCDW) management in a given territory for the current situation and for different scenarios, in order to answer the main research questions in this PhD thesis. The questions were as follows:

- Would recycling of the inert waste materials (such as CCDW as the main constituent of the inert materials) minimize the environmental impacts and decrease the dependence on primary materials?
- Could recycled products (such as Recycled Cement Concrete_ RCC) be considered as a proper alternative to natural resources (such as natural aggregates)?

Based on a review of literature carried out in Chapter 2 a traditional LCA model was developed for our case, which was recycling of CCDW into RCC and using RCC in the foundations as an alternative to basic quality natural aggregates (A1 produced in the quarry). We highlighted the limits of this approach and justified the evolution of this model. The conceptual model proposed for the territorial environmental modeling of CCDW management (Figure II.34) presented the expanded CCDW management system that included different processes associated with the management of waste in the territory. The expanded system enabled us to avoid the multi-functionality (or allocation) problems of recycling and quarry process (as a co-producing process) and give a better insight of the territory in terms of the environmental performance. The territory understudy in this PhD was *Loire-Atlantique* on the west coast of France.

The objective of this PhD was achieved by combining LCA with a local market mechanism model and MFA. LCA was used to estimate the potential environmental impacts of the territorial CCDW management. MFA provided us with information regarding the production and consumption of materials in the territory associated with the territorial waste management and accumulation of the materials in the territory (this issue is usually ignored in LCA studies). The local market mechanism model including different parameters enabled us to investigate the decision procedures of the buyers of “basic quality aggregates”. The aim was to understand how they made choices between A1 and RCC in the basic quality aggregate market (Market 3 in Figure II.34). This in turn provided us different information including the shares of A1 and RCC in Market 3, transportation distances between sellers (quarries/ recycling facilities) and buyers of basic quality aggregates and materials accumulated in the stock due to constrained demand for A1, which is the dependent co-product of the quarry process. In this model the real location of the sellers of basic quality aggregates _quarries, which provided A1, and recycling facilities, which provided RCC_ in *Loire-Atlantique* were used. As identifying the real physical locations of the buyers of basic quality aggregates was not possible, the map of *Loire-Atlantique* was divided into nine segments. The center of gravity of each segment (based on population) was assumed to represent the location of the consolidated buyers in that segment. Therefore, nine consolidated buyers were considered in this model.

In this PhD thesis different scenarios (Scenario 1, Scenario 2 and Scenario 3) were defined based on different parameters for the market mechanism model for Market 3 from which different shares of A1 and RCC in Market 3 and traveling distances between buyers and sellers resulted. This in turn led to changes in the flow of CCDW through waste management system and changes in the accumulation of A1 in the territory for each scenario. These scenarios were compared with the reference scenario, which reflected the situation in 2012 in the territory, in terms of market share and of 12 environmental impact indicators. We aimed to discover whether these scenarios improved the environmental performance of CCDW management compared to the reference scenario.

As discussed in chapter 3, Scenario 1 presented a price-based mechanism for Market 3 that considered no psychological obstacles for the nine buyers to use RCC and buyers of basic quality aggregates made choices between A1 and RCC based on the total prices of A1 and RCC in the market. Scenario 2 was defined to analyze the sensitivity of the price-based market mechanism model to the case that the nine buyers had lower confidence in the quality of RCC. Scenario 3 was defined to analyze the sensitivity of the price-based market mechanism model to the case that the nine buyers not only had confidence in the quality of RCC, but also preferred to buy RCC in the market under a specific condition that we defined.

In addition, two scenarios defined in Market 3 (Scenario 4 and Scenario 5) that showed an enforcement of law in the market to be compared with the reference scenario from an environmental point of view. Scenario 4 presented an obligatory use of RCC instead of A1 in the foundations, on the contrary Scenario 5 presented an obligatory use of A1 instead of RCC in the foundations. In the reference scenario, Scenario 4 and Scenario 5 that the shares of A1 and RCC in Market 3 were known beforehand, the market mechanism model was only used to investigate traveling distances between the sellers (quarries/recycling facilities) and the nine buyers. Therefore, the procedures in the market mechanism model were based on comparing the transportation prices, since the buyers of each resource (A1 or RCC) were expected to compare the transportation prices to get the closest seller.

As a result, the objective of this PhD thesis enabled us to answer the main research questions in this PhD and draw general conclusions as follows:

- Results of Scenario 1, Scenario 2 and Scenario 3 compared to those of the reference scenario showed that not only the total prices of A1 and RCC in Market 3 affected the buyers' choices between A1 and RCC, but also the buyers' confidence in the quality of RCC did.
- The mechanisms of Market 3 in the reference scenario were mostly close to those of Scenario 2 where the buyers had lower confidence in the quality of RCC and preferred to pay a higher price in the market but bought A1. This reflected the buyers' lack of confidence in the quality of RCC, even though RCC are technically equivalent to A1.

- Results of Scenario 1 and Scenario 3 showed that, if the nine buyers of basic quality aggregates had confidence in the quality of RCC to the same extent as they did in the quality of A1 and made choices in the market based on the total prices of the products, or if taxes on A1 increased there was a potential to increase the share of RCC in Market 3 compared to the reference scenario.
- MFA results showed that replacing A1 with RCC did not avoid the quarry process, while the unused A1 was stored in the territory. Because A1 is the dependent co-product of the quarry process.
- By replacing A1 totally with RCC in the foundations in the territory (Scenario 4), on one hand there was a circular economy for RCC, on the other hand, however, a lot of A1 was produced and stored in the territory.
- The main contributor to the environmental impacts in the territorial CCDW management was the quarry process whose impacts were significantly higher than other processes.
- Environmental impacts caused by CCDW recycling were much lower than those from producing the same amount of A1 in the quarry.
- Environmental impacts caused by CCDW landfilling were not considerable compared to other processes (except for the urban land occupation indicator), since an especial treatment for inert wastes is not required.
- The contribution of transportation in the territory to the environmental impacts was negligible compared to the environmental impacts of other processes in the territory.
- Overally, increasing the share of RCC in Market 3 (Scenario 1, Scenario 2, Scenario 3 and Scenario 4), compared to the reference scenario, improved the environmental performance of CCDW in *Loire-Atlantique*, but not significantly.
- The lower environmental impacts of CCDW recycling were offset by the impacts of the stock of unused A1.
- The environmental performance of CCDW management was mostly improved in terms of the fossil cumulative energy demand, urban land occupation and depletion of abiotic resource indicators when the share of RCC increased in the market compared to the reference scenario.

Generally speaking, policy makers should take into account the notion of determining and dependent co-products when formulating policies for recycling and for developing circular economy initiatives. Let us recapitulate some concepts and make proposals:

- Determining co-products are produced based on demand on a market. The production of dependent co-products is correlated to the demand for the determining co-products, not to demand on a market for dependent co-products.
- If ever the demand for dependent co-products is lower than production, dependent co-products will be accumulated in stocks (or will be landfilled depending on the case).
- If ever the demand for dependent co-products is higher than production, this is a situation where incentives exist for recycling, or for other alternatives to the dependent co-products.

Therefore, in order to benefit from potentially higher environmental benefits, policy makers should focus more on developing circular economy projects when:

- there are credible and technically feasible recycling solutions for determining co-products
- Or there is a demand for the dependent co-product that is higher than the production of this dependent co-product.

There is nothing much to be expected from a dependent co-product for which the demand is lower than production, because increasing the importance of recycling in this case will not lead to a decrease in the production of this dependent co-product.

The results of this PhD thesis can help the local authorities involved in the waste management in the territory. The method proposed in this PhD thesis can be adapted to any territory by using local economic and flow data, since construction materials are managed locally.

6.2 Perspectives

This PhD thesis has revealed some requirements in the construction sector and provided avenues for future research. They are mentioned below.

