École doctorale 221 : Augustin Cournot

THÈSE

pour obtenir le grade de docteur délivré par

l'Université de Strasbourg

Spécialité doctorale "Sciences économiques"

Evaluation du risque de non atteinte de la performance énergétique après rénovation :

Biais cognitifs, asymétries d'information et incitations optimales

présentée et soutenue publiquement par

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le 17 juin 2019

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À mes parents.

Abstract

This thesis aims at contributing to make the energy renovation market long-lasting and self-sustaining. To achieve this, our objective is to quantify the risk of not achieving energy performance after renovation. In a first chapter, we analyze the psychological factors that should be taken into account to improve future energy consumption prediction models. Drawing on the *Je rénove BBC* renovation program, we highlight four cognitive biases of households that negatively impact the difference between actual and predicted energy consumption. Then, we study the most appropriate contract structures to improve the flow and quality of renovation projects, encouraging craftsmen to work better. Thus, on one hand, we determine optimal contracts for an Agent who has to perform two tasks and underestimates the impact of one of them on the building's performance. On the other hand, we test individual-based and group-based incentives on the ability of several real Agents (craftsmen) to coordinate, according to their initial training (*DORéMI* training or other).

Keywords: cognitive biases, applied econometrics, contract theory, experimental economics, energy renovation

Résumé

Cette thèse vise à contribuer à rendre le marché de la rénovation énergétique durable et autonome. Pour y parvenir, notre objectif est de contribuer à quantifier le risque de non atteinte de la performance énergétique après rénovation. Dans un premier chapitre, nous analysons les facteurs psychologiques à prendre en compte pour améliorer les futurs modèles de prédictions de consommation d'énergie. En nous appuyant sur le programme de rénovation *Je rénove BBC*, nous mettons en évidence quatre biais cognitifs des ménages impactant négativement la différence entre la consommation d'énergie réelle et prédite. Par la suite, nous étudions les structures de contrats les plus appropriés pour améliorer le déroulement des chantiers de rénovation, incitant les artisans à mieux travailler. Ainsi, nous déterminons d'une part des contrats destinés à un Agent devant effectuer deux tâches et qui sous-estime l'impact de l'une d'entre elles sur la performance du bâtiment. D'autre part, nous testons des incitations individuelles et de groupe sur la capacité de plusieurs Agents réels (artisans) à se coordonner, selon leur formation initiale (formation *DORéMI* ou autre).

Mots-clés : biais cognitifs, économétrie appliquée, théorie des contrats, économie expérimentale, rénovation énergétique

Remerciements

Avant tout, je souhaiterais adresser ma plus profonde gratitude à ma directrice de thèse Sandrine Spaeter-Loehrer pour avoir été un soutien précieux tout au long de la thèse. Ses conseils constructifs pour améliorer et guider les travaux, ainsi que ses encouragements m'ont permis de mener ce travail de recherche à bien.
Je remercie également Nicolas Lampach et Mathieu Lefèbvre pour avoir été mes co-auteurs, et grâce qui j'ai beaucoup appris au niveau économétrie et économie expérimentale. Leur implication, conseils et relectures m'ont été d'une aide précieuse.
Je voudrais également remercier l'ADEME et la Région Grand Est pour avoir décidé de co-financer cette thèse pendant trois ans. En particulier, je remercie Marie-Laure Nauleau pour m'avoir encadrée au niveau de l'ADEME et donné des conseils pour avancer sur mes recherches. Au niveau de la Région Grand Est, David Lewandowski et Mathieu Flahaut pour les diverses réunions de travail et sans qui les expériences avec les artisans n'auraient pas été possibles.
Pour le bon déroulement des expériences économiques, je remercie Kene Boun My pour son assistance et aide du début à la fin, Xavier Tible pour avoir organisé une réunion avec des artisans à Saint-Dié-des Vosges, Gabriel Quentin et Florent Richard pour la réunion Oktave d'artisans à Sélestat, Agathe Simon et Arnaud Wolff pour leur aide logistique, ainsi que tous les artisans qui se sont déplacés et ont accepté de participer.
Pour les entretiens des ménages du programme *Je rénove BBC* et la bonne constitution de notre base de données, je souhaite remercier Sabine Mirtain-Roth et Ludovic Parisot pour leur support et aide, ainsi que Marilyne Delsart, Leila Cherifi et Debora Zaparova pour leur assistance dans l'administration du questionnaire.
Je souhaiterais également remercier les membres de mon jury de thèse, Dorothée Charlier, Julien Pénin et Stéphane Robin pour avoir accepté de lire cette thèse et apporter des commentaires constructifs.
Merci à l'École Doctorale Augustin Cournot et au BETA pour le cadre propice au travail dans lequel j'ai pu effectuer ma thèse, ainsi que pour le financement des diverses conférences auxquelles j'ai participé. Merci à l'Université de Constance et ses professeurs.
Pour terminer, je remercie chaleureusement mes amis Marine, Alexandra et Enrico, et tous les autres, pour avoir relu certaines parties de ma thèse. J'ai une pensée toute particulière pour mes parents, ainsi que pour Rafael qui ont su m'écouter, m'encourager et m'apporter leur aide dans les bons moments, mais surtout dans les phases plus difficiles.

Résumé étendu

L'objectif principal de cette thèse, cofinancée par l'ADEME et la Région Grand Est, est de contribuer à l'émergence d'un marché de la rénovation énergétique pérenne, plus fiable et capable de fonctionner sans intervention (notamment financière) du gouvernement et des décideurs publics. Ceci est nécessaire en vue d'entraîner une augmentation du nombre de rénovations à long terme. Ainsi, nous pourrons plus efficacement contribuer à réduire les émissions de gaz à effet de serre (GES), permettant de ralentir le réchauffement climatique. Nous répondons à cet objectif de trois manières différents. Dans un premier chapitre, nous abordons le problème d'un point de vue économétrique en analysant des données que nous avons recueillies auprès de ménages ayant participé à un programme de rénovation énergétique de grande échelle. Dans un deuxième chapitre, nous contribuons à l'objectif principal de la thèse d'un point de vue théorique en présentant un modèle Principal-Agent à deux tâches, où l'Agent peut ne pas être au courant de certaines conséquences de ces tâches sur la performance énergétique finale du bâtiment. Enfin, dans un troisième chapitre, nous adressons l'objectif d'un point de vue expérimental en mobilisant de "vrais" artisans ayant suivi différentes formations professionnelles.

Avant d'aller plus loin, commençons par développer **le contexte de cette thèse**. Les problèmes environnementaux actuels liés au changement climatique font naître le besoin de nouvelles mesures efficaces qui contribueront à réduire les émissions de gaz à effet de serre. En effet, les scientifiques sont de plus en plus alarmistes quant à la santé de notre planète et sensibilisent face à l'urgence de la situation. Depuis plus de 45 ans maintenant, nous somme témoin du *Jour de Dépassement*[1]. Il correspond au jour de l'année où les êtres humains ont consommé plus de ressources naturelles que notre planète ne peut en

[1] En 1970, le Jour de Dépassement avait lieu le 29 décembre. En 2018, il avait déjà lieu le 1er août. En moins d'un demi-siècle, nous avons donc perdu 41% d'une année (151 jours) pour consommer les ressources réellement disponibles par an.

régénérer en un an. Il ne fait donc aucun doute que les problèmes environnementaux actuels nous rendent vulnérables. Pourtant, beaucoup de gens ne se rendent pas compte que leurs actions quotidiennes et leurs décisions ont souvent un impact sur les générations futures (par exemple, les décisions politiques, l'utilisation excessive des voitures et les transports polluants, le désir de confort, le mode de vie général, etc.). Cela signifie que nous faisons partie du problème. Cependant, nous pouvons mettre en place certaines actions concrètes qui peuvent contribuer à limiter les dommages. C'est la raison pour laquelle les gouvernements du monde entier s'efforcent de voter divers accords, lois et mesures visant à lutter contre ces problèmes et, entre autres, à limiter les émissions de GES.

La plus importante conférence mondiale sur le climat discutant des solutions visant à limiter les émissions de dioxyde de carbone et d'autres GES, est la Conférence des Parties (COP). En décembre 2015, la COP 21 a permis de convenir d'une hausse maximale de la température globale de 2°C d'ici 2100 par rapport à l'ère préindustrielle. Pour respecter cette limite, une série d'objectifs ont été fixés à l'échelle de l'Union européenne (UE). Concernant les objectifs fixés pour les émissions de GES, le dernier accord, entré en vigueur en octobre 2014, est la *Stratégie Énergie 2030*, dans le cadre de la *Stratégie Europe 2020* adoptée en juin 2010. Ces stratégies visent à coordonner efficacement les différentes politiques économiques et sociales des 28 États membres. Par rapport aux niveaux de 1990, les principaux objectifs de l'UE en 2030 sont (1) une réduction de 40% des émissions de GES, (2) une part d'au moins 27% de la consommation d'énergies renouvelables et (3) 30% d'économies d'énergie. Il est d'autant plus important d'essayer de respecter ces objectifs que la consommation d'énergie a recommencé à augmenter dans l'UE entre 2014 et 2017. L'Union s'éloigne ainsi des objectifs d'efficacité énergétique pour 2020 et 2030. Entre 2016 et 2017, la consommation d'énergie primaire[2] a augmenté de 1%, ce qui montre que la tendance à la baisse depuis 2013 n'est pas assez forte pour atteindre les objectifs d'efficacité énergétique. Les États membres de l'UE devront renforcer leurs politiques et

[2] Selon Eurostat, la consommation finale d'énergie est "l'énergie totale consommée par les utilisateurs finaux, telle que comme les ménages, l'industrie et l'agriculture. C'est l'énergie qui arrive à la porte du consommateur final et exclut ce qui est utilisé par le secteur de l'énergie lui-même." D'autre part, la consommation d'énergie primaire "mesure la demande totale d'énergie d'un pays. Il couvre la consommation du secteur de l'énergie lui-même, les pertes au cours de la transformation (par exemple, du pétrole ou du gaz en électricité) et de la distribution de l'énergie, et la consommation finale des utilisateurs finaux." Par conséquent, la consommation d'énergie primaire comprend la consommation d'énergie finale.

leurs objectifs pour atteindre les résultats escomptés.

Pour atteindre l'objectif indicatif de 30% d'économies d'énergie d'ici 2030, les États membres ont transposé ces objectifs européenes en objectifs nationaux d'efficacité énergétique, et ont voté une série de lois et mis en place des mesures les atteindre. Cette transposition est basée sur les directives et règlements communautaires et sont ainsi soutenus par (1) la *directive sur l'efficacité énergétique*, qui exige de promouvoir des facilités de financement pour l'efficacité énergétique, et des programmes de sensibilisation sur le fait que les audits thermiques permettent de proposer des conseils appropriés aux maîtres d'ouvrage, (2) la *directive sur la performance énergétique des bâtiments*, qui vise à réduire la consommation d'énergie dans les bâtiments, (3) des normes minimales de performance énergétique pour les appareils électroménagers, indiquées sur des étiquettes informatives, permettant ainsi aux ménages de faire de "meilleurs" choix d'achat, (4) des normes de performance pour les voitures, (5) un financement accru par différents fonds communautaires, (6) l'installation de compteurs intelligents[3] et (7) le système communautaire d'échange de quotas d'émission[4].

Prenons comme exemple de transposition des directives et règlements de l'UE visant à réaliser les économies d'énergie requises pour 2020, 2030 et 2050, **le cas de la France**. Diverses lois, comme par exemple les lois Grenelle I et II adoptées en 2009 et 2010, visent à transposer les décisions de l'UE en matière d'environnement et d'énergie. Plus important encore, la loi sur la transition énergétique pour une croissance verte (LTECV) adoptée en août 2015 permet de contribuer plus efficacement à ces objectifs, ainsi que de renforcer l'indépendance énergétique de la France, tout en offrant à ses entreprises et citoyens un accès à l'énergie à un coût compétitif[5]. Les objectifs principaux de la loi visent une réduction de 40% (75%) des émissions de GES d'ici 2030 (2050) par rapport aux niveaux de 1990. Elle vise également à réduire la consommation finale d'énergie de 20% d'ici 2030 et de 50% d'ici 2050 par rapport à 2012. En ce qui concerne plus spécifiquement le secteur résidentiel, il représente environ 40% de la consommation d'énergie finale (dont

[3]Un compteur intelligent est un compteur d'énergie (d'électricité en général) capable de surveiller en détail et en temps réel la consommation d'électricité d'un bâtiment, d'une entreprise ou d'un ménage. L'information est généralement directement transmise aux fournisseurs d'énergie, qui peuvent détecter les postes les plus énergivores, et donc permettre aux ménages de faire des économies. De plus, la facturation différenciée peut être proposée aux ménages, en fonction de leur demande réelle d'électricité.

[4]Source : `https://eur-lex.europa.eu`

[5]Source: `https://www.ecologique-solidaire.gouv.fr/loi-transition-energetique-croissance-verte`

la plus grande partie provient du chauffage individuel, avec 66,3% en 2016) et 27% des émissions de GES en 2017[6]. À titre de comparaison, dans l'UE, le secteur résidentiel représente un quart de la consommation totale d'énergie finale (25,4%) en 2016, dont 64,6% pour le chauffage individuel, 14,5% pour l'eau chaude sanitaire et 13,5% pour l'éclairage. Étant très énergivore, ce secteur a un grand potentiel pour contribuer à l'atteinte des objectifs d'efficacité énergétique. En ce sens, de nombreux États membres de l'UE ont adopté une stratégie de rénovation des bâtiments, des programmes obligatoires en matière d'efficacité énergétique et un plan d'action national pour l'efficacité énergétique (European Commission, 2014). L'évaluation des économies d'énergie réalisées par l'UE en 2015 dans le secteur résidentiel montre que la consommation moyenne d'énergie finale a diminué de 11% au cours des dix dernières années. En France, la LTECV prévoit comme l'un de ses principaux objectifs d'améliorer l'efficacité énergétique des bâtiments en atteignant d'ici 2050 un niveau de performance énergétique conforme aux normes "Bâtiment Basse Consommation" (BBC) pour l'ensemble du parc immobilier[7]. Ces normes obligatoires sont résumées dans la Réglementation Thermique (RT) des Bâtiments Existants[8]. Pour atteindre ces objectifs, il est prévu de réaliser 500 000 rénovations énergétiques par an à partir de 2017. Cette dernière mesure a déjà été fixée par le *Plan rénovation énergétique des bâtiments* en mars 2013, avec un objectif intermédiaire de 270 000 rénovations énergétiques par an entre 2014 et 2016. De plus, la LTECV a mis en place la *Stratégie nationale bas carbone* (SNBC) ainsi que le *Programme pluriannuel de l'énergie* (PPE). Le PPE prévoit, entre autres, dans le secteur du bâtiment, la massification de la rénovation énergétique des bâtiments résidentiels et tertiaires pour atteindre une économie d'énergie de 28% d'ici 2030 par rapport à 2010. De même, la SNBC prévoit de rendre obligatoire la rénovation thermique (isolation des murs, fenêtres étanches à l'air, etc.) lors de travaux de rénovation importants, et vise 41% de bâtiments BBC en 2030.

Ainsi, une action importante de la LTECV pour soutenir les rénovations énergétiques est la création de plateformes locales de rénovation énergétique des logements privés, individuels et collectifs, qui renforcent le service indépendant d'information et de conseil fourni

[6]Source : `https://www.ecologique-solidaire.gouv.fr/strategie-nationale-bas-carbone-snbce7`

[7]Les deux autres objectifs principaux de la LTECV sont la lutte contre la précarité énergétique et l'amélioration de la qualité de vie des ménages.

[8]Source : `https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000000000822199`

par le réseau Rénovation Info Service. Les principales missions des plateformes sont de (1) mobiliser les ménages et les accompagner tout au long de leur projet de rénovation (par exemple les informer sur la rénovation énergétique, les assister dans la mise en place d'un plan de financement, les assister dans le choix des professionnels), (2) organiser des audits thermiques pour faire l'état de lieux des bâtiments et hiérarchiser les travaux à réaliser, (3) mobiliser les acteurs financiers (e.g. les banques) pour aider les ménages à obtenir un tiers financement, des prêts et des subventions liés aux travaux de rénovation énergétique, et (4) mobiliser les artisans en les aidant à créer des groupements, en les formant via des formations professionnelles spécifiques et en les aidant à accéder au marché de la rénovation énergétique. Un exemple de plateforme régionale est *Oktave* lancée par l'ADEME et la région Grand Est en 2015[9]. Elle vise à rénover des maisons individuelles uniquement. L'un des points forts de cette plateforme est le point *(4)* mentionné ci-dessus, à savoir, former et encourager les professionnels à constituer des groupements d'artisans. Pour ce faire, ils sont formés au niveau régional, puis interviennent dans le cadre de plateformes locales. Les formations proposées s'appuient sur la méthode *DORéMI*, lancée pour la première fois en 2012 dans la région Rhône-Alpes et qui s'articule autour de trois modules. Ces modules ont pour but d'enseigner aux artisans toutes les connaissances nécessaires à la coordination et à l'organisation d'un projet de rénovation complet. De plus, il enseigne aux groupements d'artisans comment efficacement coordonner leurs tâches à travers la rénovation effective d'au moins deux maisons au cours de leur formation. En effet, le point de départ de la méthode DORéMI est de dire que l'efficacité énergétique d'un bâtiment peut être très difficile, voire impossible, à atteindre sans une coordination efficace entre les artisans intervenant sur le chantier. Au chapitre 3 de la thèse, nous testons expérimentalement la capacité de coordination des artisans formés avec cette méthode, face à des incitations individuelles et collectives, et nous la comparons à des artisans non formés ou formés avec une méthode alternative moins complète.

Dans un premier temps, la plateforme régionale Oktave a été créée pour apporter une réponse aux obstacles observés dans l'accompagnement technique et financier des ménages dans leurs projets de rénovation énergétique. Ces obstacles ont été mis en évidence par

[9] Des plateformes de rénovation énergétique similaires ont été mises en place dans toutes les régions de France. On peut citer, entre autres, la plateforme *Habitat Solidaire et Durable* en Normandie, le *Picardie Pass Rénovation* dans les Hauts-de-France, ou encore le *SEM Energies POSIT'IF* en Ile-de-France.

le programme *Je rénove BBC* dans la région Grand Est, qui a été le premier programme de rénovation à grande échelle en France. Ce programme a permis de rénover 473 logements individuels jusqu'au niveau BBC en Alsace et a vu le jour grâce à une convention signée entre Électricité de France (EDF) et les autorités régionales de la région Alsace en 2008. Les ménages admissibles[10] ont eu la possibilité de rénover leur maison dans le cadre de ce programme entre 2010 et 2014, et les derniers travaux de rénovation ont duré jusqu'en 2017. L'objectif principal était de réduire les émissions de carbone en isolant au moins l'enveloppe thermique du bâtiment, mais les ménages sont souvent allé plus loin en décidant d'installer un système de ventilation mécanique contrôlée (VMC) et un système de chauffage plus efficient. L'objectif de performance énergétique de chaque bâtiment était de 104 kWh/m².an en énergie primaire[11]. Des procédures de test d'étanchéité à l'air (test d'infiltrométrie) ont permis d'attester que ce seuil ne soit dépassé en fin de travaux. La particularité de ce programme était double. Tout d'abord, l'intervention d'un maître d'œuvre pour chaque projet de rénovation était obligatoire afin de coordonner au mieux les travaux. En effet, un projet pilote de 30 rénovations BBC (50 Chantiers Pionniers), où la présence d'un chef de projet n'était pas obligatoire, a permis de constater que les chantiers où un maître d'œuvre était présent, ce dernier a permis de rassurer les propriétaires et de mieux organiser les travaux. Deuxièmement, le programme proposait des aides financières supplémentaires. Si celles-ci visaient d'abord à attirer les propriétaires, elles les ont également encouragé à aller au bout de leur démarche de rénovation. Grâce au programme *Je rénove BBC*, nous avons pu mener l'analyse du chapitre 1, présentée plus loin dans l'introduction.

La thèse dans ce contexte de "rénovation énergétique"

Étant donné que l'amélioration de l'efficacité énergétique des bâtiments existants représente un potentiel non négligeable de réduction de la consommation d'énergie, une mesure clé (adoptée par la plupart des États membres de l'UE) consiste en la rénovation énergé-

[10] Les critères d'admissibilité pour participer au programme Je rénove de la BBC étaient de rénover une maison individuelle située en Alsace, construite avant 2005, et ne comprenant pas plus de trois logements.

[11] En France, pour obtenir le label BBC-Effinergie Rénovation, la consommation du bâtiment ne doit pas dépasser 80 kWh/m².an d'énergie primaire. Cette performance est multipliée par un coefficient de rigueur climatique (déterminé par l'emplacement), multiplié en fonction de l'altitude du projet. La consommation totale d'énergie primaire est mesurée en fonction de quatre composantes : chauffage, eau chaude sanitaire, éclairage, ventilation et auxiliaires. Le refroidissement dans des bâtiments individuels n'est pas une condition préalable dans cette région.

tique du parc immobilier existant. Cependant, rénover des bâtiments au niveau BBC ne se fait pas toujours sans difficultés. En effet, il subsiste un risque de ne pas atteindre la consommation d'énergie prédite après une rénovation BBC, et donc de ne pas réaliser les économies financières prévues. En effet, de nombreux facteurs (météorologiques, comportementaux, techniques) peuvent intervenir à différents niveaux (phase de conception, phase d'exécution, phase d'utilisation). La rénovation d'un bâtiment représentant un investissement important pour les ménages, ils auraient besoin d'une garantie de pouvoir réaliser les économies nécessaire au remboursement de leur crédit et rentabiliser leur investissement sur le long terme. Pourtant, nous disposons à ce jour de relativement peu d'informations fiables sur ce risque. La grande incertitude quant à l'épargne potentielle d'un ménage après une rénovation peut rendre les banques et les compagnies d'assurance réticentes à offrir de nouveaux produits comme des prêts ou des assurances de crédit liés à la rénovation énergétique. Les banques ne peuvent pas encore baser le remboursement des prêts accordés sur les futures économies d'énergies des ménages. Jusqu'à aujourd'hui, la plupart des crédits accordés pour rénovation énergétique sont garantis par l'État (par exemple, l'"éco-prêt à taux zéro" en France, où l'État paie les intérêts). Sans intervention des États, ces difficultés contribuent à rendre le marché de la rénovation énergétique peu attractif, risqué et inaccessible pour de nombreux ménages individuels, ce qui se traduit par un faible nombre de rénovations énergétiques sur le long terme. L'objectif d'efficacité énergétique de l'UE 2030 devient donc plus difficile à atteindre.

Dans ce contexte, cette thèse vise, par le biais de trois analyses, à contribuer à (1) mieux identifier et évaluer le risque de ne pas atteindre la consommation d'énergie prédite, après une rénovation BBC, et (2) réduire le risque de ne pas atteindre la performance énergétique des bâtiments. Rendre la rénovation énergétique plus fiable et déterminer le risque (et son ampleur) de consommer plus que prédit après une rénovation pourrait encourager de plus en plus de compagnies d'assurance et de banques à entrer sur le marché de la rénovation énergétique. A long terme, cela pourrait contribuer de manière significative à rendre ce marché pérenne et capable de fonctionner sans intervention (financière) des gouvernements, ce qui permettrait d'augmenter le nombre de rénovations et d'atteindre les objectifs d'efficacité énergétique de l'UE.

Nous abordons cet objectif final d'un point de vue empirique, théorique et expérimental. Au chapitre 1, grâce à des données que nous avons collectées auprès du programme *Je rénove BBC* et à une analyse économétrique approfondie, nous cherchons à fournir de nouvelles connaissances sur les facteurs psychologiques (c.-à-d. les biais cognitifs) relativement peu étudiés dans le domaine de la consommation d'énergie, qui peuvent influer sur la différence entre la consommation d'énergie réelle et celle prédite par les bureaux d'études thermiques, après la rénovation d'un bâtiment. Cet écart est connue dans la littérature comme l'*écart de performance énergétique*. Déterminer l'impact de ces facteurs, influant sur le comportementaux liés à l'énergie des ménages, est utile pour deux raisons. Premièrement, si les banques et les compagnies d'assurance considèrent ces biais cognitifs comme un facteur de risque potentiel, ces derniers peuvent être inclus dans le calcul du risque de consommer plus (ou moins) que prédit théoriquement. Deuxièmement, s'ils sont pris en compte par les auditeurs thermiques (c'est-à-dire les ingénieurs qui calculent le potentiel d'économie d'un bâtiment en termes d'argent, d'énergie et d'émissions de CO2), cela peut les aider à améliorer la précision des simulations de consommation d'énergie. Aux chapitres 2 et 3, notre recherche est motivée par l'hypothèse selon laquelle d'autres facteurs que les facteurs comportementaux liés à l'énergie peuvent être à l'origine de bâtiments moins performants, comme par exemple des facteurs inhérents à la phase d'exécution des travaux (p. ex. la qualité de la main-d'œuvre). Ainsi, en mobilisant la théorie des contrats et l'économie expérimentale, nous visons à déterminer des structures et des caractéristiques des contrats qui incitent les artisans à déployer des efforts importants et à coordonner efficacement leurs tâches sur un chantier de rénovation. De tels contrats peuvent contribuer à améliorer l'efficacité énergétique des bâtiments et donc à réduire le risque susmentionné.

De manière plus détaillée, notre analyse empirique (chapitre 1) étudie l'impact de quatre biais cognitifs pouvant influer sur l'écart de performance énergétique en agissant sur les comportements, les attitudes ou les intentions des ménages en lien avec l'environnement et à la consommation d'énergie. Ces quatre biais sont le *biais du statu quo*, le *biais d'optimisme*, l'*écart attitude-comportement* et l'*écart intentions-comportement*.

Cette étude est motivée de la manière suivante. L'écart de performance énergétique est reconnu dans la littérature comme étant à l'origine d'effets contradictoires et décourageant ainsi les investissements dans les technologies d'efficacité énergétique (Jaffe and Stavins, 1994; Koopmans and te Velde, 2001b; Gillingham and Palmer, 2014; Delzendeh et al., 2017; Gerarden et al., 2017; Gram-Hanssen and Darby, 2018). Bien que des études aient été menées pour réduire l'écart de performance énergétique en améliorant les outils de simulation de consommation d'énergie (p.ex. en intégrant les processus de conception énergétique, en tenant compte des erreurs de conception et d'installation, en améliorant les inexactitudes dans les simulations, ...), moins d'études ont été menées sur l'impact des comportements face à l'énergie des ménages sur cet écart. De plus, comme les comportements réels sont rarement pris en compte dans les modèles de prévisions de consommation d'énergie (Branco et al., 2004; Tetlow et al., 2015; Delzendeh et al., 2017; Khoury et al., 2017), l'écart de performance énergétique se retrouve être encore plus prononcé. Pour tenter de combler ce vide, une littérature de plus en plus abondante analyse la façon dont les comportements des occupants influent sur leur consommation d'énergie (Seligman et al., 1978; Van Raaij and Verhallen, 1983a; Haas et al., 1998; Lindén A. Carlsson-Kanyama A., 2006; Guerra Santin, 2010; Tatiana De Meester Anne-Françoise Marique, 2013). Cependant, on en sait beaucoup moins sur les paramètres psychologiques et sociaux qui influent sur le comportement énergétique et sur la relation entre les comportements énergétiques et l'écart de performance énergétique (Frederiks et al., 2015b; Tetlow et al., 2015; Delzendeh et al., 2017). À ce jour, les facteurs psychologiques ont plutôt été étudiés en relation avec les décisions d'investissement des ménages dans la rénovation ou l'achat de nouveaux produits électroménagers (Häckel et al., 2017; Stadelmann, 2017; Blasch and Daminato, 2018). Ainsi, à travers notre analyse, nous suscitons le débat sur l'amélioration des modèles de simulation en tenant compte des comportements face à l'énergie des occupants, et cherchons à mieux comprendre quels biais cognitifs jouent un rôle significatif dans l'apparition systématique d'écarts de performance énergétique après rénovation.

Pour répondre à cette dernière question, nous avons administré (de visu ou par téléphone) un questionnaire (il a été élaboré en 2015 dans le cadre de mon stage Master avec EDF) à 129 ménages ayant participé au programme Je rénove BBC, entre avril 2015 et février 2017. Cela a été possible grâce à une collaboration avec EDF[12]. La base de données générée comprenait, entre autres, des informations sur les caractéristiques sociodémographiques des ménages, leur comportement, leur motivation et leurs attitudes environnementales, les prédictions théoriques de consommation d'énergie et les factures

[12]Je tiens à remercier tout particulièrement Sabine Mirtain-Roth et Ludovic Parisot pour leur soutien.

de gaz et d'électricité. Nous présentons des détails sur l'enquête ainsi que des statistiques descriptives sur les données récoltées. Pour une description détaillée de la méthodologie utilisée constituer la base de données, vous pouvez consulter le travail de thèse de Lampach (2016, , chapitre 5). Il a cependant analysé la base de données d'un point de vue au notre. Contrairement à Lampach (2016) qui a pris en compte la consommation d'énergie *ex-ante* et *ex-post* dans son analyse, nous considérons uniquement la consommation d'énergie *ex-post*, afin d'inclure plus d'observations[13]. Lampach (2016) s'est concentré sur la détermination de facteurs plus « généraux » expliquant de surconsommation des ménages, alors que nous nous concentrons plus particulièrement sur l'impact de leurs biais cognitifs. De plus, nous étudions séparément l'écart de performance énergétique des ménages qui consomment plus et de ceux qui consomment moins ou comme prévu. Cela nous permet de capturer certains effets que les biais cognitifs peuvent avoir sur un seul des groupes, et qui pourraient rester indétectables autrement. Nous proposons de mesurer les biais cognitifs étudiés à l'aide de comportements, attitudes et intentions auto-déclarés. La particularité de notre analyse réside dans la méthodologie appliquée pour surmonter les problèmes de modélisation des données (c.-à-d. problème de sur-paramétrisation, puissance statistique plus faible ou violation des hypothèses de distribution qui peuvent apparaître en raison de nos 7% de valeurs manquantes, mais aussi un problème potentiel d'endogénéité lié à la nature de nos variables qui sont déclarées). Par conséquent, nous utilisons une méthode d'imputation multiple pour remplacer les valeurs manquantes par des valeurs simulées basées sur les informations disponibles dans la base de données (Gram-Hanssen, 2011; Azur et al., 2011; Grund et al., 2016). De plus, nous effectuons et comparons un ensemble d'algorithmes d'apprentissage largement utilisés dans la littérature pour sélectionner les variables de contrôle qui affectent le plus l'écart de performance énergétique (Breiman, 2001; Ye et al., 2009; Pal and Foody, 2010; Ganjisaffar et al., 2011; Chen et al., 2015). Par ailleurs, étant donné la taille relativement petite de notre base de données, nous avons inclus un nombre limité de paramètres par régression pour éviter la sur-paramétrisation (Koebel et al., 2016). Enfin, pour exclure les problèmes potentiels d'endogénéité et approuver la robustesse de notre mesure des biais cognitifs (c'est-à-dire

[13] 50% des ménages interrogés ne vivaient pas dans la maison rénovée avant les travaux, de sorte qu'il y a moins d'informations disponibles en ce qui concerne la consommation d'énergie ex ante des ménages.

les comportements, attitudes et motivations auto-déclarés), nous utilisons l'approche de *pondération par probabilité inverse* (Austin, 2011; Stuart et al., 2014).

Nous observons que mesurer des biais cognitifs à l'aide de comportements et d'attitudes auto-déclarés peut, dans une certaine mesure, être une méthode valable. Nous trouvons que des biais ont effectivement un impact sur l'écart de performance énergétique des ménages, en particulier ceux qui consomment plus que prédit après rénovation. Ainsi, nous détectons la présence d'un biais de statu quo lié à l'ouverture des fenêtres et d'un biais d'optimisme ayant un impact négatif sur l'écart de performance énergétique des ménages qui consomment plus que prévu. De plus, nous trouvons un écart attitude-comportement et un écart intentions-comportement, car l'écart de performance énergétique des ménages pro-environnementaux et écologiquement motivés n'est pas plus faible que pour les autres ménages.

L'analyse théorique (chapitre 2) propose un cadre Principal-Agent dans le but de modéliser la relation contractuelle entre un maître d'œuvre (ou un maître d'ouvrage), et un artisan sur un chantier de rénovation. Nous partons du principe qu'il est possible d'améliorer l'efficacité énergétique des bâtiments en proposant des contrats appropriés, incitant les artisans à travailler plus consciencieusement pendant la phase d'exécution des travaux. En ce sens, nous proposons un problème d'aléa moral avec un potentiel niveau de conscience (envers certains aspects) asymétrique entre un Principal (par exemple, le maître d'œuvre) et un Agent (par exemple, l'artisan) ayant deux tâches à exécuter. La particularité de notre modèle est l'introduction d'un paramètre représentant le degré d'inconscience de l'Agent (i.e. « unawareness »). Par exemple, lorsqu'il travaille sur la rénovation d'un bâtiment BBC, un artisan n'est pas toujours au courant dans quelle mesure l'application de techniques de rénovation BBC impacte la consommation finale d'énergie du bâtiment. Les tâches de l'Agent peuvent influer sur la performance finale du bâtiment (et donc sur sa rémunération) d'une manière qui n'a jamais traversé son esprit. L'objectif de ce chapitre est de déterminer la structure de rémunération optimale que le Principal devrait offrir à l'Agent pour qu'il exerce des niveaux d'effort plus élevés, et comment le Principal prend en compte le niveau d'inconscience de l'Agent dans la rémunération.

Nous présentons d'abord un modèle de référence, dans lequel les deux parties peuvent avoir des préférences différentes en matière de risque, et sont parfaitement conscients de l'impact de la deuxième tâche de l'Agent sur la distribution de la performance. Contrairement à Sinclair-Desgagne (1999); Chaigneau et al. (2017) et Sinclair-Desgagne and Spaeter (2018) qui déterminent la rémunération optimale de l'Agent quand il a une seule tâche, nous attribuons deux tâches à l'Agent. Dans un deuxième temps, nous présentons notre "modèle à potentielle inconscience", où l'Agent n'est pas forcément conscient de l'impact de sa seconde tâche sur la distribution de la performance finale. Nous examinons le cas d'un Principal neutre au risque et d'un Agent averse au risque. Nous faisons l'hypothèse que le Principal connaît le niveau de conscience de l'Agent en ce qui concerne sa deuxième tâche. Pour résoudre les modèles, nous faisons l'hypothèse d'un rapport de vraisemblance strictement croissant et concave. Cela signifie qu'une légère augmentation de la performance dans l'ensemble des niveaux de performance faibles, donne plus d'informations sur le niveau d'effort exercé par l'Agent qu'une légère augmentation de la performance dans l'ensemble des niveaux de performance élevés. Contrairement à Von Thadden and Zhao (2012, 2014) et Auster (2013) qui étudient les modèles Principal-Agent avec inconscience, nous ne cherchons pas à rendre l'Agent conscient, mais plutôt de déterminer l'impact de son inconscience sur la structure optimale de la rémunération.

Nous trouvons que le degré de prudence de l'Agent est déterminant dans la courbure de la rémunération optimale que le Principal lui offre. De plus, notre contribution est de montrer que le Principal tient compte stratégiquement du niveau de conscience de l'Agent en adaptant la structure de la rémunération. Il augmente la rémunération moyenne de l'Agent inconscient pour des niveaux de performance finale faibles (afin d'augmenter l'incitation à travailler plus fort), et diminue sa rémunération moyenne pour les niveaux de performance qu'il ne pourra atteindre que s'il déploie des efforts importants sur les deux tâches. En effet, comme il ne connaît pas les conséquences de sa deuxième tâche, elle va la négliger.