Requirements in the construction sector:

- Improving the quality of RCC to replace A2 and A3 in a higher-grade application (such as concrete) and avoid quarries and extraction of raw materials.
- Building specialized recycling facilities for producing RCC for high-grade application (e.g. structural concrete).
- Promoting on-site recycling by using mobile crushers to avoid RCC transportation in the territory.

Future research work:

- Improving data related to recycling facilities and quarries in *Loire-Atlantique* in terms of their production volumes.
- Conducting an environmental impact assessment study to investigate how the environmental performance will be affected, if RCC replaces A2 and A3 in a higher-grade application (e.g. structural concrete) by considering the required modifications (e.g. increasing the cement content in concrete made from RCC).
- Developing a dynamic MFA model by considering the stocks-in-use in the system, such as building stocks-in-use, to provide information about dynamics of resources used and changes in the stocks and flows over a time interval (Elshkaki and van der Voet, 2004). This can provide us information about the construction and demolition activities taking place every year in the territory and subsequently about the materials consumed and demolished waste produced. This model is mainly useful for long-term perspectives.

Reference

Ablouh, H., Boucher, H., Ehrhart, G., 2015. Modélisation environnementale du traitement des déchets de la déconstruction du bâtiment. EVEA fabrique de solutions durables, Nantes, France.

ASTM C 125, 2015. Standard Terminology Relating to Concrete and Concrete Aggregates (Standard), 91.100.30 - Concrete and concrete products.

Barles, S., 2009. Urban Metabolism of Paris and Its Region. J. Ind. Ecol. 13, 898–913. https://doi.org/10.1111/j.1530-9290.2009.00169.x

Batayneh, M., Marie, I., Asi, I., 2007. Use of selected waste materials in concrete mixes. Waste Manag. 27, 1870–1876. https://doi.org/10.1016/j.wasman.2006.07.026

Bauman, H., Tillman, A.-M., 2004. The Hitch Hiker's Guide to LCA. Studentlitteratur AB, Lund.

Baynes, T.M., Müller, D.B., 2016. A Socio-economic Metabolism Approach to Sustainable Development and Climate Change Mitigation, in: Clift, R., Druckman, A. (Eds.), Taking Stock of Industrial Ecology. Springer International Publishing, pp. 117–135.

Behera, M., Bhattacharyya, S.K., Minocha, A.K., Deoliya, R., Maiti, S., 2014. Recycled aggregate from C&D waste & its use in concrete – A breakthrough towards sustainability in construction sector: A review. Constr. Build. Mater. 68, 501–516. https://doi.org/10.1016/j.conbuildmat.2014.07.003

Blanc, I., Ventura, A., 2015. Conclusion of the workshop, in: Réseau EcoSD, Blanc, I. (Eds.), EcoSD Annual Workshop: Consequential LCA 2013. Presses des Mines, Paris, pp. 81–86.

Blengini, G.A., Garbarino, E., 2010. Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix. J. Clean. Prod. 18, 1021–1030. https://doi.org/10.1016/j.jclepro.2010.01.027

Braunschweig, A., Kytzia, S., Bischof, S., 2011. Recycled concrete: environmentally beneficial over virgin concrete? Presented at the Fifth International Conference on Life Cycle Management - Towards Life Cycle Sustainability Management, Berlin, Germany.

brgm, 2016. Observatoire des matériaux. [Observations of materials] [WWW Document]. URL http://materiaux.brgm.fr/Erreur.aspx?aspxerrorpath=/CartesExploitations.aspx (accessed 4.10.17).

Brunner, P.H., Rechberger, H., 2004. Practical Handbook of Material Flow Analysis- Advanced Methods in Resource and Waste Management. Lewis.

Buck, A.D., 1977. Recycled Concrete as a Source of Aggregate. J. Proc. 74, 212–219.

Cabral, A.E.B., Schalch, V., Molin, D.C.C.D., Ribeiro, J.L.D., 2012. Performance estimation for concretes made with recycled aggregates of construction and demolition waste of some Brazilian cities. Mater. Res. 15, 1037–1046. https://doi.org/10.1590/S1516-14392012005000119

CCANZ, 2011. Best Practice Guide for the use of Recycled Aggregates in New Concrete (Technical report). Cement & Concrete Association of New Zealand.

CERC, 2013. Observation des «déchets et du recyclage» du BTP - Etude sur les volumes et les flux de déchets et matériaux recyclés du BTP. [Observation of «waste and recycling» of Building and Public Works - Study on volumes and flows of waste and recycled materials of Buildings and Public Works.].

CERC, n.d. RÉSEAU DES CERC - FILIÈRE CONSTRUCTION [WWW Document]. URL http://www.cerc-actu.com/ (accessed 3.9.18).

Chen, C., Habert, G., Bouzidi, Y., Jullien, A., Ventura, A., 2010a. LCA allocation procedure used as an incitative method for waste recycling: An application to mineral additions in concrete. Resour. Conserv. Recycl. 54, 1231–1240. https://doi.org/10.1016/j.resconrec.2010.04.001
Chen, C., Habert, G., Bouzidi, Y., Jullien, A., Ventura, A., 2010b. LCA allocation procedure used as an incitative method for waste recycling: An application to mineral additions in concrete. Resour. Conserv. Recycl. 54, 1231–1240. https://doi.org/10.1016/j.resconrec.2010.04.001
CNR, n.d. Cost price repository / Short haul 40-T / Indices & Statistics / Comité National Routier - CNR [WWW Document]. URL http://www.cnr.fr/en/Indices-Statistics/Short-haul-40-T/Cost-price-repository (accessed 4.6.17).
Coelho, A., de Brito, J., 2011. Economic analysis of conventional versus selective demolition—A case study. Resour. Conserv. Recycl. 55, 382–392. https://doi.org/10.1016/j.resconrec.2010.11.003
Colangelo, F., Petrillo, A., Cioffi, R., Borrelli, C., Forcina, A., 2018. Life cycle assessment of recycled concretes: A case study in southern Italy. Sci. Total Environ. 615, 1506–1517. https://doi.org/10.1016/j.scitotenv.2017.09.107
Corinaldesi, V., 2010. Mechanical and elastic behaviour of concretes made of recycled-concrete coarse aggregates. Constr. Build. Mater. 24, 1616–1620. https://doi.org/10.1016/j.conbuildmat.2010.02.031
Dahlbo, H., Bachér, J., Lähtinen, K., Jouttijärvi, T., Suoheimo, P., Mattila, T., Sironen, S., Myllymaa, T., Saramäki, K., 2015. Construction and demolition waste management – a holistic evaluation of environmental performance. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2015.02.073
Damanhur, E., 2012. Post-Consumer Waste Recycling and Optimal Production. InTech.
de Brito, J., Barra, M., Ferreira, L., 2011. Influence of the pre-saturation of recycled coarse concrete aggregates on concrete properties. Mag. Concr. Res. 63, 617–627. https://doi.org/10.1680/macr.2011.63.8.617
de Juan, M.S., Gutiérrez, P.A., 2009. Study on the influence of attached mortar content on the properties of recycled concrete aggregate. Constr. Build. Mater. 23, 872–877. https://doi.org/10.1016/j.conbuildmat.2008.04.012
De Schepper, M., Van den Heede, P., Van Driessche, I., De Belie, N., 2014. Life Cycle Assessment of Completely Recyclable Concrete. Materials 7, 6010–6027. https://doi.org/10.3390/ma7086010
DG ENV, 2011. SERVICE CONTRACT ON MANAGEMENT OF CONSTRUCTION AND DEMOLITION WASTE –SR1.
Directive 2006/21/EC, 2006. Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the management of waste from extractive industries and amending Directive 2004/35/EC - Statement by the European Parliament, the Council and the Commission [WWW Document]. URL http://eur-lex.europa.eu/homepage.html?locale=en (accessed 7.22.16).
DoGeocodeur, n.d. DoGeocodeur [WWW Document]. URL https://dogeo.fr/_apps/DoGeocodeur/ (accessed 3.14.18).
DREAL, 2014. déchets: donnees sur les installations classées de la région Pays de la Loir. [wastes: data on classified facilities of region Pays de la Loire.]. Service des risques naturels et technologiques, Pay De La Loire, France.
Dreal, n.d. Résultats de la recherche des IC - Inspection des Installations Classées [WWW Document]. URL http://www.installationsclassees.developpement-durable.gouv.fr/rechercheIC.php?selectRegion=13&selectDept=44&champcommune=&champNomEtabl=&selectRegSeveso=-1&selectRegEtab=-1&selectPrioriteNat=-

1&selectIPPC=-1&champActivitePrinc=-1&champListeIC=%272515%27&selectDeclaEmi=&champEtablBase=&champEtablNumero=&ordre=&champNoEnregTrouves=69&champPremierEnregAffiche=40&champNoEnregAffiches=20 (accessed 3.8.18).

Ecoinvent 3, n.d. What is a market and how is it created? – ecoinvent [WWW Document]. URL https://www.ecoinvent.org/support/faqs/methodology-of-ecoinvent-3/what-is-a-market-and-how-is-it-created.html (accessed 3.6.18).

EEA, 2016. glossary — Environmental Terminology Discovery Service — EEA [WWW Document]. URL http://glossary.eea.europa.eu/terminology/concept_html?term=glossary (accessed 7.22.16).

Ekvall, T., 2000. A market-based approach to allocation at open-loop recycling. Resour. Conserv. Recycl. 29, 91–109.

Ekvall, T., Azapagic, A., Finnveden, G., Rydberg, T., Weidema, B.P., Zamagni, A., 2016. Attributional and consequential LCA in the ILCD handbook. Int. J. Life Cycle Assess. 21, 293–296. https://doi.org/10.1007/s11367-015-1026-0

Elshkaki, A., van der Voet, E., 2004. Development of a dynamic model for Substance Flow Analysis : Part 1 - General stock model (No. IMS/R/292).

EPA, 2016. Environmental protection agency- United States [WWW Document]. URL https://www3.epa.gov/ (accessed 7.22.16).

Etxeberria, M., Marí, A.R., Vázquez, E., 2007a. Recycled aggregate concrete as structural material. Mater. Struct. 40, 529–541. https://doi.org/10.1617/s11527-006-9161-5

Etxeberria, M., Vázquez, E., Marí, A., Barra, M., 2007b. Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. Cem. Concr. Res. 37, 735–742. https://doi.org/10.1016/j.cemconres.2007.02.002

European Commission, 2016. Landfill waste - Environment - European Commission [WWW Document]. URL http://ec.europa.eu/environment/waste/landfill_index.htm (accessed 2.21.16).

European Commission, 2011. International Reference Life Cycle Data System (ILCD) Handbook – Recommendations for Life Cycle Impact Assessment in the European context- based on existing environmental impact assessment models and factors. European Commission – Joint Research Centre – Institute for Environment and Sustainability. Publications Office of the European U nion, Luxemborg.

European Commission, 2008. Directive 2008/98/EC of the European Parliament and of the Council on waste and repealing certain Directives. 3–30.

European Commission, 2010a. International Reference Life Cycle Data System (ILCD) Handbook – General guide for Life Cycle Assessment – Detailed guidance. First edition March 2010. European Commission – Joint Research Centre – Institute for Environment and Sustainability. Publications Office of the European Union, Luxemborg.

European Commission, 2010b. International Reference Life Cycle Data System (ILCD) Handbook – Framework and Requirements for Life Cycle Impact Assessment Models and Indicators. European Commission – Joint Research Centre – Institute for Environment and Sustainability. Publications Office of the European Union, Luxemborg.

European parliament, 2008. Directive of the European Parliament and of the council on waste and repealing certain Directives.

Ferreira, B., Monedero, J., Lus, J., Aliaga, C., Hortal, M., Dobn, A., 2012. The Economic Aspects of Recycling, in: Damanhuri, E. (Ed.), Post-Consumer Waste Recycling and Optimal Production. InTech.

FFB, 2016. Déchets de chantier du bâtiment : tri des déchets. [Construction waste: sorting of wastes]. [WWW Document]. URL http://www.dechets-chantier.ffbatiment.fr/ (accessed 4.10.17).

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in Life Cycle Assessment. J. Environ. Manage. 91, 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

Fraj, A.B., Idir, R., 2017. Concrete based on recycled aggregates – Recycling and environmental analysis: A case study of paris' region. Constr. Build. Mater. 157, 952–964. https://doi.org/10.1016/j.conbuildmat.2017.09.059

Guinée, J., 2002. Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards.

Guinée, J.B., 2015. Selection of Impact Categories and Classification of LCI Results to Impact Categories, in: Life Cycle Impact Assessment, LCA Compendium – The Complete World of Life Cycle Assessment. Springer, Dordrecht, pp. 17–37.

Guinée, J.B., Heijungs, R., Huppes, G., 2004. Economic allocation: Examples and derived decision tree. Int. J. Life Cycle Assess. 9, 23–33. https://doi.org/10.1007/BF02978533

Hansen, T.C., 1990. Recycled concrete aggregate and fly ash produce concrete without portland cement. Cem. Concr. Res. 20, 355–356. https://doi.org/10.1016/0008-8846(90)90024-R

Hansen, T.C., 1986. Recycled aggregates and recycled aggregate concrete second state-of-the-art report developments 1945–1985. Mater. Struct. 19, 201–246. https://doi.org/10.1007/BF02472036

Heijungs, R., Guinée, J.B., 2007a. Allocation and "what-if" scenarios in life cycle assessment of waste management systems. Waste Manag., Life Cycle Assessment in Waste Management 27, 997–1005. https://doi.org/10.1016/j.wasman.2007.02.013

Heijungs, R., Guinée, J.B., 2007b. Allocation and "what-if" scenarios in life cycle assessment of waste management systems. Waste Manag., Life Cycle Assessment in Waste Management 27, 997–1005. https://doi.org/10.1016/j.wasman.2007.02.013

Hill, A.R., Dawson, A.R., Mundy, M., 2001. Utilisation of aggregate materials in road construction and bulk fill. Resour. Conserv. Recycl. 32, 305–320. https://doi.org/10.1016/S0921-3449(01)00067-2

Hossain, M.U., Poon, C.S., Lo, I.M.C., Cheng, J.C.P., 2016. Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. Resour. Conserv. Recycl. 109, 67–77. https://doi.org/10.1016/j.resconrec.2016.02.009

IS: 2386, 1963. Aggregate Crushing Value Test [WWW Document]. URL https://prbdb.gov.in/files/Quality%20Control%20Training/Tests%20on%20Aggregates/Aggregate%20Crushing%20Value%20Test.pdf (accessed 2.21.16).

Ismail, S., Hoe, K.W., Ramli, M., 2013. Sustainable Aggregates: The Potential and Challenge for Natural Resources Conservation. Procedia - Soc. Behav. Sci., AMER (ABRA malaysia) International Conference on Quality of Life, AicQoL2013Langkawi 101, 100–109. https://doi.org/10.1016/j.sbspro.2013.07.183

ISO, 2012. ISO 14047- Environmental management - Life cycle assessment - Illustrative examples on how to apply ISO 14044 to impact assessment situations.

ISO, 2006a. ISO 14044- Environmental management - Life cycle assessment - Requirements and guidelines. The International Organization for Standardization (ISO).

ISO, 2006b. ISO 14040- Environmental management - Life cycle assessment - Principles and framework. The International Organization for Standardization (ISO).