Enfin, l'analyse expérimentale (chapitre 3) présente une expérience d'effort réel en laboratoire dans laquelle nous comparons, dans une configuration intra-groupe, des incitations individuelles et collectives, dans leur capacité à inciter à la coordination sur des niveaux d'effort élevés. L'originalité de l'expérience est qu'elle teste ces incitations auprès de "vrais" artisans du secteur du bâtiment, où la coordination est essentielle compte tenu de la propriété de maillon faible de leurs tâches (c'est-à-dire que si un artisan ne parvient pas à atteindre son objectif, tout le travail est impacté négativement). En outre, une contribution principale de cette expérience est que nous ne comparons pas seulement les effets des différentes incitations, mais nous examinons également l'effet des "formations professionnelles insistant sur l'importance de la coordination" en comparant les sujets ayant été formés de manière endogène et ceux qui ne l'ont pas été. Nous visons donc à déterminer (1) s'il est possible d'inciter les artisans vers une meilleure coordination avec un contrat de type « maillon-faible » (c.-à-d. incitation collective) et (2) si ce contrat a le même effet incitatif sur les deux groupes d'artisans (c.-à-d. formés et non formés à la coordination). En d'autres termes, nous voulons déterminer si un simple mécanisme de formation exogène à la coordination peut suffire à assurer la coordination à des niveaux d'effort élevés.

Cette analyse peut contribuer à une meilleure exécution des travaux de rénovation en déterminant des types de contrats appropriés pour un groupe d'artisans intervenant sur la rénovation BBC d'un bâtiment. Un chantier de rénovation est typiquement une situation de type « maillon faible » : si au moins un des artisans n'exécute pas correctement sa tâche (pour laquelle il est le seul à être spécialisé), la performance énergétique finale du bâtiment est impactée négativement. Nous partons donc de l'hypothèse générale selon laquelle la mise en œuvre de mesures incitatives correspondantes (où les travailleurs sont tous rémunérés en fonction de la plus mauvaise performance des membres de leur équipe) peut encourager les travailleurs à coordonner leurs efforts à des niveaux élevés. En outre, le fait d'avoir été spécifiquement formé et sensibilisé à une coordination efficace peut constituer un mécanisme supplémentaire incitant à déployer des efforts importants.

En plus d'être l'une des premières (après Bortolotti et al., 2016) à tester conjointement l'effet des incitations individuelle et collective sur l'effort et la capacité de coordination lorsque les sujets doivent déployer un effort réel lors de l'expérience au lieu de choisir leur action, la nouveauté de notre expérience est double. Tout d'abord, nous assignons spécifiquement aux sujets des objectifs de performance individuels qu'ils doivent atteindre. Brandts and Cooper (2007) montrent que le fait de permettre la communication entre les managers (c.-à-d. l'expérimentateur) et les employés (c.-à-d. les artisans) mène à une coordination plus efficace et à de meilleurs résultats. Ils recommandent ainsi aux managers d'exiger un niveau d'effort spécifique. Deuxièmement, nous examinons l'impact d'une formation de coordination exogène sur la coordination de groupe d'artisans. Les participants à l'expérience sont des artisans travaillant, entre autres, sur des projets de rénovation BBC dans la Région Grand Est (9 artisans formés et 26 artisans non formés). La région Grand Est ayant été co-financeur de cette thèse, leur réseau nous a permis de rencontrer et réunir des artisans du bâtiment. Les plateformes de rénovations locales travaillant avec la Région Grand Est ont ainsi organisé deux réunions d'information (le programme *Habiter Mieux en Déodatie* pour rencontrer les artisans non formés en novembre 2018, et la plateforme *Oktave* pour rencontrer les sujets formés en décembre 2018), durant lesquelles les artisans ont reçu des informations sur des aides financières et des futurs projets de rénovations énergétiques. En début de chaque rencontre, les artisans ont été invités à participer à notre expérience, sans que nous leur en expliquions la finalité exacte. Ceux qui ont été formés de manière endogène ont participé à la formation DORéMI décrite précédemment, c'est-à-dire qu'ils ont appris (1) les techniques de rénovation BBC, (2) l'importance d'une coordination efficace des travaux dans la performance énergétique finale du bâtiment et (3) comment coordonner leurs tâches (complémentaires) avec leurs collègues de travail. Malgré la difficulté que nous avons rencontrée pour mobiliser des artisans formés pour participer à notre expérience (ce qui signifie qu'il faut considérer les résultats ultérieurs comme préliminaires), l'analyse non-paramétrique et paramétrique des résultats de l'expérience suggère que l'incitation individuelle a des effets différents selon si les artisans sont formés ou non. En effet, les sujets formés semblent se coordonner à des niveaux d'effort plus élevés que les sujets non formés lorsqu'ils sont confrontés à une incitation individuelle. Cependant, face à une incitation collective, les sujets formés se coordonnent de manière semblable à quand ils sont face à une incitation individuelle, alors qu'il permet aux sujets non formés de "rattraper" les niveaux de performance des sujets formés. Finalement, nos résultats suggèrent que les incitations de groupe sont très efficaces pour augmenter le niveau de performance des sujets non formés.

Contents

General Introduction

The main objective of this thesis, co-financed by the ADEME and the Grand Est Region in northeastern France, is to contribute to the emergence of a long-lasting and self-sustaining energy renovation market leading to an increased number of retrofit measures in the long-term. This can efficiently contribute in reducing emissions of greenhouse gases (GHG), thus slowing global warming down. We address the objective from three different perspectives. In a first chapter, we approach it from an econometric perspective by analyzing self-collected data from a large-scale french weatherization project. In a second chapter, we consider the objective from a theoretical perspective by presenting a two-task Principal-Agent model, where the Agent is possibly unaware of some contingencies. Finally, in a third chapter, we focus on the objective from an experimental perspective by mobilizing "real" craftsmen with different training backgrounds. Before explaining more in detail how we contributed to the main objective of the thesis, let us first develop below **the context of the thesis**.

The current environmental issues related to climate change raise the need for efficient measures that will contribute to reducing greenhouse gas emissions. Indeed, scientists are more and more alarmist about the health of our planet and raise awareness about the urgency of the situation. For more than 45 years now, we acknowledge an *Earth Overshoot Day*[14]. It corresponds to the day where humans have consumed more natural resources than our planet is able to regenerate in one year. Hence, there is no doubt that the current environmental issues make us vulnerable. Yet, many people do not realize that their actions and decisions often impact future generations (e.g. political decisions, excessive use of cars and polluting transports, the desire of comfort, the general lifestyle). This means that we are part of the global problem. However, some concrete actions can help to address these issues and limit the damages. This is why governments all over the

[14]In 1970, the *Earth Overshoot Day* occurred on 29 December. In 2018, it occurred already on 1 August. In less than half a century, we lost 41% of a year (151 days) in using actually available resources per year.

world strive to work on agreements, laws and measures to help fighting the problems and, among others, limit GHG emissions.

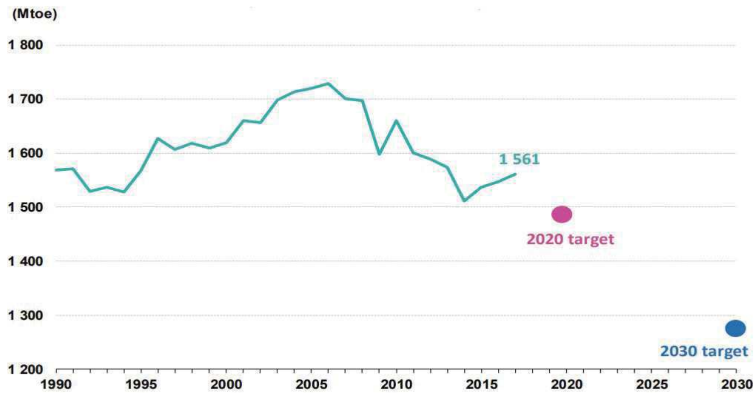
To discuss solutions aiming at limiting emissions of carbon dioxide and other GHG, the most important world climate conference is the *Conference of Parties* (COP). In December 2015, the COP 21 permitted to agree on a global warming increase limit of 2°C by 2100 compared to the pre-industrial era. To meet this target, a range of additional objectives have been set on a European Union (EU) wide level. To limit our discussion on goals set for GHG emissions, the most recent agreement, entered in force in October 2014, is the *2030 Energy Strategy*, as part of the *Europe 2020 Strategy* adopted in June 2010. The purpose of these strategies is to effectively coordinate the various economic and social policies of the 28 Member States. In comparison to the 1990 levels, the main targets for the EU in 2030 are (1) a 40% decrease of GHG emissions, (2) a share of at least 27% of renewable energy consumption, and (3) 30% of energy savings. Trying to meet these objectives is all the more important since energy consumption started to raise again in the EU between 2014 and 2017. This makes the Union moving away from the 2020 and 2030 energy efficiency targets, as depicted on Figure 1. Between 2016 and 2017, primary energy consumption[15] raised by 1%, showing that the declining trend since 2013 is not strong enough to achieve the energy efficiency targets. EU Member States will need to strengthen their policies and targets to achieve the expected outcome.

To work towards the indicative target of 30% energy savings by 2030, Member States put in place a range of laws and measures to meet (non-binding) national energy efficiency targets. Their transposed targets are based on European directives and regulations, and are thus supported by (1) the *Energy Efficiency Directive*, which requires to promote financing facilities for energy efficiency, and programs to raise awareness about the fact that thermal energy audits permit to propose appropriate advice services, (2) the *Energy Performance of Buildings Directive* to make buildings consume less energy, (3) minimum energy performance standards for appliances, where informative labels permit households to make "better" purchasing choices, (4) CO_2 performance standards for cars, (5) increased financing through various EU funds, (6) the installation of smart meters[16], and (7) the

[15] According to Eurostat, *final* energy consumption is "the total energy consumed by end users, such as households, industry and agriculture. It is the energy which reaches the final consumer's door and excludes that which is used by the energy sector itself." On the other hand, *primary* energy consumption "measures the total energy demand of a country. It covers consumption of the energy sector itself, losses during transformation (for example, from oil or gas into electricity) and distribution of energy, and the final consumption by end users." Hence, *primary* energy consumption includes *final* energy consumption.

[16] A *smart meter* is an energy meter (of electricity in general) capable of monitoring in detail and in

EU Emissions Trading System.[17]



Source: Eurostat
Note: primary energy consumption is indicated in million tonnes of oil equivalent (Mtoe).

Figure 1: Primary energy consumption in the EU

Let us below consider **the case of France** as a transposition example of these EU directives and regulations towards the required energy savings for 2020, 2030 and 2050.

Various laws, as for instance the *Grenelle I* and *II laws* adopted respectively in 2009 and 2010, aimed at transposing EU decisions in terms of environment and energy. More importantly, the *Law on Energy Transition for Green Growth* (LETGG) adopted in August 2015 enables to contribute more effectively to these decisions, as well as to strengthen France's energy independence, while offering its companies and citizens access to energy at a competitive cost[18]. The global objectives of the law target a 40% (75%) reduction of GHG emissions by 2030 (2050) compared to 1990-levels. It also aims at reducing final energy consumption by 20% by 2030, and by 50% by 2050 compared to the levels of 2012. Regarding more specifically the residential sector, it represents roughly 40% of final energy consumption (among which the largest part comes from space heating, with 66.3% in 2016[19]) and 27%[20] of GHG emissions in 2017. As a comparison, in the EU, the residential sector accounts for a quarter of total final energy consumption (25.4%) in 2016, among which space heating represented 64.6%, water heating 14.5%, and lighting appli-

real time, the electricity consumption of a building, a company or a household. Information is generally directly transmitted to the energy facilities which can detect the most energy consuming items, and thus permit households to make savings. Furthermore, real-time energy and differentiated billing can be done based on the actual electricity demand.

[17]Source: `https://eur-lex.europa.eu`

[18]Source: `https://www.ecologique-solidaire.gouv.fr/loi-transition-energetique-croissance-verte`

[19]Additionally to space heating, 0.2% came from space cooling, 10% from water heating, 5.5% from cooking, and 17.4% from lighting appliances.

[20]Source: `https://www.ecologique-solidaire.gouv.fr/strategie-nationale-bas-carbone-snbc#e7`

ances 13.5%. This sector, thus, has a huge potential in contributing to achieve the energy efficiency targets. In this sense, many EU Member States adopted a *Building Renovation Strategy*, *Energy Efficiency Obligation Schemes* and a *National Energy efficiency Action Plan* (European Commission, 2014). The 2015 EU assessment of energy savings with respect to the residential sector shows that the average final energy consumption decreased by 11% over the last ten years. In France, the LETGG foresees as one of its main objectives to improve buildings' energy efficiency by achieving an energy performance level that meets the "low-energy building" standards for the entire housing stock by 2050.[21] These mandatory standards are summarized in the french *Thermal Regulation of Existing Buildings*[22]. To meet the objectives, it is planned to realize 500 000 energy renovations per year from 2017 onward. This last measure was already fixed by the *Housing Energy Renovation Plan* in March 2013, with an intermediate objective of 270 000 energy renovations per year between 2014 and 2016. In addition, the LETGG developed the *National Low-Carbon Strategy* (NLCS) as well as the *Multi-Annual Energy Programming* (MAEP). The MAEP foresees, among others, in the building sector, the massification of the energy renovation of residential and tertiary buildings to achieve a 28% of energy savings by 2030 compared to 2010. Closely related, the NLCS expects to render thermal renovation (e.g. wall insulation, airtight windows) mandatory during major renovation work, and account for 41% of energy efficient buildings in 2030, that is, meet the above mentioned low-energy standards.

As such, an important action of the LETGG to trigger energy renovations is the creation of **local platforms for the energy renovation** of private, individual and collective dwellings, which strengthen the independent information and advice service provided by the *Renovation Info Service* network. The platforms' main missions are to (1) mobilize households and support them throughout their renovation project (e.g. informing them about energy renovation, assisting them in setting up a financing plan, assist them in the choice of professionals), (2) organize thermal energy audits to make the state of a building and prioritize the works to be implemented, (3) mobilize the financial actors (e.g. banks) to help the households getting a third party financing, loans and grants related to energy renovation works, and (4) mobilize craftsmen by helping them to create complementary worker groups, training them through specific courses and help craftsmen to get access

[21] The two additional main objectives of the LETGG are fighting fuel poverty and improving households' life quality.

[22] Source: `https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000000822199`

to the energy renovation market (ADEME, 2016). An example of a regional platform is the ***Oktave* platform** launched by the ADEME and the Grand Est region in northeastern France in 2015.[23] It aims at renovating individual houses only. One of the key strength of this platform is the above mentioned point (4), that is, to train and encourage professionals to build up groups of craftsmen. To do this, they are trained at a regional level, and then intervene within the framework of local platforms. The proposed **training courses** are **based on the *DORéMI* method**, launched for the first time in 2012 in the Rhône-Alpes region and which is organized around three extensive training modules. These modules aim at teaching the craftsmen all the necessary background to be able to conduct and organize an entire renovation project. Moreover, it teaches the groups of craftsmen how to efficiently coordinate their tasks through the actual renovation of at least two houses during their training course. Indeed, the starting assertion of the *DORéMI* method is that achieving energy efficiency in a building may be very hard, if not impossible, without efficient coordination among craftsmen. In Chapter 3 of the thesis, we experimentally test the coordination capacity of craftsmen having been trained with this method, when facing individual-based and group-based incentives, and compare it with non-trained craftsmen.

Initially, the regional *Oktave* platform emerged to provide an answer to the obstacles observed in the technical and financial support of households in deep energy renovation projects. These barriers have been highlighted through the preceding temporary **energy conservation program *Je rénove BBC***, which was the first **large scale energy conservation program** in France. This program renovated 473 individual dwellings up to the level of low energy buildings in northeastern France, and emerged due to a convention signed between Électricité de France (EDF) and the regional authorities of the Alsace region in 2008. Eligible households[24] had the possibility renovate their house through this program between 2010 and 2014, and the renovation works lasted until 2017. The main objective was to reduce carbon emissions by at least insulating the building's thermal shell, but households often decided to also install an improved mechanical ventilation system and upgrade their heating system. The target energy performance of each building was 104 $kWh_{PE}/m^2.year$ in primary energy.[25] Air-tightness testing procedures (i.e. blower door

[23]Similar energy renovation platforms have been implemented in every region of France. We may cite, among others, the *Habitat Solidaire et Durable* platform in the Normandie region, the *Picardie Pass Rénovation* platform in the Hauts-de-France region, or the *SEM Energies POSIT'IF* platform in the Ile-de-France région.

[24]The eligibility criteria to participate in the *Je rénove BBC* program was to renovate an individual house in the Alsace region constructed before 2005, comprising not more than three dwellings.

[25]In France, in the residential sector, to obtain the "BBC-Effinergie Rénovation" label (a certification for

test) permitted to assess that this threshold was not exceeded at the end of the works. The particularity of this program was twofold. First, there was a mandatory intervention of a project manager for each renovation project to coordinate the work. A first pilot project of 30 low energy renovations (called *50 Chantiers Pionniers*), where the presence of a project manager was not mandatory, showed that his presence resulted in reassured owners and better organized renovation works. Second, the program proposed additional financial aids to the owners. This latter measure was meant to attract owners in the first place, but encouraged them to go through the entire process. On the grounds of *Je rénove BBC*, we conducted the analysis presented in Chapter 1, which will be introduced later in this general introduction.

The thesis in this "energy renovation" context

Since making existing buildings more energy efficient represents a potential to achieve high reductions of energy consumption, a key measure (adopted by most EU Member States) is thus the energy renovation of the existing building stock. However, carrying out energy efficient buildings is not always done without difficulties. There exists a risk of not achieving the predicted energy consumption after a low energy renovation, and thus not making the predicted financial savings. Indeed, many factors (e.g. meteorological, behavioral, technical) can intervene at different levels (e.g. design phase, renovation phase, utilization phase). Since renovating a building is an important investment for households, they would need the guarantee to carry out the necessary savings to reimburse their credit loan and make their investment cost-effective in the long term. Furthermore, households would need to have access to specific energy renovation credit loans, where its reimbursement would be based on the actual energy (and thus financial) savings. Yet, relatively little and unreliable information is available about the risk of not making the predicted savings after renovation. The high uncertainty about the potential savings of a household after a renovation may make banks and insurance companies reluctant to offer new products like energy renovation related credit loans or insurances. Until today, most credit loans granted by the banks for energy renovations are guaranteed by the State (e.g. the 'eco-loan at zero interest rate' in France, where the State pays the interest rates). Without

low energy level), the consumption of the building should not exceed $80kWh_{PE}/m^2.year$. This performance is multiplied by a coefficient of climatic rigor (determined by the location), increased according to the altitude of the project. The total primary energy consumption is measured based on four components: heating, hot water, lighting, ventilation and auxiliaries. Cooling in individual buildings is not a prerequisite in this region.

intervention of the States, these difficulties contribute to making the energy renovation market unattractive, risky and inaccessible for many individual households, resulting in a low number of energy renovations in the long term. This makes the EU 2030 energy efficient target harder to achieve.