Johnson, J.X., McMillan, C.A., Keoleian, G.A., 2013. Evaluation of Life Cycle Assessment Recycling Allocation Methods: The Case Study of Aluminum. J. Ind. Ecol. n/a-n/a. https://doi.org/10.1111/jiec.12050

Jullien, A., Proust, C., Martaud, T., Rayssac, E., Ropert, C., 2012. Variability in the environmental impacts of aggregate production. Resour. Conserv. Recycl. 62, 1–13. https://doi.org/10.1016/j.resconrec.2012.02.002

Knoeri, C., Nikolic, I., Althaus, H.-J., Binder, C.R., 2014. Enhancing recycling of construction materials: An agent based model with empirically based decision parameters. J. Artif. Soc. Soc. Simul. 17.

Knoeri, C., Sanyé-Mengual, E., Althaus, H.-J., 2013. Comparative LCA of recycled and conventional concrete for structural applications. Int. J. Life Cycle Assess. 18, 909–918. https://doi.org/10.1007/s11367-012-0544-2

Ligthart, T., Ansems, T., 2012. 37113.pdf, in: Modelling of Recycling in LCA, Post-Consumer Waste Recycling and Optimal Production. InTech.

Ligthart, T.N., Ansems, T. (A)M M., 2012. Modelling of Recycling in LCA. https://doi.org/10.5772/34054

Limbachiya, M.C., Leelawat, T., Dhir, R.K., 2000. Use of recycled concrete aggregate in high-strength concrete. Mater. Struct. 33, 574–580. https://doi.org/10.1007/BF02480538

Loiseau, E., Roux, P., Junqua, G., Maurel, P., Bellon-Maurel, V., 2014. Implementation of an adapted LCA framework to environmental assessment of a territory: important learning points from a French Mediterranean case study. J. Clean. Prod. 80, 17–29. https://doi.org/10.1016/j.jclepro.2014.05.059

Loiseau, E., Roux, P., Junqua, G., Maurel, P., Bellon-Maurel, V., 2013. Adapting the LCA framework to environmental assessment in land planning. Int. J. Life Cycle Assess. 18, 1533–1548. https://doi.org/10.1007/s11367-013-0588-y

Malešev, M., Radonjanin, V., Marinković, S., 2010. Recycled Concrete as Aggregate for Structural Concrete Production. Sustainability 2, 1204–1225. https://doi.org/10.3390/su2051204

Marie, I., Quiasrawi, H., 2012. Closed-loop recycling of recycled concrete aggregates. J. Clean. Prod. 37, 243–248. https://doi.org/10.1016/j.jclepro.2012.07.020

Marinković, S., Radonjanin, V., Malešev, M., Ignjatović, I., 2010. Comparative environmental assessment of natural and recycled aggregate concrete. Waste Manag., Special Thematic Section: Sanitary Landfilling 30, 2255–2264. https://doi.org/10.1016/j.wasman.2010.04.012

Martaud, T., 2008. Évaluation environnementale de la production de granulats naturels en exploitation de carrière - Indicateurs, Modèles et outils. [Environmental assessment of the natural aggregate production in quarry- Indicators, models, and tool.]. Ph.D. thesis, Université d'Orléans, Orléans, France.

Massari, S., Sonnemann, G., Balkau, F., 2016. Life Cycle Approaches to Sustainable Regional Development. Routledge.

Mathew, T.V., Krishna Rao, K.V., 2007. Introduction to Transportation Engineering. NPTEL.

Matias, D., de Brito, J., Rosa, A., Pedro, D., 2013. Mechanical properties of concrete produced with recycled coarse aggregates – Influence of the use of superplasticizers. Constr. Build. Mater. 44, 101–109. https://doi.org/10.1016/j.conbuildmat.2013.03.011

McNeil, K., Kang, T.H.-K., 2013. Recycled Concrete Aggregates: A Review. Int. J. Concr. Struct. Mater. 7, 61–69. https://doi.org/10.1007/s40069-013-0032-5

Moriguchi, Y., Hashimoto, S., 2016. Material Flow Analysis and Waste Management, in: Clift, R., Druckman, A. (Eds.), Taking Stock of Industrial Ecology. Springer International Publishing, pp. 247–262.

Müller, E., Hilty, L.M., Widmer, R., Schluep, M., Faulstich, M., 2014. Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods. Environ. Sci. Technol. 48, 2102–2113. https://doi.org/10.1021/es403506a

Mymrin, V., Correa, S.M., 2007. New construction material from concrete production and demolition wastes and lime production waste. Constr. Build. Mater., Fracture, Acoustic Emission and NDE in Concrete (KIFA-4) 21, 578–582. https://doi.org/10.1016/j.conbuildmat.2005.09.007

Napolano, L., Menna, C., Graziano, S.F., Asprone, D., D'Amore, M., de Gennaro, R., Dondi, M., 2016. Environmental life cycle assessment of lightweight concrete to support recycled materials selection for sustainable design. Constr. Build. Mater. 119, 370–384. https://doi.org/10.1016/j.conbuildmat.2016.05.042

NF EN 1097-1, 2011. Tests for mechanical and physical properties of aggregates - Part 1: Determination of the resistance to wear (micro-Deval) (European standard).

NF EN 1097-2, 2010. Tests for mechanical and physical properties of aggregates - Part 2: Methods for the determination of resistance to fragmentation (European standard).

NF EN 15804, 2014. Sustainability of construction works- Environmental product declarations- Core rules for the product category of construction products (European standard).

Ni, H.-G., Wang, J.-Z., 2000. Prediction of compressive strength of concrete by neural networks. Cem. Concr. Res. 30, 1245–1250. https://doi.org/10.1016/S0008-8846(00)00345-8

Nitschelm, L., Aubin, J., Corson, M.S., Viaud, V., Walter, C., 2016. Spatial differentiation in Life Cycle Assessment LCA applied to an agricultural territory: current practices and method development. J. Clean. Prod. 112, 2472–2484. https://doi.org/10.1016/j.jclepro.2015.09.138

O'Mahony, M.M., 1990. Recycling of Materials in Civil Engineering. PH.D. thesis, Oxford University.

Pacheco-Torgal, F., 2014. Eco-efficient construction and building materials research under the EU Framework Programme Horizon 2020. Constr. Build. Mater. 51, 151–162. https://doi.org/10.1016/j.conbuildmat.2013.10.058

Pacheco-Torgal, F., Tam, V., Labrincha, J., Ding, Y., Brito, J. de, 2013. Handbook of Recycled Concrete and Demolition Waste. Elsevier.

Pepe, M., 2015. A Conceptual Model for Designing Recycled Aggregate Concrete for Structural Applications, Springer Theses. Springer International Publishing, Cham.

Pradel, M., Aissani, L., Villot, J., Baudez, J.-C., Laforest, V., 2016. From waste to added value product: towards a paradigm shift in life cycle assessment applied to wastewater sludge – a review. J. Clean. Prod. 131, 60–75. https://doi.org/10.1016/j.jclepro.2016.05.076

Rao, A., Jha, K.N., Misra, S., 2007. Use of aggregates from recycled construction and demolition waste in concrete. Resour. Conserv. Recycl. 50, 71–81. https://doi.org/10.1016/j.resconrec.2006.05.010

Roberts, F.L., Kandhal, P.S., Brown, E.R., Lee, D.Y., Kennedy, T.W., 1996. Hot Mix Asphalt Materials, Mixture Design, and Construction. National Asphalt Pavement Association Education Foundation.

Rosado, L.P., Vitale, P., Penteado, C.S.G., Arena, U., 2017. Life cycle assessment of natural and mixed recycled aggregate production in Brazil. J. Clean. Prod. 151, 634–642. https://doi.org/10.1016/j.jclepro.2017.03.068

Sagoe-Crentsil, K.K., Brown, T., Taylor, A.H., 2001. Performance of concrete made with commercially produced coarse recycled concrete aggregate. Cem. Concr. Res. 31, 707–712. https://doi.org/10.1016/S0008-8846(00)00476-2

Sala, S., Crenna, E., Secchi, M., Pant, R., 2017. Global normalisation factors for the Environmental Footprint and Life Cycle Assessment. Publ. Off. Eur. Union. https://doi.org/10.2760/775013

Sandberg, N.H., Sartori, I., Heidrich, O., Dawson, R., Dascalaki, E., Dimitriou, S., Vimmr, T., Filippidou, F., Stegnar, G., Šijanec Zavrl, M., Brattebø, H., 2016. Dynamic building stock modelling: Application to 11 European countries to support the energy efficiency and retrofit ambitions of the EU. Supplementary material. Energy Build. https://doi.org/10.1016/j.enbuild.2016.05.100

Sandén, B.A., Karlström, M., 2007. Positive and negative feedback in consequential life-cycle assessment. J. Clean. Prod. 15, 1469–1481. https://doi.org/10.1016/j.jclepro.2006.03.005

Schiller, G., Gruhler, K., Ortlepp, R., 2017. Continuous Material Flow Analysis Approach for Bulk Nonmetallic Mineral Building Materials Applied to the German Building Sector. J. Ind. Ecol. 21, 673–688. https://doi.org/10.1111/jiec.12595

Schneider, L., Berger, M., Finkbeiner, M., 2011. The anthropogenic stock extended abiotic depletion potential (AADP) as a new parameterisation to model the depletion of abiotic resources. Int. J. Life Cycle Assess. 16, 929–936. https://doi.org/10.1007/s11367-011-0313-7

Schrijvers, D., 2017. Environmental evaluation of recycling options according to the Life Cycle Assessment methodology: Establishment of a consistent approach applied to case studies from the chemical industry (phdthesis). Université de Bordeaux.

Serres, N., Braymand, S., Feugeas, F., 2016. Environmental evaluation of concrete made from recycled concrete aggregate implementing life cycle assessment. J. Build. Eng. 5, 24–33. https://doi.org/10.1016/j.jobe.2015.11.004

Shayan, A., Xu, A.M., 2003. Performance and Properties of Structural Concrete made with Recycled Concrete Aggregate. Aci Mater. J. 100, 371–380.

Silva, R.V., de Brito, J., Dhir, R.K., 2014. Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. Constr. Build. Mater. 65, 201–217. https://doi.org/10.1016/j.conbuildmat.2014.04.117

Sonawane, T.R., Pimplikar, S.S., 2013. Use of Recycled Aggregate Concrete. IOSR J. Mech. Civ. Eng. IOSR - JMCE 52–59.

Stahel, W.R., Clift, R., 2016. Stocks and Flows in the Performance Economy, in: Clift, R., Druckman, A. (Eds.), Taking Stock of Industrial Ecology. Springer International Publishing, Cham, pp. 137–158.

Tam, V.W.Y., Tam, C.M., Le, K.N., 2007. Removal of cement mortar remains from recycled aggregate using pre-soaking approaches. Resour. Conserv. Recycl. 50, 82–101. https://doi.org/10.1016/j.resconrec.2006.05.012

Tavakoli, M., Soroushian, P., 1996. STRENGTHS OF RECYCLED AGGREGATE CONCRETE MADE USING FIELD-DEMOLISHED CONCRETE AS AGGREGATE. ACI Mater. J. 93.

Thomassen, M.A., Dalgaard, R., Heijungs, R., Boer, I. de, 2008. Attributional and consequential LCA of milk production. Int. J. Life Cycle Assess. 13, 339–349. https://doi.org/10.1007/s11367-008-0007-y

Thorn, N.H., Brown, S.F., 1989. 17 - The mechanical properties of unbound aggregates from various sources, in: Unbound Aggregates in Roads. Butterworth-Heinemann, pp. 130–142.

Tillman, A.-M., 2000. Significance of decision-making for LCA methodology. Environ. Impact Assess. Rev. 20, 113–123. https://doi.org/10.1016/S0195-9255(99)00035-9 van der Harst, E., Potting, J., Kroeze, C., 2016. Comparison of different methods to include recycling in LCAs of aluminium cans and disposable polystyrene cups. Waste Manag. 48, 565–583. https://doi.org/10.1016/j.wasman.2015.09.027

Ventura, A., 2013. Raising questions on system expansion and CLCA through examples from the construction sector, in: Consequential Life Cycle Assessment. Presented at the EcoSD Annual workshop, Presses de l'Ecole des Mines, Paris, France.

Ventura, A., Monéron, P., Jullien, A., 2008. Environmental Impact of a Binding Course Pavement Section, with Asphalt Recycled at Varying Rates: Use of Life Cycle Methodology. Road Mater. Pavement Des. 9, 319–338.

Wagih, A.M., El-Karmoty, H.Z., Ebid, M., Okba, S.H., 2013. Recycled construction and demolition concrete waste as aggregate for structural concrete. HBRC J. 9, 193–200. https://doi.org/10.1016/j.hbrcj.2013.08.007

Weidema, B., 2001. Avoiding Co-product Allocation in Life-Cycle Assessment 4, 11–33.

Weidema, B.P., 2003a. Market information in life cycle assessment (Environmental Project No. 863). Danish Environmental Protection Agency.

Weidema, B.P., 2003b. Market information in life cycle assessment (Environmental Project No. 863). Danish Environmental Protection Agency.

Wijayasundara, M., Mendis, P., Crawford, R.H., 2017. Methodology for the integrated assessment on the use of recycled concrete aggregate replacing natural aggregate in structural concrete. J. Clean. Prod. 166, 321–334. https://doi.org/10.1016/j.jclepro.2017.08.001

Wilburn, D.R., Goonan, T.G., 1998. AGGREGATES FROM NATURAL AND RECYCLED RESOURCES Economics Assessment for construction Applications- A Materials Flow Study.

Woodward, R., Duffy, N., 2011. Cement and concrete flow analysis in a rapidly expanding economy: Ireland as a case study. Resour. Conserv. Recycl. 55, 448–455. https://doi.org/10.1016/j.resconrec.2010.12.006

Yazdanbakhsh, A., Bank, L.C., Baez, T., Wernick, I., 2017. Comparative LCA of concrete with natural and recycled coarse aggregate in the New York City area. Int. J. Life Cycle Assess. 1–11. https://doi.org/10.1007/s11367-017-1360-5

Zamagni, A., Guinée, J., Heijungs, R., Masoni, P., Raggi, A., 2012. Lights and shadows in consequential LCA. Int. J. Life Cycle Assess. 17, 904–918. https://doi.org/10.1007/s11367-012-0423-x

Appendixes

Appendix A- Inert and non-hazardous waste management in Charier Company in *Loire-Atlantique*, France

In part, inert waste and non-hazardous waste contents and how they are assessed and treated in two recycling platforms in Charier Company (located in *Pays de la Loire* in France) are explained as an example based on visits.

A1. Inert waste storage facility and recycling platform- example of Theix, Morbihan, *Loire-Atlantique*

Inert waste contents in the platform

Trucks arriving at this platform are loaded with inert wastes, which mostly including binder asbestos, clay, rocks, concrete, asphalts and soil.

Quality assessment of the waste materials reaching the platform

Prior to admission of the inert waste at inert waste storage facility, the customers are required to fill a form about the original detail of the wastes. This form is entitled FIP (Fiche d'Information Préalable). According to the regulations, it is mandatory to fill a FIP at least once a year. FIP provides information about company name, identification of the construction site (including name and address of the construction site), type of the construction site (if it is earthwork, demolition, waste disposal etc.) as well as construction site environment, transport type, state of the wastes and information regarding pollution contents of the wastes (if they are diagnosed by the construction site). In some special cases, such as the demolition of a petrol station, a further evaluation is required to analyze the contaminants inside the materials to recognize if they should be classified into other categories, non-hazardous or hazardous wastes. In spite of FIP, the contents of the truck go through olfactory and visual tests as they enter the site. Should there any doubt of pollution, further analysis will be required. Gypsum is always a reason to refuse a load. Concrete blocks and any materials with coated surface are always sent to the landfills. In general, one of the main origins of the waste is municipal drop-off center.