In this context, this thesis aims, through three analyses, at contributing to (1) better identify and assess the risk of not achieving the predicted energy consumption after a low energy renovation and (2) reduce the risk of not achieving energy efficient buildings. Making energy renovation more reliable and determining the risk (and magnitude) of consuming more than predicted after a renovation could encourage more and more insurance companies and banks to enter the energy renovation market. In the long term, this might significantly help making this market sustainable and capable of functioning without (financial) intervention of the States, allowing to increase the number of renovations and helping to achieve the EU energy efficiency target.

The thesis addresses the main objective from an empirical, theoretical and experimental perspective. In **Chapter 1**, through a self-elaborated database from the *Je rénove BBC* program and an extensive econometric analysis, we aim at providing new insights about relatively little investigated psychological factors (i.e. cognitive biases) that can impact the difference between the actual and the predicted energy consumption after the renovation of a building, known in the literature as the *Energy Performance Gap*. Determining the influence of these energy related behavioral factors can help in two manners. First, if banks and insurance companies consider these cognitive biases as a potential risk factor, they can be included in the calculation of the risk of consuming more (or less) than predicted. Second, if they are taken into account by thermal energy auditors (i.e. engineers calculating a building's savings potential in terms of money, energy and CO_2 emissions), it can help them enhance the accuracy of the calculation of the energy consumption predictions. In **Chapters 2 and 3**, the motive of our research arises from the assumption that other factors than energy related behavioral factors might also cause less energy efficient buildings, such as factors inherent to the renovation phase (e.g. workmanship). Thus, through mobilizing contract theory and experimental economics, we aim at determining contract structures and features that incentivize craftsmen to exert high effort levels and coordinate efficiently on a renovation site. Such contracts can contribute to achieve more energy efficient buildings and thus reduce the above mentioned risk.

Going more into detail, our empirical analysis (**Chapter 1**) studies the influence of four cognitive biases which may affect the Energy Performance Gap through impacting households' energy related behaviors, attitudes or intentions, namely the *Status Quo Bias*, the *Optimism Bias*, the *Attitude-Behavior Gap* and the *Intention-Behavior Gap*.

The rationale for such an analysis is the following. The Energy Performance Gap is known in the literature for leading to counter-effects and thus deterring investments in energy efficiency technologies (Jaffe and Stavins, 1994; Koopmans and te Velde, 2001a; Gillingham and Palmer, 2014; Delzendeh et al., 2017; Gerarden et al., 2017; Gram-Hanssen and Darby, 2018). While investigations have been made to close the Energy Performance Gap through enhancing the energy simulation tools, (e.g. integrating energy design processes, accounting for workmanship installation errors, improving the inaccuracies in the energy simulation), less has been done with respect to the impact of households' energy behaviors on the gap. Moreover, as actual behavioral patterns are rarely taken into account in the energy consumption predictions (Branco et al., 2004; Tetlow et al., 2015; Delzendeh et al., 2017; Khoury et al., 2017), the Energy Performance Gap may be even more pronounced. In an attempt to fill this void, a growing literature analyzes how occupants' behaviors affect their energy consumption (Seligman et al., 1978; Van Raaij and Verhallen, 1983a; Haas et al., 1998; Lindén A. Carlsson-Kanyama A., 2006; Guerra Santin, 2010; Tatiana De Meester Anne-Françoise Marique, 2013). However, far less is known about the psychological and social parameters driving energy behavior, and the inter-relationship between energy behaviors and the Energy Performance Gap (Frederiks et al., 2015a; Tetlow et al., 2015; Delzendeh et al., 2017). Hence, through our analysis, we trigger the debate on the improvement of simulation models through accounting for occupant's energy related behaviors, and to better understand which cognitive biases play a significant role in explaining systematic variations of the Energy Performance Gap after renovation.

To fulfill our analysis in **Chapter 1**, we administrated (face-to-face or per phone) a self-elaborated questionnaire (this questionnaire was elaborated in 2015 as part of my Masters' thesis) to 129 households of the weatherization program *Je rénove BBC*, between April 2015 and February 2017. This has been possible through a collaboration with EDF[26]. The generated database comprised, among others, information about households' socio-demographic characteristics, self-reported energy behavior, motivation and attitudes, theoretical energy consumption predictions and actual energy consumption billing. We present

[26] I would like to specially thank Sabine Mirtain-Roth and Ludovic Parisot for their support.

details about the survey and descriptive statistics about the panel data. For an extensive description about the methodology used to gather information for the database, you may refer to Lampach (Chapter 5 in 2016). He analyzed the database, for the purpose of his doctoral thesis, from an different perspective. Contrary to Lampach (2016) who considered *ex-ante* and *ex-post* energy consumption in his analysis, this thesis considers solely *ex-post* energy consumption in our analysis, in order to include more observations[27]. He aimed at determining general factors of household's over-consumption, whereas we focus on the impact of their cognitive biases. Moreover, we separately study the Energy Performance Gap of households consuming more and those consuming less or as predicted, which may be undetectable otherwise. This permits us to capture some effects cognitive biases may have on only one of the groups. We propose to measure the studied cognitive biases with self-reported energy related behaviors, and environmental related attitudes and motivations. The particularity of our analysis may lie in the methodology applied to overcome data modeling challenges (i.e. overfitting problem, lower statistical power or violate distributional assumptions which may appear due to our 7% of missing values, but also a potential endogeneity problem related to the self-declared behaviors). As such, we use a multiple imputation method to replace missing values with predicted ones, based on information available in the database (Graham et al., 2007; Azur et al., 2011; Grund et al., 2016). Moreover, we perform and compare a set of most widely used supervised machine learning algorithms to select control variables which most affect the EPG. (Breiman, 2001; Ye et al., 2009; Pal and Foody, 2010; Ganjisaffar et al., 2011; Chen et al., 2015) Furthermore, since the size of our database is relatively small, we included a limited number of parameters per regression to avoid overparametrization.(Koebel et al., 2016) Finally, to exclude potential endogneity problems and approve the reliability of our measurement of cognitive biases (i.e. the self-reported behaviors, attitudes and motivations), we implement the 'inverse probability weighting' approach. (Austin, 2011; Stuart et al., 2014)

We see that measuring cognitive biases through self-reported behaviors and attitudes may to some extent be a valid method and that they indeed impact the households' Energy Performance Gap, especially regarding those consuming more than predicted after renovation. As such, we detect the presence of a *Status Quo Bias* related to manual ventilation and an *Optimism Bias* negatively impacting the EPG of households consuming

[27] 50% of the interrogated households did not live in the renovated house before the works, so that there is less available information about households' *ex-ante* energy consumption.

more than predicted. Moreover, we find an *Attitude-Behavior Gap* and an *Intention-Behavior Gap* emerging from the households, since pro-environmental and ecologically motivated households do not have a smaller EPG than the others.

The theoretical analysis (**Chapter 2**) presents a Principal-Agent framework with the purpose to model the contractual relationship between an project manager or owner, and a craftsman, on a renovation site. We indeed believe that it is possible to enhance the buildings' energy efficiency through proposing appropriate contracts, incentivizing craftsmen to work harder during the renovation stage. In this sense, we propose a moral hazard problem with possible asymmetric awareness between one Principal (e.g. the project manager) and one two-task Agent (e.g. the craftsman). The particularity of our model is the introduction of a parameter representing the Agent's degree of unawareness. For instance, while working on a low energy renovation of a building, a craftsman may not necessarily be aware to what extent applying recent low energy renovation techniques impacts the buildings' final energy consumption. There may be relevant contingencies affecting the performance distribution (and thus her payment) that have never crossed the Agent's mind. The main objective of this chapter is to determine the optimal reward the Principal should offer the Agent to exert higher effort levels, and how the Principal takes into account the Agent's unawareness through the offered reward.

We first present a baseline model, where both parties may have different risk preferences, and are completely aware about the Agent's second task's impact on the distribution of the performance. Contrary to Sinclair-Desgagne (1999); Chaigneau et al. (2017) and Sinclair-Desgagne and Spaeter (2018) who partially make the same analysis, we attribute two tasks to the Agent. In a second step, we present our 'possible unawareness model' by considering the case of a risk neutral Principal and a risk averse Agent. We assume that the Principal knows the Agent's degree of awareness with respect to her second task. To solve the models, we make the assumption of a strictly increasing and concave likelihood ratio. This means that a small increase of performance in overall low performance levels gives more information about the effort level exerted by the Agent than a small increase of performance in overall high performance levels. Contrary to Von Thadden and Zhao (2012, 2014) and Auster (2013) who study principal-agent models with unawareness, we do not intend to make the Agent aware, but rather to determine the Agent's unawareness' impact on the optimal contract structure.

We point out that the Agent's degree of prudence (also called aversion to downside risk) is determinant in the curvature of the optimal reward the Principal offers her. Moreover, our contribution shows that the Principal strategically takes the Agent's awareness level into account to adapt the structure of the reward. He will increase the unaware Agents' payoff for lower final performance levels (in order to increase the incentive to work harder), and decrease her reward for performance levels she could only reach when exerting high efforts on both tasks. Indeed, since she is unaware about the consequences of her second task, she will neglect it.

Finally, the experimental analysis (**Chapter 3**) presents a real-effort lab experiment in which we compare, in a within-group design, individual-based and group-based incentives to coordinate on high effort levels. The originality of the experiment is that it gathers "real" craftsmen from the construction sector where coordination is essential given the weak-link property of their tasks (i.e. if one worker fails to achieve his goal, all the work is spoiled). Furthermore, as a main contribution of this experience, we do not only compare the effects of different incentives, but also look at the effect of 'coordination training courses' by comparing subjects having endogenously been trained to coordination and others who have not. We thus aim at determining (1) if it is possible to incentivize towards more coordination through a weakest-link contract (i.e. the group-based incentive) and (2) whether this contract has the same incentive effect on both subject groups (i.e. trained and non trained to coordination). In other words, we want to determine if a simple mechanism of exogenous training about coordination can be sufficient to achieve coordination at high effort levels.

The rationale for this analysis to contribute to better executed renovation works can be found in determining efficient contract types for multiple craftsmen intervening on a building's low energy renovation. A renovation site typically presents the weak-link property: if at least one of the craftsmen does not correctly execute his task (for which he is the only one to be specialized), the final energy performance of the building is at sake. We thus depart from the general assumption that implementing corresponding incentives (where workers are all paid according to the worst performance of the members of their team) may encourage workers to coordinate at high effort levels. Moreover, having specifically been trained and sensitized to efficient coordination may be an additional mechanism incentivizing to exert high effort levels.

In addition to be one of the first (after Bortolotti et al., 2016) to provide joint evidence of the effect of individual and group-based weak-link incentives on effort provision and coordination when subjects have to exert a real effort instead of choosing their action, the novelty of our experiment is twofold. First, we specifically assign subjects' individual performance targets they should achieve. Brandts and Cooper (2007) show that allowing communication between managers (i.e. the experimenter) and employees (i.e. the craftsmen) leads to increased efficient coordination and higher payoffs. They recommend that managers request a specific effort level. Second, we look at the impact of an exogenous coordination training on group coordination. Our pool of subjects is composed of craftsmen working, among others, on low energy renovation projects in the Region Grand Est in northeastern France (9 trained craftsmen and 26 non trained craftsmen). The regional authorities of the Grand Est region partially financing this thesis, they gave us the possibility to meet and reunite craftsmen. They organized two information meetings in the name of local energy renovation platforms (the *Programme Habiter Mieux en Déodatie* to meet the non trained craftsmen in November 2018, and the *Oktave* platform to meet the trained subjects in December 2018), where craftsmen were given information about financial aids and future energy renovations. At the beginning of each meeting, craftsmen were invited to participate in our experiment, without being told the exact purpose of it. Those having been trained endogenously participated in the *DORéMI* training course detailed earlier, that is, where they learned (1) efficient renovation techniques, (2) the importance of efficiently coordinated works in the building's final energy performance and (3) how to coordinate their (complementary) tasks with their co-workers.

Despite the difficulty we encountered to mobilize trained craftsmen to participate in our experiment (which indicates to take the subsequent results "prudently"), our non-parametric and parametric analysis of the experience's results, suggest that individual-based incentives have different effects on both subject groups. Indeed, trained subjects seem to coordinate at higher effort levels than non trained subjects when facing an individual-based incentive. However, when facing a group-based incentive, trained subjects do not coordinate significantly differently, whereas it permits non trained subjects to "catch up" trained subjects' performance levels. Moreover, our results suggest that group-based incentives are very efficient to increase non trained subjects' worst performance levels.

Chapter 1

How cognitive biases affect the Energy Performance Gap in low energy buildings

sectionIntroduction

A growing debate in the energy literature is whether energy efficiency measures actually reduce individual households' energy consumption, and, thus, make it possible to significantly achieve the energy policy objectives. It has been widely recognized in the literature on energy efficiency that there is an important difference between actual and predicted energy consumption (called the Energy Performance Gap), which may lead to counter-effects and thus deterring investments in energy efficiency technologies (Jaffe and Stavins, 1994; Koopmans and te Velde, 2001a; Gillingham and Palmer, 2014; Delzendeh et al., 2017; Gerarden et al., 2017; Gram-Hanssen and Darby, 2018).

The Energy Performance Gap (EPG) may be attributed to the divergence among (1) the energy simulation (i.e. theoretical predictions from energy audits) in the design phase, (2) the workmanship and installation during the construction phase, and (3) the energy behavior of occupants during the utilization phase (Delzendeh et al., 2017). Although, many attempts have been made to close the EPG, as, for instance, the integration of energy design processes, the accountancy of workmanship installation errors and the improvement of inaccuracies in the energy simulation, the impact analysis of occupants' energy behavior has been neglected by this strand of literature. This shortcoming is all the more pronounced by the fact that energy simulation tools rarely take into account static or dynamic behavioral patterns, causing significant errors in the energy consumption prediction of the building energy use (Tetlow et al., 2015).

In an effort to improve this situation, scholars attribute more and more attention to the impact of households' energy behavior (e.g. the use of electricity appliances, temperature control, ventilation habits) on energy consumption (Seligman et al., 1978; Van Raaij and Verhallen, 1983a; Haas et al., 1998; Lindén A. Carlsson-Kanyama A., 2006; Guerra Santin, 2010; Tatiana De Meester Anne-Françoise Marique, 2013).[1] However, far less is known about the psychological and social parameters driving a given energy behavior, and the relationship between energy behaviors and the EPG (Frederiks et al., 2015a; Tetlow et al., 2015; Delzendeh et al., 2017; Blasch and Daminato, 2018). As an example of a psychological factor impacting household electricity consumption, we may cite Blasch and Daminato (2018), who study the status quo bias as a behavioral anomaly, with respect keeping energy-consuming appliances. They find that households presenting such a bias consume 5.7% more electricity than the others.

[1] An extended literature review can be found in Section 1.1.

To fill this void, this chapter analyzes the impact of households' cognitive biases on the EPG[2] after renovation works. Cognitive biases are thinking errors when processing information. When receiving information, the brain starts a mental process to understand this information, which allows us to make decisions or judgments. However, in an attempt to simplify these information processes, we unconsciously take mental shortcuts, that do not always lead us to make optimal decisions. These biases may lead households to adopt behaviors, which are not necessarily in adequacy with those taken into account by the prediction models. They may thus partly explain the EPG. This chapter thus contributes to the extensive nergy literature by considering the impact analysis of occupant's cognitive biases as an integrated component of the EPG analysis, and by triggering the debate on the improvement of simulation models through accounting for occupants' energy-related behaviors. We seek to better understand which cognitive biases play a significant role in explaining systematic variations of the EPG after renovation.

Drawing on recent theoretical advances of the energy behavior literature, we select four prevalent cognitive biases which may affect the EPG: the (i) *Status Quo Bias* with respect to manual ventilation, the (ii) *Optimism Bias*, the (iii) *Attitude-Behavior Gap* and the (iv) *Intention-Behavior Gap*. To verify how these cognitive biases influence EPG, we collect information on households' socio-demographic characteristics, self-reported energy behaviors, self-reported environmental attitudes and motives, thermal audits (for the predicted energy consumption) and consumption billing (for the actual energy consumption) through a self-administrated questionnaire between April 2015 and February 2017, based on the energy conservation program *Je Rénove BBC* presented in the General Introduction of the thesis. We apply a multiple linear regression analysis by using a sample of 129 households. An early version of this database has been used by Lampach (2016) to analyze various determinants affecting the Energy Saving Gap, including households' *ex-ante* energy consumption. We are rather interested in the impact of cognitive biases in the EPG, with respect to solely *ex-post* consumption.

To do this, we focus on two potential outcomes of the EPG: (i) *Net Losing Energy Savings* (i.e. when households consume more than predicted) and (ii) *Net Gaining Energy Savings* (i.e. when households consume less or equal than predicted). The latter has been mostly disregarded by the energy literature. Studying both scenarios provides a clearer picture of the determinants affecting the EPG, and gives the opportunity to get key insights

[2] The total actual energy consumption includes heating, hot water, ventilation and auxiliaries.

into the capacity of households to achieve higher energy savings than predicted.

Nevertheless, our relatively small sample comprises approximately 7% of missing values, making data modeling more challenging (e.g. overfitting problem, lower statistical power, violating distributional assumptions). Moreover, relying the cognitive biases on *self-reported* energy behaviors, motivations and attitudes may be prone to endogeneity (i.e. omitted variable bias).

To overcome these data modeling challenges, we use a multiple imputation method to replace missing values with predicted ones, based on information available in the database (Graham et al., 2007; Azur et al., 2011; Grund et al., 2016). Since the application of recently developed 'predictive modeling' tools helps to substantially reduce the problem of overfitting by selecting the most relevant variables affecting the EPG, we perform and compare a set of most widely used supervised machine learning algorithms: the (i) *Random Forest* (RF), the (ii) *Gradient Tree Boosting* (GTB), and the (iii) *Non-Linear (Radial) Support Vector Machine* (SVM) algorithms (Breiman, 2001; Ye et al., 2009; Pal and Foody, 2010; Ganjisaffar et al., 2011; Chen et al., 2015). To rule out potential endogneity problems and to validate our measurement of cognitive biases (i.e. the self-reported behaviors, attitudes and motivations), we implement the 'inverse probability weighting' approach (Austin, 2011; Stuart et al., 2014).

Our findings confirm the presence of the four studied cognitive biases (i.e. 'status quo bias' and 'optimism bias' only for certain households consuming more than predicted, and the 'attitude-behavior gap' and 'intention-behavior gap' for certain households consuming more or less than predicted). We show that keeping the *status quo* on the manual ventilation behavior negatively affects the EPG for households consuming more than predicted. Still for occupants consuming more than predicted, our results indicate the presence of an *optimism bias* associated with their energy consumption behavior. Moreover, these empirical findings suggest evidence for an *attitude-behavior gap* from occupants with high pro-environmental attitudes: households do not have a significantly smaller EPG than those with low pro-environmental attitudes. This is also the case for households reporting ecological motives, who thus present an 'intention-behavior gap'. We show that our main empirical results are not affected by endogeneity, apart from the *intention-behavior gap* revealing that occupants reporting high ecological motives do not yield significantly higher EPG than others. We thus suggest that self-reported energy behaviors and attitudes toward the environment can to some extent be a valid instrument to measure cognitive biases.

The chapter proceeds as follows. Section 1.1 briefly presents existing literature studying the EPG. Section 1.2 outlines the main relevant cognitive biases discussed in the energy literature and proposes a testable set of hypotheses. Section 1.3 shows the survey design and explains how the database has been created. Section 1.4 displays descriptive statistics about the households of the database. Section 1.5 presents the analyzed EPG and the measurement variables selected to test the cognitive biases. Furthermore, Section 1.6 selects control variables using learning models, and presents the econometric model and the multiple imputation method that is applied. Section 1.7 reports the empirical results. Finally, Section 1.8 tests the presence of potential endogeneity related to the variables used to analyze the biases, and Section 1.9 discusses the implications of these findings for energy policy in the residential sector.

1.1 Related literature

The literature studying the Energy Performance Gap (EPG) has been growing over the last decade. As mentioned in the introduction, the efficiency of energy measures in the residential sector has been questioned. So far, researchers have pointed out that the gap between the predicted and the actual energy consumption can have opposite effects, and thus alleviate energy achievements (Koopmans and te Velde, 2001a). In addition, evaluating energy efficiency programs is difficult due, among others, to intertwined factors. Broadly speaking, the root causes of the EPG are still partly unclear. A systematic and effective identification of the causes, and how to manage them, may become more and more accurate with further research on this important issue.

Let us first focus on the definition of the buildings' energy related gaps studied in the literature. It is understandable that some variation will always exist, and that a gap will always be present due to uncertainties in energy consumption predictions and inaccurate measurements. It might however be possible to decrease certain uncertainties. Causes for the gap can appear at different stages of the building renovation process (de Wilde, 2014; Khoury et al., 2017). They might occur at the design stage (e.g. it is difficult to fully predict the future use of the building), at the construction and execution stages (e.g. the quality of the execution), at the operational stage after renovation (e.g. non-optimal user behavior of the building), but it can also be due to either inaccuracies in the calculation method of the theoretical energy consumption, model limitations or non-optimal choice of input variables by the model operator. Note that in most cases, a combination of these factors might determine the gap. The literature distinguishes between the EPG and the Energy *Saving* Gap (ESG): the former considers only *ex-post* consumption, whereas the latter also takes into account *ex-ante* energy consumption. The definition of the EPG has still not been clearly defined until today. For instance, by reviewing literature on it, de Wilde (2014) was able to point out three main definitions: (1) the difference between predicted (from thermal energy auditors) and actual energy consumption, (2) the difference between predicted (with models using machine learning) and actual energy consumption, and (3) the difference between "*energy ratings provided by compliance test methods and energy display certificates as [embedded] in regulation*". Galvin (2014) defines the EPG as the ratio of the difference between the *ex-post* actual ($E_{A_{ex\text{-}post}}$) and predicted ($E_{P_{ex\text{-}post}}$) energy consumption, and the predicted energy consumption: $EPG_{Galvin2014} = \frac{(E_{A_{ex\text{-}post}} - E_{P_{ex\text{-}post}})}{E_{P_{ex\text{-}post}}}$. In the present chapter, we define the EPG in a similar way. We analyze the ratio of the actual and the predicted energy consumption: $EPG^* = \frac{E_{A_{ex\text{-}post}}}{E_{P_{ex\text{-}post}}}$. The distribution of the EPG in our chapter is thus the same as with Galvin (2014)'s definition. An advantage of these *ex-post* EPG definitions is that they can be used as well on new as on renovated buildings, where *ex-ante* information on consumption is not available. Although it does not take the '*ex-ante* dimension' into account, it permits to make an evaluation of the building's energy performance. A further advantage mentioned by Galvin (2014) is that they can help scientists and renovation programs to identify households needing advice and help in controlling their energy consumption after renovation. Now, when *ex-ante* actual and predicted consumption are available, it becomes possible to analyze the *Energy Saving Gap* (ESG). An energy saving is the difference between the *ex-post* and the *ex-ante* energy consumption. Galvin (2014) calls the ESG the *Energy Saving Deficit*, and defines it as the ratio of the actual energy savings, and the predicted energy savings: $ESG = \frac{E_{A_{ex\text{-}post}} - E_{A_{ex\text{-}ante}}}{E_{P_{ex\text{-}post}} - E_{P_{ex\text{-}ante}}}$. Note that a confusion can be found in the literature, such that some authors claim to analyze the EPG, while they actually analyze the ESG (for example Khoury et al., 2017). It is thus important to relate on how the dependent variable has been defined. In the present chapter, it was not possible to analyze the ESG because of too few available information on the *ex-ante* consumption[3]. We thus decided to consider only *ex-post* energy consumption and analyze the EPG.

[3] About 50% of the households in our database did not live in the renovated building before renovation.

Let us now explore the various aspects analyzed in the literature that were shown to affect the EPG. Three main categories have been studied: (1) technical components (e.g. heating system, insulation), (2) households' characteristics (e.g. household size, income, age, education level) and (3) households' actual behaviors (e.g. temperature setting, ventilation behavior, occupancy time).

A number of scholars studied how technical components of energy systems and insulation affect energy consumption savings (see for example Hewett et al., 1986; Bell and Lowe, 2000; Sanders and Phillipson, 2006; Hens et al., 2010; Rosenow and Galvin, 2013, for more details about these features). Van den Brom et al. (2017) recently confirmed that the building's physical characteristics impact the EPG. They, among others, show that the EPG highly impacts elderly households' actual energy consumption (maybe because they are more often at home and heat for longer hours during the day). This indicates that these technical characteristics may be closely related to occupants' behavior. Thus, they recommend policy makers to focus on energy renovation of houses inhabited by elderly occupants. Khoury et al. (2017) conclude in their paper that it is possible to contribute closing the EPG through building optimization, associated with a responsible behavior from households. As stated by Visscher et al. (2016), it is crucial to understand occupants' behavior to correctly predict buildings' energy performance.

Regarding households' characteristics, many studies show their impact on the EPG. For instance, Van den Brom et al. (2017) find that electricity consumption increases with the income and the number of occupants. With regard to gas consumption and based on a 127 183 dutch households from the SHAERE database, they find that those with higher income make more gas savings (from heating) than those with lower income. Yet, the household size does not significantly impact the ESG in their study. This latter finding is in contradiction with Majcen et al. (2013) who study the gas consumption gap of 193 859 dutch households from databases issued by the AgentschapNL and the CBS (Statistics Netherlands). They find that the households' size actually has an impact on the gap.

Now regarding individuals' behaviors, their influence on the energy consumption of existing buildings has been highlighted by many authors (see, for instance, Seligman et al., 1978; Van Raaij and Verhallen, 1983a; Guerra Santin, 2010; Haas et al., 1998; Lindén A. Carlsson-Kanyama A., 2006; Majcen et al., 2013; Tatiana De Meester Anne-Françoise Marique, 2013; Khoury et al., 2017). Some authors even stress that the EPG may primarily be caused by households' behaviors (Aydin et al., 2017; Gram-Hanssen, 2011). Indeed, while it may partially be due to the renovation works and the insulation performance (Sanders and Phillipson, 2006), it may also be due to consumer behaviors like indoor temperature (Hens et al., 2010), occupancy time (Van den Brom et al., 2019) or ventilation behaviors (Guerra Santin, 2013). Moreover, Khoury et al. (2017) pointed out that heating more than predicted and opening windows more than recommended increased global energy consumption.

Since behavioral factors impact consumption, some authors question the use of standard calculation methods to determine the predicted energy consumption that consider normalized conditions of utilization (i.e. conventional instead of real behaviors from the occupants) (see, for instance, Khoury et al., 2017). The ability of these methods to perform accurate predictions is indeed questionable. In this sense, Delzendeh et al. (2017) pointed out that theoretical simulation tools fail to include dynamic occupant behaviors, since only "*fixed and scheduled patterns of behavior*" beside technical components of the building are considered. Similarly, by analyzing the heating consumption gap in a low energy dwelling in Switzerland, Branco et al. (2004) observed that real conditions of utilization like room temperature or ventilation rate was not considered by the predicted energy consumption calculations. To confirm the important influence of these latter behaviors, Majcen et al. (2013) find that they largely affect the predicted gas consumption. Still in the Netherlands, Van Raaij and Verhallen (1983b) determined five energy-related behavioral patterns based on self-reported behaviors of 145 households in the Netherlands: conservers, spenders, cool households, warm households and average households. They found significant consumption differences among these five clusters. A last example we may cite here emerges from the study of Van den Brom et al. (2017). They analyzed occupants' electricity consumption of 1 431 019 households in the Netherlands (by using the national SHAERE database of 2014) and highlighted that predictions did not take into account electrical appliances and lighting, yet daily manipulated by individuals.

By reviewing the literature on the EPG, it becomes clear that household-dependent characteristics and behaviors may play a significant role in the observed discrepancy. Nevertheless, very few authors consider the notion of households' cognitive biases, which can however have an important influence too. Such biases may indirectly influence occupants' energy related behavior and thus the EPG. Frederiks et al. (2015a) intend to highlight the relationship between cognitive biases and energy related behavior in the literature. They list biases and motivational factors that could explain why energy behaviors may not always correspond to personal values or material interests of occupants. Blasch and Daminato (2018) empirically study the impact of the status-quo bias as a behavioral bias making households delay their energy efficiency investment decisions. Their study is based on a total of 4 899 households from the Netherlands, Switzerland and Italy. The survey had been administrated in the context of the EU H2020 Project PENNY. They propose to measure households' bias toward the status quo through creating an index based on six items capturing preferences for the status quo and loss aversion in different situations. They show that households having the general tendency to be biased toward the status quo consume more electricity than the others. Still regarding households' investment decisions to buy new appliances, Stadelmann (2017) discuss in a review, how behavioral anomalies might explain the energy performance gap, through their impact on households' purchase decisions of durables. They discuss more particularly limited attention, reference-dependent preferences, hyperbolic time discounting, biased beliefs and decision heuristics.

The main reason biases have rarely been considered for an analysis of the EPG is that it is very difficult to construct a reliable measurement capturing occupant's cognitive biases. In this chapter, we intend to determine their influence on the EPG based on self-reported energy behaviors, motivations and attitudes.

The following section defines the notion of 'cognitive bias' and explains those studied in this chapter.

1.2 Cognitive biases related to energy behavior

Various factors explain the observed EPG: technical failures, non-optimal renovation works, harsh weather conditions, etc. However, behavioral factors seem to play a significant role, as pointed out in previous literature. These behaviors often emerge due to cognitive biases.

Cognitive biases refer to individuals' mistakes occurring when reasoning and making decisions. They are generally induced by mental shortcuts (i.e. heuristics), emerging when the brain tries to process and simplify information it is receiving. These shortcuts do not always lead us to make optimal decisions, and can event unconsciously alter someone's behavior. A number of these cognitive biases can directly impact energy consumption behaviors and indirectly impact energy savings of renovated buildings. In this study, we focus on four biases, namely (1) the *Status Quo Bias*, (2) the *Optimism Bias*, (3) the

Attitude-Behavior Gap and (4) the *Intention-Behavior Gap*.

Our analysis applies these cognitive biases to energy consumption related behaviors, because they can intuitively induce occupants to consume more and save less energy than initially predicted. They were selected in order to analyze a combination of largely studied cognitive biases that could be applied to energy consumption behaviors (1 and 2), and often studied pro-environmental related behaviors (3 and 4). We consider the two behavioral gaps as cognitive biases: as stated by Frederiks et al. (2015b), attitudes and intentions (i.e. a motivation toward a goal-directed behavior) are psychological factors, which potentially affect occupant's energy behavior, and thus their energy consumption.

Note that the literature recognizes that it is difficult to exactly measure cognitive biases, even though the concept behind them seems clear. It has mostly been studied through experiments in controlled environments. In this chapter, we propose to measure cognitive biases through self-declarations. These self-reported behaviors are only possible indicators, measuring cognitive biases indirectly. We present the selected self-declarations in Section 1.5. In the following, we define the concept of the fours above mentioned biases and deduce testable hypotheses from psychology and the theory of behavior.

The *status quo bias*: It refers to the behavioral tendency of preferring to do nothing, or to exert no effort to adapt a behavior (Samuelson and Zeckhauser, 1988), although doing nothing may lead to a change (Baron and Ritov, 2004). This tendency might arises due to people's general loss aversion (Thaler, 1980; Kahneman and Tversky, 1984; Samuelson and Zeckhauser, 1988; Kahneman et al., 1991). Individuals perceive losses as being bigger than the potential gains they can obtain by adapting their behavior.

It has been recognized that a person perceives the present state as a reference point (Baron, 2011). The shift from this point towards a more energy friendly behavior induces the perception of losses even when benefits are offset by gaining energy savings (Baron and Ritov, 2004; Rabin, 1998). In other words, individuals are more negatively affected by the occurrence of a change, in light of this reference point, than by the potential benefits to save energy (Helson, 1964).

In the context of renovating individual buildings, the *status-quo bias* may occur as follows. Before renovation, occupants experienced specific daily habits. Having to change their behaviors might appear too restrictive to them, compared to the expected benefits of energy savings. Thus, a majority of individuals may find it more convenient to not adapt its behavior to the low energy building. This means that they keep the *status quo* (on their 'previous' behavior). Yet, in a renovated building, occupants should adapt their manual ventilation habits and open their windows less than before. Otherwise, the efficiency of the new ventilation system may be deteriorated, and electricity consumption may increase.[4] We can thus formulate our first hypothesis about the *status quo bias* as follows:

Hypothesis 1 *Occupants keeping the status quo on their window opening habits are less likely to achieve the predicted energy consumption, and thus tend to have a larger Energy Performance Gap (than those changing their manual ventilation habits compared to before renovation).*

The *optimism bias*: It is the tendency to overestimate positive outcomes, and underestimate negative outcomes (Sharot, 2011b). It is thus the difference between what a person expects and the subsequent outcome (Sharot, 2011a). In an early work, this bias has been studied by Rosenhan and Messick (1966) and is also known as the *unrealistic optimism*. This phenomenon has been revisited and interpreted as the main driver against anxiety (Lund, 1925; Kirscht et al., 1966). Conducting psychological experiments, Weinstein (1980) demonstrated that people are generally convinced that they are less likely to experience a bad event compared to others. They determined the presence of two conditions entailing this phenomenon. First, the situation has to appear controllable, and second, the result has to be strongly associated with personal investment or motivation from the person.

Knowing this, we may explain the presence of an *optimism bias* in our sample as follows. In general, studies have demonstrated that the predicted energy consumption of renovated buildings are erroneous and inaccurate (Herbig et al., 1994). Before beginning the renovation of their houses, households participating in the energy conservation program were informed about the predicted *ex-post* energy consumption. It is natural to assume that they may have been influenced by these predictions. Scholars recognized that individuals' expectations tend to match with their preferences and perceptions (Weinstein, 1980; Sharot, 2011b). It seems plausible that theoretical predictions may match households' predictions. Hence, they may be over-optimistic when 'deciding' how to live on a daily

[4]In our sample, all the renovated houses have been equipped by mechanical ventilation systems (i.e. single or double flow ventilation system). Predicting the energy consumption after renovation measures often involves set points in conventional simulation scenarios. It is assumed that occupants should pursue manual ventilation no more than 5 to 10 minutes each time, according to the ADEME agency.

basis, and adopt behaviors that are less likely to end up in the expected returns (Kahneman, 2011). For example, the interrogated households may react to the *optimism bias* by paying less attention to their daily energy consumption. The second hypothesis about *optimism bias* can thus be formulated as follows:

Hypothesis 2 *Occupants having the tendency to pay less attention to their energy consumption may be more likely to have a larger Energy Performance Gap (than those paying equally attention to their energy consumption than before). This may be due to an optimism bias.*

The *attitude-behavior gap*: It is the discrepancy between attitudes and beliefs toward something, or can more generally be expressed as the adoption of a particular behavior matching both (Frederiks et al., 2015b). Attitudes are defined as "*enduring positive or negative feelings about a person, object, or an issue*" (Kollmuss and Agyeman, 2002). In other words, this gap points to a significant difference between how people declare to act and how they actually behave. One of the first psychologists highlighting this phenomenon is LaPiere (1934) by conducting experiments in the United States, when strong prejudices existed against Asians. The author accompanied a random selected Chinese couple to more than 200 restaurants and reported that, from all of those, only one did not accept the couple. Thereupon, a questionnaire was sent out to all restaurants to ask the managers the question "*Will you accept members of the Chinese race in your establishment?*". They could answer "*yes*", "*no*", or "*depends on circumstances*". 90% of respondents answered with "*no*". The findings of the experiment manifest that individuals are highly inconsistent and often do not act in the way they declare in a questionnaire.
The presence of an *attitude-behavior gap* in the context of energy renovation, may appear as explained hereafter. Contradictory findings persist in the energy literature. While some scholars find a positive relationship between pro-environmental attitudes and sustainable behaviors (Gadenne et al., 2011; Hines et al., 1987; Kollmuss and Agyeman, 2002; Seligman et al., 1978; Becker et al., 1981; Samuelson and Biek, 1991; Sapci and Considine, 2014), others report no link between pro-environmental attitudes and reduction of energy use (Anker-Nilssen, 2003; Poortinga et al., 2004; Ozaki, 2011; Valkila and Saari, 2013). A possible explanation for this latter finding could be that old habits are very difficult to change and constitute a strong challenge to pro-environmental behavior (Kollmuss and Agyeman, 2002). Another reason could be that people are more likely to act pro-environmentally

according to their attitudes, when such a behavior demands low effort costs. On the contrary, if a sustainable behavior is too costly in terms of effort, and subsequently induces a loss in comfort, the adoption of the behavior is likely to be lessened (Diekmann and Preisendörfer, 1992). In general, individuals have the tendency to make selfish choices (i.e. paying less attention to their energy consumption, increasing their comfort, implementing less effort to adopt their behavior, etc.) rather than acting in a way that would be most beneficial for the environment (Becker et al., 1981; Samuelson and Biek, 1991). Our third hypothesis concerning the *attitude-behavior gap* can thus be stated as:

Hypothesis 3 *Occupants who declared to have adopted a (higher) pro-environmental attitude do not have a lower Energy Performance Gap than those who did not change their attitude.*

The *intention-behavior gap*: It displays the difference between the intention of a person to pursue a goal, and his actual behavior following such an intention. An intention is a motivation inducing people to adopt a goal-directed behavior (Frederiks et al., 2015b). While a range of scholars suggest that individuals with higher intrinsic motivation[5] tend to exhibit more sustainable and pro-environmental behavior (Deci, Edwards and Ryan, 1985; De Young, 2000; Pelletier et al., 2002; Pelletier and Sharp, 2008), others like Kollmuss and Agyeman (2002) however point to the fact that there exist two types of motivations: (i) the *selective motives* and (ii) the *primary motives*. Selective motives can for instance be the driver for a given action to sustain environmental benefits, and primary motives induce actions and behavior to maintain or increase personal comfort. When primary motives outweigh selective motives, an *intention-behavior gap* may appear in the energy conservation field. The hypothesis related to an *intention-behavior gap* can be expressed as follows:

Hypothesis 4 *Occupants who declared high sustainable motivations do not have a smaller Energy Performance Gap than the others.*

[5] Deci, Edwards and Ryan (1985) define 'intrinsic motivation' as the motivation that comes from individuals' personal interest without being stimulated neither by social pressure nor by incentives.