Inert waste management

There are mainly three scenarios for inert waste management. They can be reused on the same land for new construction for the reason that they do not need much treatment or they could be recycled or land-filled. Beside different types of waste that they receive, Charier just recycles concrete and asphalt. In other words, the only recycled products from this platform are asphalt and recycled concrete. The stockpile of the demolished concrete, which is mixed with steel reinforcements, is crushed and the steel is separated using magnets. The remaining waste, which is not usable, will be disposed into the landfills.

A2. Non-hazardous waste storage facility- example of La Vraie Croix, Morbihan

Non-hazardous waste contents in the platform

Trucks loaded with such waste mainly contain industrial wastes such as plastics, PVC, polyethylene and polystyrene. The only non-hazardous construction and demolition wastes are wood and glass that comes from demolition of the inside of the building.

Quality assessment of the waste materials reaching the platform

The trucks are weighted and controlled as soon as they arrive to the platform. The trucks' content is evaluated in order to identify if the loaded waste should be sent to the landfill or recycling platforms, or at all reclassified as hazardous waste. There is also a detector at the entrance for radioactivity detection.

Non- hazardous waste management

Charier does not sort unsorted wastes but just separates wood waste and disposes the rest into the landfill.

Each landfill has the capacity of 0.9-1 ton of waste per 1 m^3. Disposal areas for non-hazardous waste are also equipped for producing biogas from organic waste. Water is pumped inside the waste to increase biogas production. Then waste water is treated and used in a closed-loop process. Prior to energy production, biogas needs to be desulfurized. When a given area is full, it will be covered with soil, but biogas production will still continue for 7 years. The electricity provided to the network corresponds to 4,000 to 5,000 liters of fuel per year. There is 60% of energy loss from gas conversion to electricity, but biogas due to the presence of H_2S is not pure enough to be injected in the network.

Appendix B- Economic profits gained from two recycling platforms in Charier Company

B1. Economic profits gained from different activities in inert waste recycling platform- example of Theix, Morbihan

This platform accepts only inert waste materials. Customer have to pay 2€/ton of sorted wastes and 4€/ton of unsorted wastes to the platform.

In order to gain economic profits from recycling process, 50,000 tons recycled material should be sold per year, while currently 17,000 tons are sold per year. However, the facility is combined with landfilling. The top soil of the landfill is adequate for agriculture; thus farmers can rent the land for a specific period of time. In addition, the facility economically benefits from selling steels separated from the crushed concrete to the steel recycling companies.

B2. Economic profits gained from different activities in non-hazardous waste recycling platform- example of La Vraie Croix, Morbihan

Waste providers pay less for sorted wastes compared to unsorted wastes. But Charier will not sort the wastes due to the labor cost. It is economically interesting if it only takes 20 minutes per truck.

As mentioned in Appendix A, this platform is equipped with biogas extraction and heat generation equipment. Biogas installation requires an investment of 5,000,000 €. However, this platform receives profits from selling the electricity generated from biogas to the industrial neighbors, being paid about 70 € per ton by the customers for landfilling unsorted non-hazardous wastes and reduction in taxes (TGAP: Taxe Générale sur les Activités Polluantes), about 10€/ton, due to biogas production.

Appendix C- Obstacles that facility owners in *Loire-Atlantique* face regarding recycling or recovering CDW

A questionnaire was conducted in *Loire-Atlantique* to identify different obstacles that facility owners were facing concerning recycling and recovering the waste. Eight facility managers (out of 57, which took part in the survey) recognized the following barriers to recycling and valorization. Six out of eight respondents were among inert waste facility owners (CERC, 2013).

C1. Administrative and land barriers

Some facility owners have difficulties with finding a place for receiving and sorting inert and hazardous wastes.

C.2 Economic barriers

Many respondent facilities reported that the cost of recycling was still too expensive compared to the cost of natural materials and of landfilling.

C3. Bad previous sorting

Some of the waste which reaches the facilities is mixed and this causes a decrease in the efficiency of sorting in the facility.

C4. Lack of will to use recycled materials

There is a lack of interest and knowledge from customers as concerns recycled materials. For example, very few public calls for tenders explicitly mention that bidders have to use recycled materials.

Appendix D- Optional elements in LCIA according to ISO 14044

D1. Selection of impact categories, category indicators and characterization models

Elementary flows gained from the LCI phase (e.g. resource consumption, emissions etc.) are assigned to different impact categories based on their contribution to different environmental problems (European Commission, 2010b). The assignment of elementary flows to impact categories is performed based on existing impact assessment methods, such as CML, IMPACT 2002, ReCipe etc. (Guinée, 2015). According to European Commission (2011), there are different impact categories including climate change, ozone depletion, eutrophication, acidification, human toxicity (cancer and non-cancer related),respiratory inorganics, ionizing radiation, ecotoxicity, photochemical ozone formation, land use, and resource depletion.

Each impact category should be transformed to a category indicator using characterization factors, which are calculated by impact assessment methods (or also called characterization models) (ISO, 2012). For instance, category indicator of global warming potential or climate change is kg CO_2 equivalent (NF EN 15804, 2014).

Selected impact categories, category indicators and characterization models should be justified and consistent with the goal and scope of the LCA study and reflect the environmental issues caused by the product system understudy (ISO, 2006a).

D2. Assignment of LCI results to the selected impact categories (classification)

In this step, elementary flows gained from LCI phase are assigned to the respective impact categories. For instances, greenhouse gases, such as CO_2 and CH_4, are classified as emissions that contribute to global warming potential or climate change compared to CO_2 (European Commission, 2010b).

D3. Calculation of category indicator results (characterization)

In this step, impact indicators related to the selected impact categories are calculated. To do so, the amount of elementary flows are multiplied with the respective characterization factors (ISO, 2012). The magnitude of the characterization factors is based on the contribution of the elementary flow to the respective impact category. As an example, greenhouse gas emissions such as CO_2 and CH_4, have different characterization factors. Because, CH_4 has higher contribution to global warming (European Commission, 2010b).

Calculation of the category indicator of global warming potential for an LCI, which contains CO_2 and CH_4, is as follow:

$$I_{GWP} = CF_{CO_2} * M_{CO_2} + CF_{CH_4} * M_{CH_4} \quad D.1$$

Where I_{GWP} is category indicator of global warming potential in kg CO_2 equivalent, *CF* refers to characterization factors and *M* is mass of CO_2 and CH_4.

It should be noted that by applying an impact assessment method, which has been already made, classification and characterization will be done automatically.

Appendix E- Methods to solve multi-functionality problems in LCA according to ISO 14044 standard (ISO, 2006a):

"Step 1: Wherever possible, allocation shall be avoided by: 1) dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes; 2) expanding the product system to include the additional functions related to the coproducts [. . .]

Step 2: Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.

Step 3: Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products."

There is the same hierarchy to overcome multi-functionality problems of recycling according to ISO but additional elaborations need to be taken into account. Because:

- "reuse and recycling (as well as composting, energy recovery and other processes that can be assimilated to reuse/recycling) may imply that the inputs and outputs associated with unit processes for extraction and processing of raw materials and final disposal of products are to be shared by more than one product system;" from this it is understood that allocation procedures are not applied on use phase and distribution.
- "Reuse and recycling may change the inherent properties of materials in subsequent use;"

As mentioned in section 2.6.4.2, in ISO standards "allocation" refers to "partitioning", which could be either physical or economic partitioning.

Appendix F- Sellers of basic quality aggregates (quarries and recycling facilities) in *Loire-Atlantique* with their production volumes

Table F. 1 List of quarries in Loire-Atlantique (brgm, 2016)

Quarry's name	Postal code	Commune	Authorized Production (ton)	Actual production (ton)	A1 production (ton)
La Mariais	44480	DONGES	1, 000,000.0	600,000.0	226,200.0
Les Maraîchères	44020	BOUGUENAIS	1, 000,000.0	549776	207,265.6
La Faubretière et Les Rocherons	44070	LA HAIE-FOUASSIERE	600,000.0	550,000.0	207,350.0
La Margerie	44190	GORGES	830,000.0	447,691.0	168,779.5
La Clarté	44410	HERBIGNAC	2, 500,000.0	1, 400,000.0	527,800.0
La Touche	44212	VALLET	600,000.0	309,576.0	116,710.2
La Coche	44186	SAINTE-PAZANNE	300,000.0	129,426.0	48,793.6
La Pointe des Chemins	44145	ROUANS	830,000.0	447,691.0	168,779.5
Les Mortiers	44202	TEILLE	200,000.0	69,376.0	26,154.8
La Guibourgère	44202	TEILLE	250,000.0	99,401.0	37,474.2
Le Grand Coiscault	44191	SAINT-SULPICE-DES-LANDES	550,000.0	99,401.0	37,474.2
Le Bois de la Roche	44153	SAINT-AUBIN-DES-CHATEAUX	350,000.0	159,451.0	60,113.0
Le Petit Betz	44139	QUILLY	300,000.0	100,000.0	37,700.0
Landes Coeffard	44750	QUILLY	160,000.0	45,356.0	17,099.2
Bel Air	44025	CAMPBON	600,000.0	309,576.0	116,710.2
Le Padé	44025	CAMPBON	400,000.0	189,476.0	71,432.5
La Répennelais	44219	VRITZ	1, 200,000.0	669,876.0	252,543.3
La Métairie Neuve	44780	MISSILLAC	300,000.0	129,426.0	48,793.6
Le Pont	44460	AVESSAC	40,000.0	40,000.0	15,080.0

La Bobatière	44119	PAULX	50,000.0	50,000.0	18,850.0
La Vallée	44077	JOUE-SUR-ERDRE	150,000.0	39,351.0	14,835.3
Lambrun	44065	GRAND-AUVERNE	120,000.0	21,336.0	8,043.7
Forêt de Javardan	44058	FERCE	150,000.0	39,351.0	14,835.3
L'Ennerie	44320	CHAUVE	1, 000,000.0	549,776.0	207,265.6
La Recouvrance	44027	CASSON	600,000.0	309,576.0	116,710.2
La Lande du Cens	44224	LA GRIGONNAIS	150,000.0	39,351.0	14,835.3
La Guillonnais	44224	LA GRIGONNAIS	42,000.0	42,000.0	15,834.0
Barel	44530	GUENROUET	600,000.0	309,576.0	116,710.2
La Pommeraie	44122	PETIT-MARS	1, 000,000.0	549,776.0	207,265.6
Le Tronc	44680	CHEMERE	600,000.0	309,576.0	116,710.2
La Gagnerie	44155	SAINT-COLOMBAN	350,000.0	159,451.0	60,113.0
La Grande Garde	44155	SAINT-COLOMBAN	550,000.0	279,551.0	105,390.7
Le Gros Buisson	44320	SAINT-VIAUD	450,000.0	219,501.0	82,751.9

Table F. 2 List of recycling facilities (FFB, 2016; DREAL, n.d.)

Recycling facility's name	**Postal code**	**Commune**	**RCC Production (ton)**
LAFARGE GRANULATS FRANCE	44340	BOUGUENAIS	12,319.0
LAFARGE GRANULATS FRANCE	44750	CAMPBON	12,319.0
SOCAC	44750	CAMPBON	12,319.0
BAGLIONE SA	44390	CASSON	12,319.0
FOCAST CHATEAUBRIANT	44143	CHATEAUBRIANT	12,319.0
LAFARGE GRANULATS FRANCE	44320	CHAUMES EN RETZ	12,319.0
EDF SA	44360	CORDEMAIS	12,319.0
ARC EN CIEL	44220	COUERON	12,319.0
SOCIETE DES CARRIERES CHASSE	44220	COUERON	12,319.0
CHARIER CM - CARRIERES ET MATERIAUX	44480	DONGES	12,319.0
GROUPE MEAC SAS	44110	ERBRAY	12,319.0
LAFARGE GRANULATS FRANCE	44660	FERCE	12,319.0
DEDIENNE AUTOMOTIVE	44190	GETIGNE	12,319.0
CARRIERE AUBRON ET MECHINEAU	44190	GORGES	12,319.0
CHARIER CM - CARRIERES ET MATERIAUX	44410	HERBIGNAC	12,319.0
SOFERTI	44610	INDRE	12,319.0
BOUYER LEROUX Structure SAS	44430	LA BOISSIERE DU DORE	12,319.0
CHARIER CM - CARRIERES ET MATERIAUX	44690	LA HAIE FOUASSIERE	12,319.0
ECOTERRE DU CELLIER	44850	LE CELLIER	6,500.0
BLANCHARD TP ECOCENTRE	44430	LE LOROUX BOTTEREAU	12,319.0
ACTIPLAST	44370	LOIREAUXENCE	12,319.0
TECHNA FRANCE NUTRITION	44260	MALVILLE	12,319.0
CETRA GRANULATS	44550	MONTOIR DE BRETAGNE	12,319.0
CHARIER TP	44550	MONTOIR DE BRETAGNE	12,319.0
EQIOM	44550	MONTOIR DE BRETAGNE	12,319.0
IMERYS Metalcasting France	44550	MONTOIR DE BRETAGNE	12,319.0

OTCM	44550	MONTOIR DE BRETAGNE	12,319.0
Sablières de l'Atlantique	44550	MONTOIR DE BRETAGNE	12,319.0
ALCEA	44326	NANTES	12,319.0
GSM OUEST Pays de la Loire	44000	NANTES	12,319.0
LAFARGE GRANULATS FRANCE - Secteur Ouest	44000	NANTES	12,319.0
SAREMER	44000	NANTES	12,319.0
TIMAC AGRO SAS	44000	NANTES	12,319.0
GUINGAMP	44270	PAULX	12,319.0
CARRIERES CHASSE	44390	PETIT MARS	12,319.0
SOCAC - STE DES CARRIERES DE CAMPBON	44750	QUILLY	12,319.0
CARRIERES GSM	44640	ROUANS	12,319.0
CARRIERES GSM	44310	ST COLOMBAN	12,319.0
LAFARGE GRANULATS FRANCE	44310	ST COLOMBAN	12,319.0
TEN (TOLERIE EMAILLERIE NANTAISE)	44800	ST HERBLAIN	12,319.0
AGERA	44540	ST MARS LA JAILLE	12,319.0
SOCIETE DRAGAGES D'ANCENIS	44540	ST SULPICE DES LANDES	12,319.0
CARRIERES CHASSE	44320	ST VIAUD	12,319.0
CARRIERES GSM	44680	STE PAZANNE	12,319.0
CARRIERES GSM	44440	TEILLE	12,319.0
SYNDICAT MIXTE CENTRE NORD ATLANTIQUE	44170	TREFFIEUX	12,319.0
CARRIERE BLANLOEIL	44330	VALLET	12,319.0
GAUTIER VALORISATION	44330	VALLET	12,319.0
CARRIERS ET MATERIAUX DU GRAND OUEST	44116	VIEILLEVIGNE	12,319.0
ORBELLO GRANULATS LOIRE	44540	VRITZ	12,319.0
SOCACHEM	44680	CHEMERE	12,319.0
BARBAZANGES TRI OUEST	44110	CHATEAUBRIANT	12,319.0
PHILVALOR	44850	LE CELLIER	12,319.0
2B RECYCLAGE	44300	NANTES	12,319.0
Pf Le Bréhet	44420	la turballe	7,601.0