1.3 "*Je rénove BBC*" renovation program: survey, questionnaire and database

In this section, we explain the survey design, the elaboration of the questionnaire and the elaboration of the database used for our analysis.

1.3.1 The survey

In many European countries, scarce information is available on the total energy consumption –including heating, hot water, lighting, cooling, ventilation and auxiliaries of low energy buildings owing to the high costs or absence of smart metering, complex calculation method of the total energy consumption and lacking knowledge about the share of electronic appliances from total electricity consumption.

As explained in the General Introduction of the thesis, the collaboration of EDF and the regional authorities aimed to carry out a large pilot project, named *"Je Rénove BBC"* (JRBBC)[6], between 2010 and 2014, to renovate nearly 500 individual houses up to the level of low energy in the region Alsace located in northeastern France.

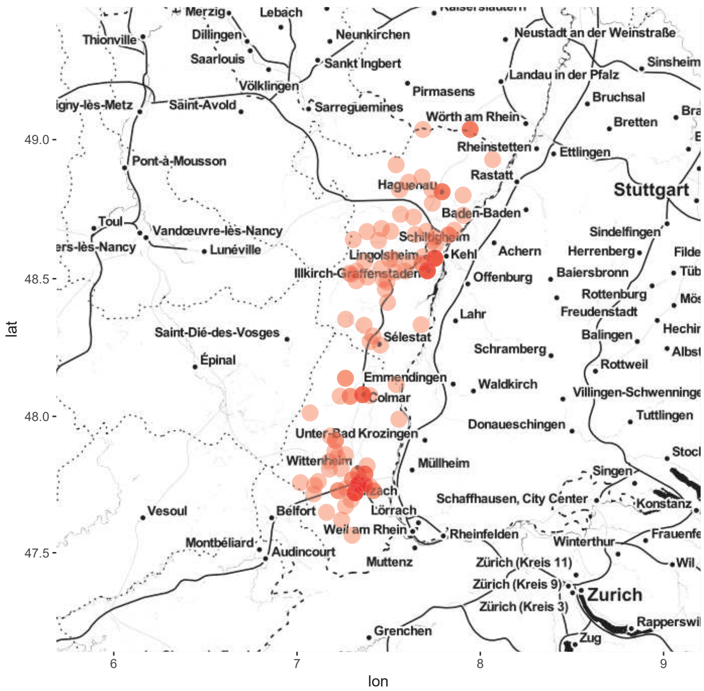
The motivation of conducting a survey among households having renovated their house with the JRBBC program was initiated by EDF. They were initially interested in getting a feedback about the program and gathering information about the renovation works, household's satisfaction, and their *ex-post* behaviors. Thereafter, we undertook a large data collection effort to gather information on occupants' energy bills, audits, energy-related behaviors and socio-demographic characteristics.

The survey started in April 2015, as part of my masters' thesis, and ended in February 2017, during three consecutive waves.[7] Collecting information about households' actual energy consumption was essential to evaluate the renovated houses' energy performance compared to the initially predicted energy consumption. To obtain an whole season of consumption information, only households whose home renovation ended at least one year earlier could be interrogated. In March 2015, 432 home renovations had been initiated, among which 187 met the latter mentioned condition (i.e. 43%). Invitations to participate in the survey were thus sent from EDF to these 187 households. Having signed a chart of acceptance to answer to any solicitation from EDF during the two years following the

[6] More information on the JRBBC program can be found in the General Introduction.

[7] We thank Nicolas Lampach, Debora Zaparova, Leila Cherifi and Maryline Delsart for their help in the questionnaire administration, especially during the second and third wave.

end of the works, a majority of them replied positively to this invitation. A total of 139 households accepted to participate. This represents 74% of the invited households and 32% of all the households of the program. All occupants living in an at most 3-dwelling building constructed before 2005 had the possibility to participate in the survey. The selected households came from all over the Alsace region. The sample's distribution across the Alsace region is mapped in Figure 1.1.



Note: The darker the circle in the map, the higher the density of households having participated in the project.

Figure 1.1: Households participating in the *"Je Rénove BBC"* renovation program

Most households are located in the two main urban agglomerations (i.e. Strasbourg and Mulhouse). Our sample is not national representative, as the Alsace region presents some particular differences from other regions in France: there are relatively higher revenues, it is the most urbanized region of France, and the population is sensitive to the environment due to cultural aspects (Héraud, 2011). The region Alsace is fostering cross-border co-operation with Germany and Switzerland, and there are also divergences between Alsace and other regions in its legal and historical character. Comparing the regional statistics from the national INSEE institute with our sample characteristics, we see that our sample is representative for the residential sector in the region Alsace.

The households of the program were interviewed *in situ* and on the phone. We tried to meet the majority of them, and accepted phone interviews only in case they did not have time for face-to-face interviews. The oral interaction was important to get the most precise feedback possible. Households could express themselves more freely, and we could clarify questions which seemed unclear to them, which limited possible *response biases*. To guide the interviews and collect quantitative information from the households, we used a questionnaire, detailed below.

1.3.2 The questionnaire

A first questionnaire had already been elaborated by EDF for the survey of the "*50 chantiers pionniers*" (50CP) program. We entirely restructured it for the needs of our analysis, and completed it with questions necessary for EDF's program feedback. In the following subsection, we explain how we structured the questionnaire to limit possible response biases. Indeed, depending on how a question is formulated, biases can occur following psychological reactions from the respondent. These reactions are generally unconscious defense mechanisms, where the respondent wishes to give a certain image of himself.

Elaboration of the JRBBC questionnaire

The questionnaire[8] is divided into ten distinct parts (i.e. Parts A to J), with an additional appendix (i.e. Part K) about households' appliances and lighting equipment. This appendix was only intended for households having an electric heating system[9].

The questionnaire's **introduction** and the survey invitations sent to the households explain the purpose of the JRBBC survey in comprehensible words, without going too much into detail. We thus avoid an *expectation effect* that influences respondents' answers and behaviors (Oliver, 1977). Indeed, if respondents know the entire purpose of the survey, they might select the answer they consider to be "right" to meet the expectations of the survey. We specify that all the answers will remain anonymous according to the legal obligations from the EU General Data Protection Regulation (GDPR).[10]

[8]A table with all the questions in English is available in Appendix A.1. The original questionnaire in French is available in Appendix A.2.

[9]This information should enable us to better determine the part of the electricity consumption used for heating, and the part used for other usages.

[10]Since 25 May 2018, the GDPR on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, has come into force.

The entire questionnaire has been structured according to the chronology of the renovation works to avoid the respondents' *resistance to sudden change of theme*. *Fear of change* is a systematic resistance when a modification or an abrupt change occurs, which can bring the respondent to not answer a question (Aktouf, 1987). Oral transitions have thus been made between the different themes.

The first four parts of the questionnaire (i.e. Parts A to D) concern households' motivations to renovate, the renovation process and households' satisfaction.

Part A, about households' deep-renovation motivations and their interest towards the JRBBC program, addresses questions about how they learned about the program and why they chose it. These questions typically introduce the subject and project the respondents to the pre-renovation period. From the first question, we have been cautious to avoid the following response biases: (1) the *central tendency bias*, and (2) the *anchoring effect*.

	Not important at all	Not very important	Quite important	Very important
• Own an environmental friendly house	☐	☐	☐	☐
• Make energy savings	☐	☐	☐	☐
• Make financial savings	☐	☐	☐	☐
• Have a better comfort	☐	☐	☐	☐

Figure 1.2: Extract from question A.1. of the JRBBC questionnaire

Figure 1.2 shows an extract from the first question of the questionnaire. Introducing a pair number of possible answers permits to avoid the problem of a median answer, also known as *central tendency bias*. Payne (2014) advises against proposing a central answer, because respondents generally have the tendency to avoid "extreme" answers and converge to the median one. A median answer would thus lead to information loss in our final results. By orally administrating the questionnaires, we paid attention to the *anchoring effect* (closely related to the *spatial bias*, the *dominance effect* and the *order effect*): respondents have the tendency to answer what they were proposed first. Psychologists noticed that answers to a same survey were strongly influenced, and thus biased, by the order of the proposed answers in close questions. This is also true for orally spoken questions: the respondent has the tendency to recall and answer what he heard first (Nairne and Crowder, 1982; Ganassali and Moscarola, 2004). To avoid this bias, we changed the order of possible answers from one respondent to another, while keeping the orders unchanged for a given respondent.

Thereafter, **part B** mentions the financial aids obtained and the encountered difficulties to receive them, while **part C** addresses the choice of the project manager and the importance paid to quality by selecting the renovation materials. **Part D** focuses on households' satisfaction towards the program and the project manager. A general satisfaction question as shown in Figure 1.3 hereafter is asked. This is one of the only binary questions of the questionnaire where an opinion of the respondent is asked.

D.1.1. Are you satisfied...

• about the general service of the project manager?	☐ yes	☐ no
• about the general work of the firms and craftsmen?	☐ yes	☐ no
• about the program « Je rénove BBC »?	☐ yes	☐ no
• about the final result of the renovation works?	☐ yes	☐ no

Figure 1.3: Question D.1.1. of the JRBBC questionnaire about general satisfaction

Binary questions have been limited as much as possible to avoid the *bias towards 'yes'*, also known as the *tendency to agree*. This tendency to be attracted by the positive answer is well-known in social psychology (Watson, 1992; Moss, 2009). Reasons can be multiple: politeness, sympathy, convenience, not upset the investigator or simply not wanting to justify a negative answer. The bias can be amplified for leading questions (Aktouf, 1987). This is why we were careful in the neutral formulation of the questions[11]. The remaining binary questions are not opinion, but simple fact questions[12].

Parts E to I were essential for our database and empirical analysis. The post-renovation period is now addressed.

Trying to be as intuitive as possible for the respondent, **part E** covers questions about households' energy consumption before and after energy renovation: the installed heating and sanitary hot water systems, and consumption details for electricity, heating and sanitary hot water[13]. Furthermore, multiple-choice questions concerning the installed heating system comprise the option to answer "other" to avoid non-responses in case of a non-exhaustive list of choices.

In **part F**, about households' habits before and after renovation (e.g. heating, occupation, attitudes), we voluntarily avoided the term "behavior" since it could have a pejorative connotation for the respondent. A *conformism bias* could otherwise emerge if he thinks that a "right" behavior (and answer) exists. In other words, to reflect a social and moral

[11] As mentioned earlier, the respondent should not feel that an answer is better than another.
[12] For example: "Did you already lived in the renovated house before the works?".
[13] Asked when the energy used for heating and sanitary hot water was not electricity.

ideal in his answers, the respondent might try to comply with a social norm[14].

Part G, addressing pre- and post-renovation comfort, and **part H** covering households' profiles and characteristics, were voluntarily placed at the end of the questionnaire to avoid boredom and discouragement that could occur with these types of questions. Beginning with them could give the respondent the feeling that his characteristics and profile are more important than his opinion or renovation experience. Besides, these questions being easy to answer, they are adapted to end a questionnaire[15].

Part I, with respect to the occupants' revenues, asks the amount of net resources of the whole household. For more precision, we first ask it as an open question, and then propose a close question[16]. We do not give the choice to answer "*I do no wish to answer.*" to avoid the respondent to directly selecting this answer. Indeed, adding this answer choice can make the question sound less important, which is not the case since it is often used as a control variable in empirical studies.

Finally, we have to keep in mind that the hardly detectable "*social desirability bias*" can occur when the respondent wants to idealize himself and give a positive image. Despite the anonymity of the answers, he could for example be tempted to increase his revenues in part I.

1.3.3 A new database on deep energy renovation in France

The survey and its questionnaire led to the elaboration of a database. This section explains how it has been compiled and how theoretical energy consumption were calculated.

To **minimize missing observations on actual energy consumption**, we asked households to prepare their energy bills (e.g. electricity, gas) in advance. During the interviews, the investigators filled out paper questionnaires to discuss more fluently with the respondents. They should feel comfortable to answer honestly.

The **compilation of the collected data** into an Excel file was done with *Adobe Acrobat Pro*. The PDF version of the questionnaire was transformed into an interactive 'PDF form', where every button was programmed under the needed form (e.g. binary, categorical, text,

[14]The psychologist Roger Mucchielli (1919-1981) defines conformism as "*the social attitude of submitting to and making one's own, the opinions, rules, norms and models that represent the collective mentality or value system of the group one has joined.*"

[15]Note that the survey lasts between 25 minutes and 1 hour depending on how much the respondents had to say about their experience. Indeed, in addition to answering the questions, they should feel free to express their opinion and feelings. In case of any issues following the renovation, we communicated these information to EDF, who could then intervene when necessary.

[16]It proposes different categories of revenue.

single answer) and with an appropriate variable name. This form being fillable on the computer, we manually copied the completed paper questionnaires. After gathering all the electronic PDF forms, the software creates a corresponding Excel file. This method has two advantages: (1) the number of transcription errors are drastically decreased and limited, and (2) the time needed to elaborate the Excel file containing the entire database is remarkably reduced.

The predicted energy consumption

Households' predicted energy consumption were calculated through energy audits by external energy consultation firms during the planning of the renovation works.

The energy audits are made with the *TH-C-E ex* standard calculation method based on the *French thermal Regulation* entered into force in 2012 (Centre scientifique et technique du bâtiment (CSTB), 2008)[17]. The method predicts the energy consumption of existing buildings after renovation measures. It takes into account specific set points, standard building characteristics and real values for all the replaced and renovated elements. On the household side, standard behavioral and occupants' characteristics are considered: any evolution or change of the household are not included. It thus represents a static prediction where real conditions of use are not considered. Concerning heating habits, a standard heating temperature of 19°C during occupation times (i.e. 16 hours per day during weekdays, and 24 hours per day during weekends), and 16°C otherwise are taken into account. These temperature settings are optimal in terms of comfort in isolated buildings, but are low enough to permit energy savings.

1.4 Descriptive statistics of the "*Je rénove BBC*" panel

To gain some insights about the characteristics, consumption, renovation and habits of the interviewed JRBBC households, this section presents a number of descriptive statistics.

Table 1.1 presents descriptive statistics of the dependent, behavioral and potential control variables[18]. To briefly describe the variables used as proxies to test the cognitive biases (BEH_WO, BEH_CONS, TEMP.N, BEH_ENV, M.ECOLO, EDUC), occupants have not changed their behaviors related to window opening and are paying similar at-

[17] A detailed (but non-exhaustive) list of the main elements taken into account by this calculation method is available in Section A.3 of the Appendix.

[18] Their definitions are available in Section A.5 of the Appendix.

tention to their energy consumption as before renovation measures. The average temperature setting at night is 18.36°C with a standard deviation of 1.75°C. Occupants' pro-environmental attitudes did mostly not alter after renovation (BEH_ENV), however 94% of the households exhibit (strong) motivation to live in an environmental friendly building (M.ECOLO) and the majority (59%) is higher educated (i.e. obtained at least a bachelor's degree).

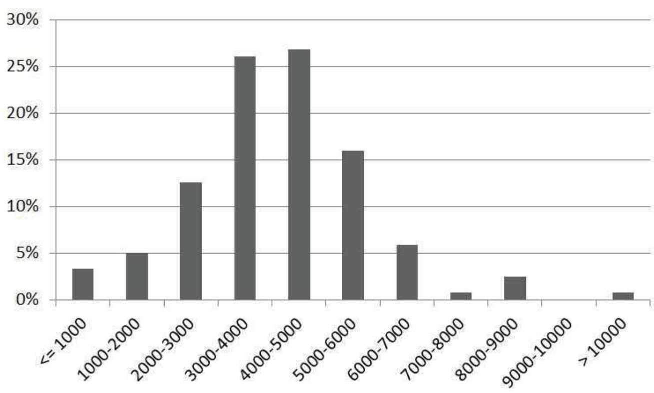
Furthermore, respondents were asked to report their perceived comfort in the renovated building on a scale from one to ten, yielding an average rating of 8.66 with a standard deviation of 1.14. Half of the households installed a room thermostat to adapt their indoor temperature according to their occupation habits. Occupants, on average, set the temperature during the day at 20.38°C with a standard deviation of 1.13°C and 32% of the households heat a higher number of rooms than prior renovation. The hours of occupation are on average 15.32 hours per day and a large majority of occupants spend more than three weeks per year on holidays.

Table 1.1: Statistics on the outcome variable and selected covariates

Variable	**N**	**Mean**	**SD**	**Min**	**Max**	**Range**	**SE**
Dependent Variable							
Energy Performance Gap (E^A/E^P)	95	−0.118	0.436	−1.252	0.843	2.095	0.045
Net losing energy savings (NLS)	36	1.410	0.361	1.017	2.324	1.307	0.060
Net gaining energy savings (NGS)	59	0.709	0.177	0.286	0.984	0.698	0.023
Cognitive Biases and Energy-Related Behaviour							
Behavior w.r.t. window opening (BEH_WO)	128	1.633	0.651	1	3	2	0.057
Paying attention to energy cons. (BEH_CONS)	128	0.062	0.243	0	1	1	0.021
Temp. set. gap night [declared vs. 19°C] (TEMP.N)	118	−0.644	1.754	−6	5	11	0.161
Pro-environmental attitudes (BEH_ENV)	128	0.297	0.459	0	1	1	0.041
Environmental sensitivity (M.ECOLO)	124	0.935	0.247	0	1	1	0.022
Higher education (EDUC)	126	0.595	0.493	0	1	1	0.044
Potential Control Variables							
Heating system (SYST)	127	0.496	0.502	0	1	1	0.045
Motiv. to reduce energy costs (M.ECON.FIN)	124	2.548	0.642	1	3	2	0.058
Motiv. to reduce energy cons. (M.ECON.NRJ)	125	2.776	0.437	1	3	2	0.039
Age of respondent (AGE)	128	0.445	0.499	0	1	1	0.044
Profession (PROF)	128	0.477	0.501	0	1	1	0.044
Presence of children (CHILD)	129	0.535	0.501	0	1	1	0.044
Perceived comfort (COMFORT)	125	8.664	1.136	1	10	9	0.102
Presence of room thermostat (THERM)	128	0.508	0.502	0	1	1	0.044
Temp. set. gap day [declared vs. 19°C] (TEMP.D)	121	1.382	1.129	−1	5	6	0.103
Additional rooms heated (ROOM)	116	0.319	0.468	0	1	1	0.043
Hours of occupation (OCCUP)	126	15.322	5.864	3	24	21	0.522
More than three weeks in holidays (VACATION)	122	0.533	0.501	0	1	1	0.045
Size of the household (HSIZE)	119	3.328	1.513	1	9	8	0.139
High income (REV)	115	0.522	0.502	0	1	1	0.047

1.4.1 Socio-demographic characteristics

From the 139 households having participated in the survey, about 89% live as a couple (married or not), and an average of 3.38 persons live per renovated house. Indeed, 90% of the households have children under the age of 18 living with them. No couples aged between 18 and 24 were interrogated: young people generally do not have the financial capacity to become landlord, and on top of that, finance a deep energy renovation. However, 16% of the respondents are between 25 and 34 years old, which shows that deep energy renovation can also be accessible to younger landlords. The vast majority of the households are between 35 and 59 (71%), and only 13% are older. Nearly half of the respondents (i.e. 47%) work as an executive, liberal or executive intellectual. Interestingly, higher educated households seem predominant in the JRBBC program: 83% of the panel have a higher education, among which 39% have a Master's degree or more. Only 1% have no diploma at all. Figure 1.4 shows that a majority (53%) of the households have a monthly net revenue lying between 3 000€ and 5 000€.



Number of observations: 119

Figure 1.4: Net monthly revenues of the households

On average, we estimate the monthly revenues to be around 4 168€ (in particular for the 119 respondents of this question). This shows that the panel is on average financially comfortable. However, the fact that 21% earns less than 3 000€ per month for the entire household, indicates that, partially due to the public financial aids and tax benefits, deep renovation can be accessible even to households with lower income, and that thermal comfort is not exclusively dedicated to rich households.

The above descriptive statistics concern all the households having participated in the JRBBC survey (i.e. 139 households), regardless whether they consumed more or less than predicted. As a comparison and to gain further insight on the interrogated households, Table 1.2 shows a summary of these information for (1) households which consumed less than predicted, and (2) households which consumed more than predicted. We have complete and exploitable energy consumption data for 95 households, among which 36 consume more than predicted (38%) and 59 consume less than predicted (62%).

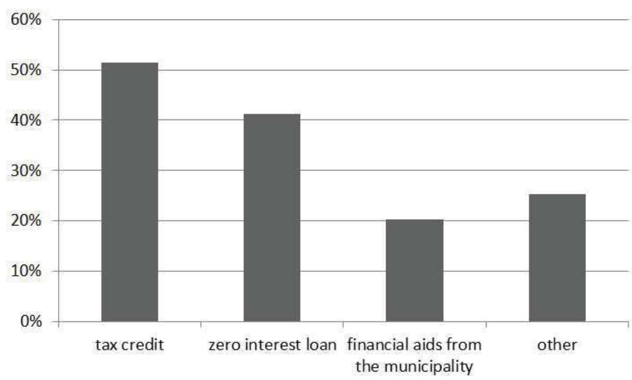
Table 1.2: Household's socio-demographic characteristics

Socio-demographic characteristic	**(1) Consume *less* than predicted**	**(2) Consume *more* than predicted**
Proportion of households	62%	38%
Family status: as a couple	89%	97%
Average household size	3.24	3.35
Average net revenues	3 980 €	5 032 €
Average age of respondents	between 35 and 44	between 35 and 44
High educated	84%	88%
Work as an executive, liberal or executive intellectual	46%	40%

Source: "*Je rénove BBC*" program ; Number of observations: 95

1.4.2 Importance of financial aids and tax benefits

92% of the survey respondents estimate that the financial aids proposed by the JRBBC program is clearly an advantage of the program, even though 25% of them found the administrative procedures not very simple and clear. 20% of the households could also benefit of financial aids from their municipality or territory. However, as can be seen on Figure 1.5, tax benefits have been largely asked by the owners.

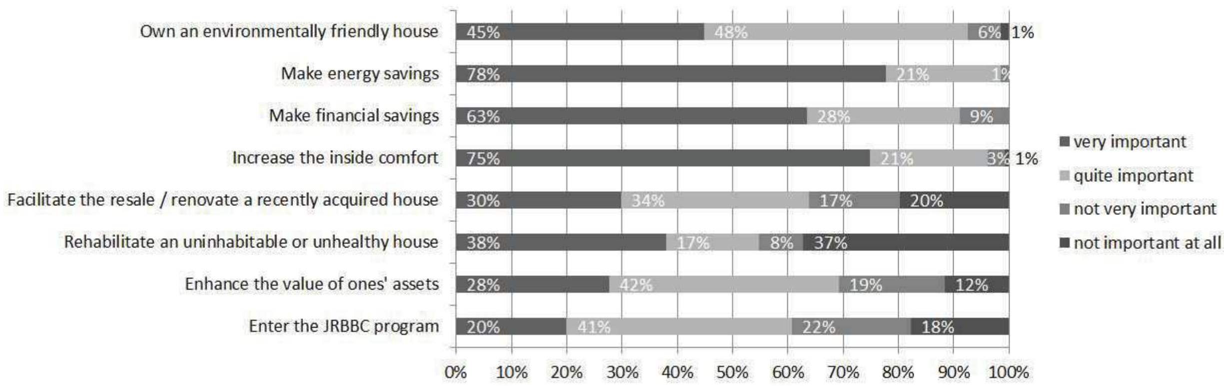


Number of observations: 138 ; "other": aids for using specific materials or for low-income households.

Figure 1.5: Tax benefits and other perceived financial aids

1.4.3 Renovation motivations

Four main motives were identified, with respect to households' actual motivations to engage in deep energy renovations: (1) owning an environmental friendly house, (2) make energy savings, (3) make financial savings, and (4) increase inside comfort. However, we notice that owning an environmental friendly house is often only a motive of second importance, and that it seems more to be a positive side effect of the renovation works. Increasing personal comfort (being considered as a primary motive) is a much stronger motive than making something that is good for the environment (which is considered as a selective motive). This observation can be seen on Figure 1.6 and was the initiator to test the presence of an "*intention-behavior gap*".

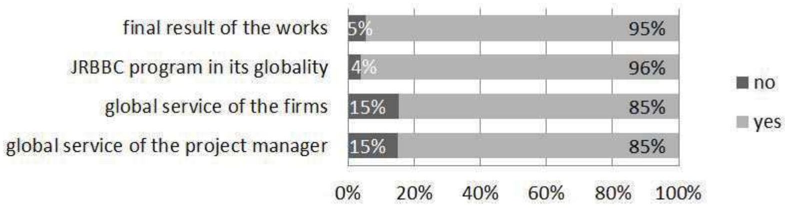


Number of observations: 139

Figure 1.6: Households' renovation motivations

1.4.4 Households' satisfaction

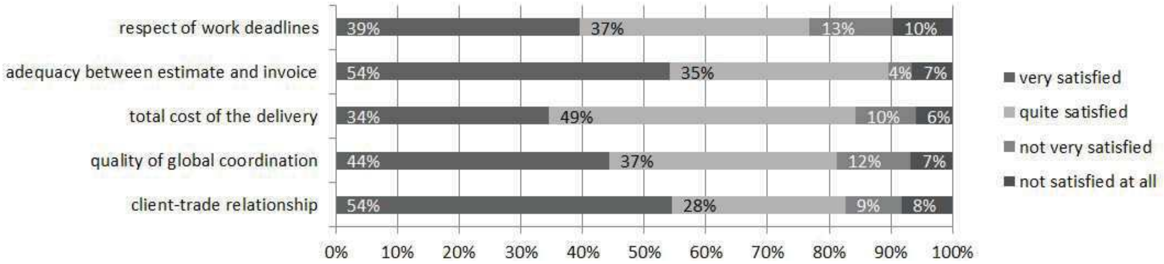
As depicted in Figure 1.7, a large majority of the households feels satisfied about the general services of the JRBBC program.



Number of observations: 138

Figure 1.7: Households' general satisfaction

A slightly lower but still high percentage of satisfaction concerns the firms, craftsmen and the project manager's intervention. Even though 85% are globally satisfied about the project manager's work, Figure 1.8 shows that there is still place for improvement, as the percentages of not very satisfied and not satisfied households at all vary between 10% and 23%.



Number of observations: 133

Figure 1.8: Satisfaction toward the project manager

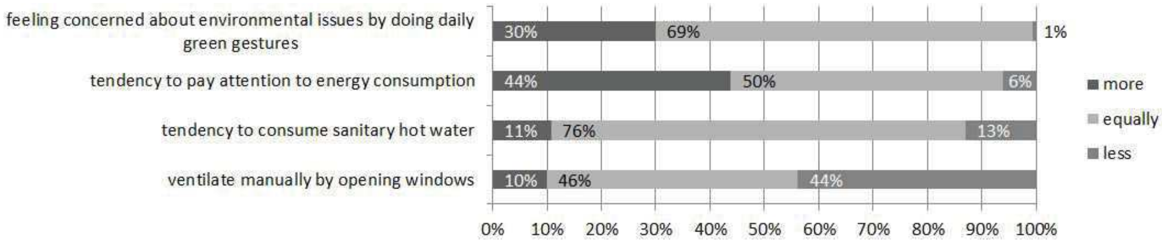
The 23% level corresponds to the respect of the planned work deadlines. More importantly, 19% of the households not very satisfied about the global quality of the work coordination, that is, the task coordination among the firms and craftsmen. When a project manager is present on a construction or a renovation site, his main task is to coordinate all the interventions and task of the craftsmen, and to be the intermediary between the client (i.e. the project owner, that is, the household) and the craftsmen. He has the technical knowledge to ensure an efficient chronology of the interventions, so that the building's performance ends at its best. The fact that some households are unsatisfied about this coordination has to be analyzed seriously because it can lead among others to a final energy performance loss of the renovated (or new) building and contribute to the EPG[19].

1.4.5 Habits in the renovated houses

Households' habits and behaviors can play a significant role in a low-energy house. In low-energy buildings equipped with mechanical ventilation systems (as it is the case for all the households of the program), opening windows too long and often can impact electricity consumption (cf. the *status quo bias* justification in Section 1.5). As the main ventilation method before renovation was opening windows for about 76% of the households, a "good" behavior consists in ventilating less manually than before renovation. This latter habit

[19]This issue is addressed in Chapter 3. We determine whether better and adapted contracts (i.e. better incentives) could lead craftsmen to better coordinate their tasks, and if specifically trained craftsmen perform better in general. In other words, to encourage task coordination, should we work on improve training programs or incentives? This issue, analyzed with the help of an economic experiment with craftsmen, is however addressed in cases without the presence of a project manager.

modification has been declared by 44% of them as depicted in Figure 1.9. However, 46% declare not having changed their ventilation habits, and 10% even declare to open their windows more often. This can be problematic to achieve the predicted energy consumption.



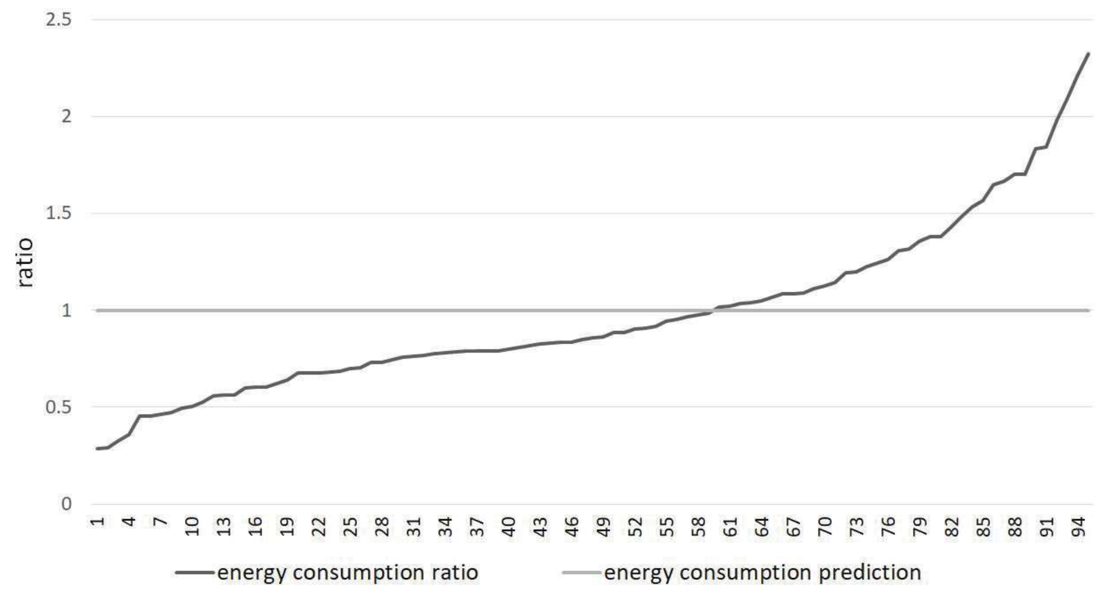
Number of observations: 129

Figure 1.9: Households' habits compared to before renovation

Observing further habits and behavior evolution, an important percentage declares to feel more concerned about the environment (and thus make more daily green gestures as for instance making compost, switching the light off, unplug chargers, ...) (30%) and having the tendency to pay more attention to energy consumption than before renovation (44%). The deep-energy renovation process might for a fact have increased households' environmental consciousness, even though an initial positive consciousness was certainly already present. It is also important to keep in mind that during surveys, people generally have the tendency to wanting to give a positive self-image, the so-called "*social desirability bias*" mentioned in Subsection 1.3.2. These environmentally positive declarations might thus also be partly over-estimated. This is why we analyzed the presence of an "*attitude-behavior gap*" in this Chapter. We find that for higher educated households consuming more than predicted, those declaring to feel more concerned about the environment than before do not have a smaller *ex-post* EPG than the others. This can suggest an *attitude-behavior gap* from high educated households declaring to be ecological.

1.4.6 Households' energy consumption

As mentioned in the previous Subsection, a predicted *ex-post* energy consumption has been calculated before the renovation works to illustrate households their potential energy savings by undertaking specific modifications. The predictions have not always been met as can be clearly seen on Figure 1.10.

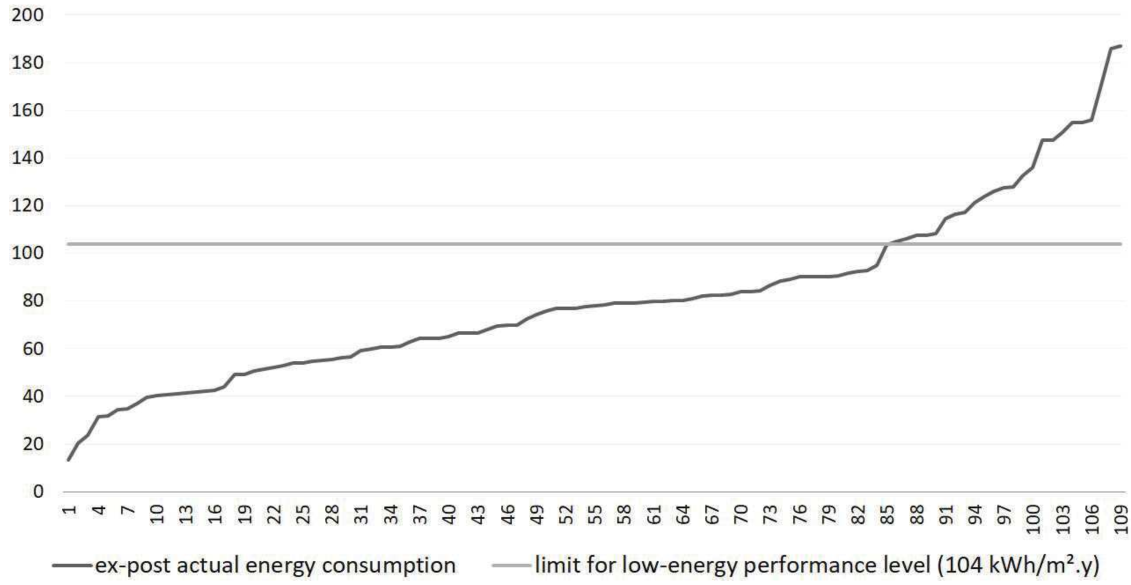


Number of observations: 95
The ratio measures the actual over the predicted energy consumption in primary energy.
Note: Under the gray line they consume less than predicted, otherwise they consume more than predicted.