Legend

Dedicated recycling facility

Recycling facility jointly operating with landfills

Recycling facility jointly operating with quarries

Appendix G- Production and consumptions of materials in *Loire-Atlantique*, France

Table G. 1 Production and consumptions of materials in Loire-Atlantique (year 2012)

Parameters in section 4.24.2.3	Amount	Unit
$M_{CDW_{Loire-Atlantique}}(Y_n)$ *(equation IV. 2)*	7,833,093.7	tons
$M_{CCDW_{Loire-Atlantique}}(Y_n)$ *(equation IV. 3)*	3,133,237.5	tons
vol.CC (cement concrete)	1,100,000.0	m^3
D_{A3CC} *(equation III. 4)*	1,327,700.0	tons
Vol.BC (bituminous concrete)	855,000.0	tons
D_{A3BC} *(equation III. 5)*	812,250.0	tons
D_{A3} *(equation III. 3)*	2,139,950.0	tons
P_{A3} *(equation III. 2)*	2,139,950.0	tons
P_{A1} *(equation III. 6)*	1,850,369.0	tons
P_{A2} *(equation III. 7)*	917,822.6	tons
D_{A1}	1,607,319.3	tons
[a]D_{A2}	917,822.6	tons
D_{RCC}	100,000.0	tons
[b]D_{BQA}	1,707,319.3	tons

[a] Due to the lack of data, it is assumed that A2 is demanded as much as it is produced. Because its production obtained from equation (III. 7) is less than its consumption.

[b] is the summation of D_{A1} and D_{RCC}.

Table G. 2 Demands of the nine buyers for basic quality aggregates in 2012 in Loire-Atlantique in the nine segments in Figure IV. 3

D_{BQA_m} **(equation III. 21)**	**Amount (ton)**
D_{BQA_1}	80,681.0
D_{BQA_2}	101,810.9
D_{BQA_3}	51,979.2
D_{BQA_4}	247,899.2
D_{BQA_5}	845,576.6
D_{BQA_6}	77,453.2
D_{BQA_7}	98,968.8
D_{BQA_8}	121,747.4
D_{BQA_9}	81,203.0
D_{BAQ}	1,707,319.3

Disclaimer

This PhD thesis has developed a method to integrate local conditions to evaluate the environmental performance of Cement Concrete Demolition Waste Management in the territory understudy _ Loire-Atlantique on the west coast of France.

Tremendous effort has been made to collect local data related to the territorial waste management. However, due to difficulties to have an access to some local data, such as total waste generated in Loire-Atlantique, this figure was literature-based.

As a development of this PhD, we repeated the calculations with a new figure for the total waste generated for the publications. The new figure is also literature based but closer to the reality according to the experts' opinions in the territory, though, changes in this figure would not change either the conclusions made or the environmental comparison results in this PhD.

However, the methodology proposed in this PhD can be used for any set of local data and territory. We suggest the readers to refer to the scientific articles published after this PhD thesis for consolidated results.

List of publications and contributions to conferences

The author of this PhD thesis has submitted parts of the work in the following papers:

Paper I: **M. Mousavi**, A. Ventura, N. Antheaume, « Material Flow Analysis and Life Cycle Assessment of Territorial Cement Concrete Demolition Waste Management. Part I: Current Situation Analysis» Submitted to the journal of cleaner production.

Paper II: **M. Mousavi**, A. Ventura, N. Antheaume, « Territorial Environmental Modeling of Cement Concrete Demolition Waste Management with a Life Cycle Approach. Part II: Local Market Mechanism Model and Scenarios» Submitted to the journal of cleaner production.

Besides, the author has presented in various scientific conferences:

M. Mousavi, A. Ventura, N. Antheaume, «Can LCA tool alone conduct environmental performances of circular economy in construction sector? A case study of Cement Concrete Demolition Waste (CCDW) management. » 8th International Conference on Life Cycle Management, Luxembourg, Luxembourg, 2017.

M. Mousavi, A. Ventura, N. Antheaume, «Does circular economy in construction sector lead to improving environmental performances? A case study of Cement Concrete Demolition Waste management. » ISIE-ISSST 2017, Illinois, USA, 2017.

M. Mousavi, A. Ventura, N. Antheaume, «LCA Modeling of Cement Concrete Waste Management. » 35èmes Rencontres universitaires de génie civil, AUGC, Nantes, France, 2017.

M. Mousavi, A. Ventura, N. Antheaume, « LCA Modeling of Cement Concrete Waste Management. » Life Cycle Assessment and Other Assessment Tools for Waste Management and Resource Optimization, Engineering Conferences International, ECI, Cetraro (Calabria), Italy, 2016.

UNIVERSITE BRETAGNE LOIRE

UNIVERSITÉ DE NANTES

Thèse de Doctorat

Marjan MOUSAVI

Territorial Environmental Modeling of Cement Concrete Demolition Waste (CCDW) Management with a Life Cycle Approach

Résumé

L'objectif de cette thèse est d'évaluer la performance environnementale de la gestion des déchets de béton en ciment issus de la démolition (DBCD), sur un territoire donné, pour évaluer si le recyclage améliorer e la performance environnementale de la gestion des déchets sur le territoire et minimise la dépendance envers les ressources primaires. Le territoire étudié est la Loire-Atlantique. Le béton recyclé issu de ciment (BRC), recyclé à partir de DBCD a été pris en compte comme une alternative possible à A1 (granulat de qualité basique et co-produit lié au processus d'extraction dans une carrière), utilisé pour des fondations en tant qu'agrégats de qualité basique (AQB). Une combinaison de différentes méthodes a été appliquée à la gestion étendue des DBCD sur le territoire, y compris des flux d'ACV, de MFA et un mécanisme de marché à l'échelle locale. Le modèle de marché à l'échelle local est basé sur les procédures de décisions des acheteurs entre A1 et BRC disponibles sur le marché des AQG. Ceci a permis en conséquence d'identifier les stocks de A1 inutilisés sur le territoire, les flux de déchets vers le système de gestion des déchets, les distances de transport et le degré de confiance des acheteurs dans le BRC. Bien que les impacts environnementaux du recyclage des DBCD soient bien inférieurs à ceux du processus d'extraction d'une carrière, augmenter la part de marché du BRC sur le marché des AQB, par comparaison avec la situation actuelle, n'apporte pas de bénéfices environnementaux substantiels du fait de l'accumulation des A1 produits, mais non utilisés.

Mots clés
Gestion des déchets du BTP, expansion de système, analyse de cycle de vie conséquentielle, analyse flux matière, mècanism économique, modélisation de marché local, impact territoriaux

Abstract

The aim of this PhD was to evaluate the environmental performance of Cement Concrete Demolition Waste (CCDW) management in a given territory to answer whether recycling would improve the environmental performance of waste management in the territory and minimize the dependence on primary materials. The territory understudy was *Loire-Atlantique*. Recycled Cement Concrete (RCC) recycled from CCDW was considered as an alternative to A1 (dependent co-product of the quarry process) to be used for foundations as basic quality aggregates (BQA). A combination of different methods was applied on the expanded territorial CCDW management including different reference flows: LCA, MFA and a local market mechanism model. The local market mechanism model revealed the decision procedures of buyers in the BQA market based on which they made choices between A1 and RCC in this market. This in turn identified the stock of unused A1 in the territory, waste streams to the waste management systems, transport distances and the mechanism in the market, which was based on comparing the prices and the buyers' degree of confidence in RCC. Although the environmental impacts of CCDW recycling process were much lower than those of the quarry process, increasing the share of RCC in the BQA market compared to the current situation in the territory did not show substantial environmental benefits, because of the accumulation of produced but unused A1 in the territory.

Key Words
Construction and Demolition Waste (CDW) management, system expansion, consequential Life Cycle Assessment, Material Flow Analysis, Local market mechanism, modeling local market, territorial impacts

L'Université Bretagne Loire