Figure 1.10: *Ex-post* energy consumption ratios for each household

As mentioned in Section 1.5, we note that 62% of the households consume less than predicted and 38% consume more than predicted one year after the energy renovation works. If we include households consuming only approximately up to 10 $\text{kWh}_{\text{PE}}/m^2$.year less or more than predicted in those "meeting the predictions", we make the following observation: 23% meet the predictions, 50% consume less, and 27% still consume more than predicted. The 27% consuming more than predicted are the most "problematic", because they might need more time to pay back the contracted credit loans, or will have more difficulties to pay energy performance related insurances if they subscribed some. Their return on investment will also take longer.

Furthermore, recall that the objective of the program was to permit households to renovate their houses to low-energy buildings. The maximum consumption in Alsace to have a low-energy building is 104 $\text{kWh}_{\text{EP}}/m^2$.year. Figure 1.11 shows that about 79% of the renovated houses meet the criteria. The remaining 21% cannot be qualified as low-energy buildings. It is important to mention here that 38% of them did not change their heating system. These buildings might meet the low-energy performance level when changing the heating and sanitary hot water system. Moreover, while most households have a heating system depending on fossil fuel energy (i.e. gas, electricity or fuel), solely 11% of them installed a heating system supplied with renewable energies (i.e. wood, pellets, heating pump, solar energy or photovoltaic). The high fixed cost of installing renewable energy heating systems and the scanty financial support may have discouraged many households to invest in renewable systems during a first renovation stage. Supposing that households who did not change their heating system will do it in the future, the JRBBC program could reach up to 87% (i.e. + 8%) of low-energy buildings[20].



Number of observations: 109
Note: Buildings under the gray line meet the low-energy performance criteria.

Figure 1.11: *Ex-post* actual energy consumption in primary energy ($kWh_{PE}/m^2.year$)

1.5 Energy Performance Gap and proxies for the cognitive biases

In this section, we present the variable of interest and the proxy variables used to test the cognitive biases.

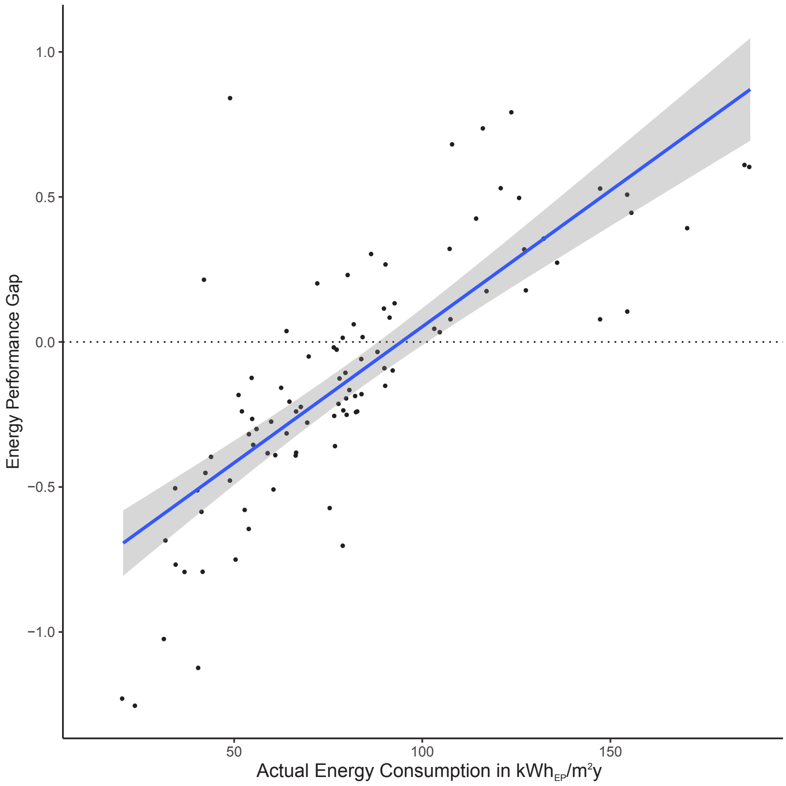
Our dependent variable is the Energy Performance Gap (EPG) of the individual household measured as the logarithmic ratio of the *ex-post* actual and predicted total energy consumption. Actual energy consumption is normalized by heating degree days, altitude and location of the individual building.[21]

Figure 1.12 depicts the relationship between the EPG and actual energy consumption of our sample. A positive and increasing relationship between both measures can be observed. This means that the higher the actual energy consumption of a household, the

[20]In the 50CP program, were changing the heating system was mandatory, 95% of the houses became low-energy buildings.

[21]A detailed description about the calculation of the actual energy consumption in primary energy is given in Section A.4 of the Appendix.

more likely is the underestimation of the predicted energy consumption. An EPG greater (lower) than zero represents the Net Losing (Gaining) Energy Savings of the individual household (Sunikka-blank and Galvin, 2012). This observation is in line with the one made by Raynaud (2014). The likelihood of achieving at least the required energy performance is approximately 62% as a relatively large percentage of households of our sample actually consume lower levels of energy than predicted. However, 38% of the sample reveals an over-consumption pattern.



The dotted line denotes the presence of no energy performance gap: actual energy consumption matches perfectly the predicted energy consumption.

Figure 1.12: Relationship between Energy Performance Gap and Actual Energy Consumption

If we consider that a success would be to consume as predicted, by allowing an error margin of only 10 $kWh_{PE}/m^2.year$ in the EPG, the likelihood of success would dramatically decline from 62% down to 23%.

Which are the key determinants driving the EPG? What explains the divergence of the EPGs among individual households? Derived from our theoretical insights, we suggest a number of proxy variables measuring individuals' cognitive biases which might explain the

EPG. In doing so, we focus on two potential outcomes of the EPG, namely the *Net Losing* and *Net Gaining Energy Savings*. Although the latter has been mostly disregarded by the energy literature, it constitutes the opportunity to get key insights into the capability of occupants to achieve higher energy savings than prior predicted.

We measure the *status quo bias* (Hypothesis 1) on manual ventilation habits by comparing occupants who did not change their ventilation habits (i.e. status quo on manual ventilation) and those who adapted their window opening habits by opening them less (or more) than before renovation. Low energy buildings are furnished with a mechanical ventilation system to control air circulation. Energy engineers plead to nearly not open the windows in a low energy building (or only five minutes at a time), otherwise it deteriorates the energy efficiency of the building. We use a categorical variable *manual ventilation behavior*[22], where occupants report their behavioral change of window opening (i.e. less, equally, more) compared to prior renovating the building. As the theoretical predictions consider that occupants do nearly not open their windows anymore, we expect that those who do not adapt their behavior will have larger Net Losing Energy Savings than the other groups.

The *optimism bias* (Hypothesis 2) is measured by the interaction term *paying attention to daily energy consumption*[23] and *temperature setting difference at night*[24]. In our questionnaire, occupants report their behavior by indicating on a scale to pay less, equally or more attention to their energy consumption than prior renovation. As explained in Section 1.2, we assume that occupants are confident about the theoretical predictions, and thus tend to be over-optimistic about the energy performance of the refurbished building (Williamson, 2012). This excessive trust may imply an optimistic behavior by paying less attention to their energy consumption. Nishant et al. (2014) find that although there is a positive effect of technology on the energy efficiency, there is also a negative effect of the rebound effect, which can compensate each other. Mitchell (2012) calls this a *"technophilic optimism"*. The intuition behind the *optimism bias* is similar: while households can be over-optimistic about the energy performance of the building, a rebound effect can appear and incentivize them to unconsciously adopt a more energy-consuming behavior. This phe-

[22] See question F.7. of the survey in Section A.1 of the Appendix, about how they open their windows prior to renovation.

[23] See question F.7. We re-code the categorical variable into a dummy variable, where "paying equally or more attention" (BEH$_C ONS.Same)isthebaselinewithwhich"payinglessattention"(BEH_C ONS.less)iscomparedto.$

[24] Recall that the temperature setting during night is 19 $^{\circ}C$ in the theoretical predictions. We thus deduct the declared temperature setting in question F.2.1.2. from the prescribed 19 $^{\circ}C$.

nomenon could even be more visible from households setting higher temperature at night than the threshold of 19 $°C$ assumed in conventional simulation scenarios. We base our intuition on the finding of Guerra Santin (2010), who reveals that the default temperature at night and in the evening has more impact on total energy use than the default temperature setting during the day. Moreover, it is natural to argue that households paying less attention to their energy consumption, also tend to less reduce their temperature setting at night. For these reasons, we compare households who report to pay less attention and setting higher temperature than 19 $°C$ at night with those who report not having changed their attention to their energy consumption prior to renovation and also heating above 19 $°C$ at night. We aim to set up interaction terms to account for non-linear effects in the model. Explaining variations of EPG are highly complex and influenced by many factors. The interaction term allows us to measure the direct effects of our independent variables on the outcome.

As a proxy for the *attitude-behavior gap* (Hypothesis 3), we employ the categorical variable *pro-environmental attitudes*[25]. This variable contains information on occupants' pro-environmental attitudes and is quantified by asking households about their behavioral change on the degree of daily sustainable actions (i.e. less, equally or more) prior to renovation. We compare households who report to seek more sustainable actions with those who have not changed their habits. The presence of an *attitude-behavior gap* would mean that households who exhibit greater pro-environmental attitudes do not yield a lower EPG compared to others.

The *intention-behavior gap* is measured by the interaction term *pro-environmental sensitivity*[26], *high education*[27] and *high revenue*[28]. Recall from Section 1.2 that an intention is a motivation toward both a goal-directed behavior and change. The variable *pro-environmental sensitivity* is dichotomous and provides us information on occupants' motivation to live in a environmental-friendly building. However, may be biased to only test the impact of this variable on the EPG. First, Hines et al. (1987) finds a positive correlation between environmental behavior and education level. Belaid and Garcia (2016)

[25] See question F.7. about the tendency to be concerned about ecological and environmental issues prior to renovation. We re-code the categorical variable into a dummy variable, where "being equally or less concerned" (ENV.Low) is the baseline with which "being more concerned" (ENV.High) is compared to.

[26] See question A.1. on how important it is to own an environmental friendly house. We re-code the categorical variable into a dummy variable, where "finding it not important or not important at all" (Non-Ecolo) is the baseline with which "finding is important or very important" (Ecolo) is compared to.

[27] See question H.8.

[28] See question I.

thereupon state that "*households with a higher education level [are] more receptive to environmental friendly ideas or [are] better informed about issues related to global warming, exhibiting better behaviors*". In accordance, a report by the United Nations Educational, Scientific and Cultural Organization (Benavot et al., 2016) emphasizes that higher educated individuals tend to be more sensitive to environment. Second, it is well known that there exists a significant positive correlation between education and revenue level (see, for instance, Blaug, 1972; Polachek and Siebert, 1993). Hence, we interact the three variables, since the variable *pro-environmental sensitivity* alone may otherwise be too correlated with the error term of the regression. The presence of an *intention-behavior gap* would mean that higher educated and 'richer' households with a pro-environmental sensitivity would not yield a lower EPG compared to those being less educated, less 'rich', and reporting no pro-environmental sensitivity.

1.6 Control variables and modeling approach

In this section, we discuss our data-driven approach to select the most relevant control variables. We then explain our modeling approach. To deal with the problem of missing values, we assess the nature of missingness in order to apply multiple imputation method.

1.6.1 Selecting control variables using learning models

To curb adverse effects from confounding variables and to control for observed heterogeneity among occupants, we have a wide range of socio-demographic and technical covariates available as controls.

However, our sample size is small, which might lead to the problem of overfitting in the subsequent estimation model, especially when the number of parameters is too large for a particular dataset. While there exists no exact rule about the number of covariates to be included in a model, we apply the thumb rule in accordance with Koebel et al. (2016) by using 10 observations per covariate. To prevent the problem of overfitting, we seek to select a restricted number of control variables constituting a common classification problem.

Instead of using a forward selection method to select covariates, we apply a more data-driven approach, by employing *machine learning* and *predictive modeling*. These are powerful tools helping to identify strong predictors of the EPG, and therefore to select most relevant variables affecting the Net Losing Energy Savings (NLS) on the one hand, and the Net Gaining Energy Savings (NGS) on the other hand. Data-driven approaches are receiving widespread attention from scholars in different fields, and the success of their application is due to the effective use of models capable of detecting complex data dependencies and capturing non-linear or non-monotonic data patterns (Breiman, 2001; Cranmer and Desmarais, 2017; Varian, 2014). To this purpose, we apply a set of most widely used supervised machine learning algorithms: (i) random forest (RF), (ii) gradient tree boosting (GTB), and (iii) non-linear (radial) support vector machine (SVM).

The basic procedure of machine learning can be summarized as follows. First, the data is split into 'training sets' (to train the model) and 'test sets' (to evaluate/validate the trained model). Various validation methods are available to divide the data. We use the *Leave One Out Cross Validation* (LOOCV) method, because it constitutes an effective internal validation method when the sample size is relatively small. It uses one single observation from the original sample as a validation data (i.e. 'test set') and the remaining are used as training data (i.e. 'training set'). This is repeated N-times, such that every single observation from the sample is used as a 'test set'. Second, the algorithm of the LOOCV attempts to predict the value of interest Y (the outputs NLS and NGS in our case) given an input of a feature set X (variables). The aim is to develop a finely tuned function $h(X)$ that maps input data into the output of interest. The algorithm optimizes this function, given the input data, to accurately predict the target value Y, by using the 'training set'. For each 'training set', we evaluate the difference between the predicted value $h(X)$ and the output Y from the 'test set'. By doing so, the algorithm can learn from the 'training set' in order to measure and minimize the wrongness of $h(X)$.

Once the data is divided, we apply a machine learning algorithm. We implement the three algorithms (i.e. learning models) mentioned earlier, to finally select the one with the highest performance, using the *Root-Mean-Square Error* (RMSE). This method compares forecasting errors of different models for one particular dataset (Hyndman and Koehler, 2006). Hence, a lowest RMSE indicates the best model.

Let us first explain how these learning algorithms work.

RF and GTB are decision learning methods using recursive binary partitioning of the vector space. Instead of growing a single decision tree, the RF method searches for the best feature (i.e. relationship among the data) among a random subset of features. The general bootstrap technique is applied to the 'training set', by repeatedly choosing a random sample with replacement of the 'training set', which leads to better model performance (Breiman, 2001). A similar approach is the GTB method, computing a sequence of simple trees, where each tree is constructed for the prediction residuals of previous trees, also called *additive weighting expansions*. At each iteration, a simple tree is determined through recursive partitioning and the variances of the observed values from the means are computed. The next tree will then be fitted only to those residuals, that will continue partitioning to reduce the variance of the data (Chen et al., 2015; Ganjisaffar et al., 2011; Ye et al., 2009).

Alternatively, the SVM method maps the data into high dimensional space with the value of each feature as the value of a specific coordinate. It uses a linear and non-linear hyperplane to segregate best two classes. A powerful characteristic of SVM is the kernel function used for non-linear separation. Low-dimensional input space is transformed into high-dimensional space through the kernel function, allowing to convert non-separable problems into separable problems. Generally, SVM performs better with a low sample size, since the required training time is higher compared to alternative machine learning algorithms (Pal and Foody, 2010).

To effectively improve the model performance, we tune specific parameters in our algorithms (see Table 1.3). The choice of the tuning parameters is based on standard recommendation.[29] Tuning plots are displayed in Section A.6 of the Appendix.

Table 1.3: Tuning Parameters of Machine Learning Algorithm

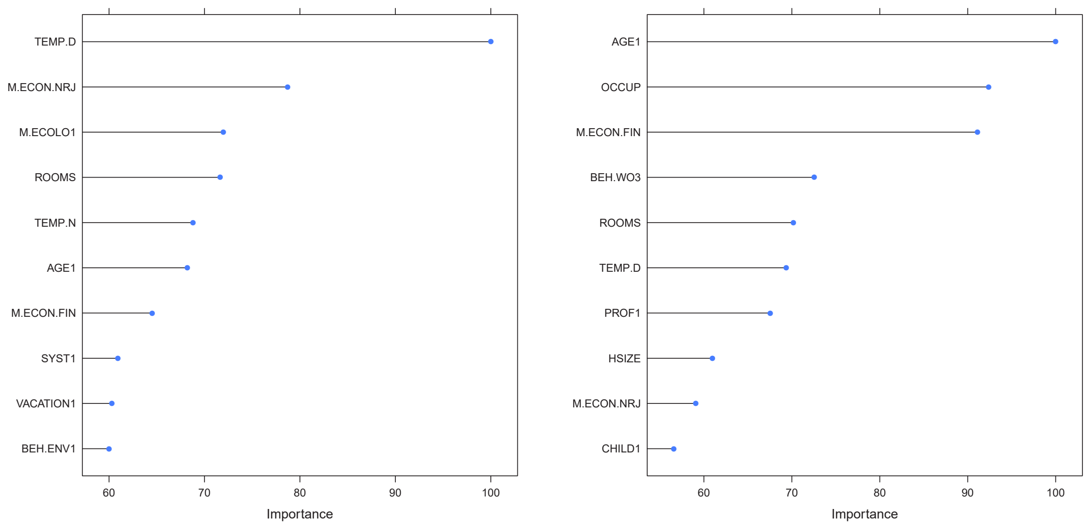
Parameters	**RF**	**GTB**	**SVM**
Number of trees	{500,1000,1500,2000,2500}		
Number of random variables	[1,16]		
Boosting iterations		{1000,5000,10000}	
L2 Regularization (Ridge)		Default {0,0.0001}	
L1 Regularization (Lasso)		Default {0,0.0001,0.1}	
Step size shrinkage		Default {0.3}	
Number of cost values			{0.25,0.50,1}

Caret (Kuhn and Others, 2008), party (Hothorn et al., 2006; Zeileis et al., 2008), randomForest (Liaw and Wiener, 2002) and xgboost (Chen et al., 2015) package in R are used to run predictive modeling.

We divide our data based on households' achievement of the EPG for the following reason. One could argue that, for a given household, distinct factors are responsible for

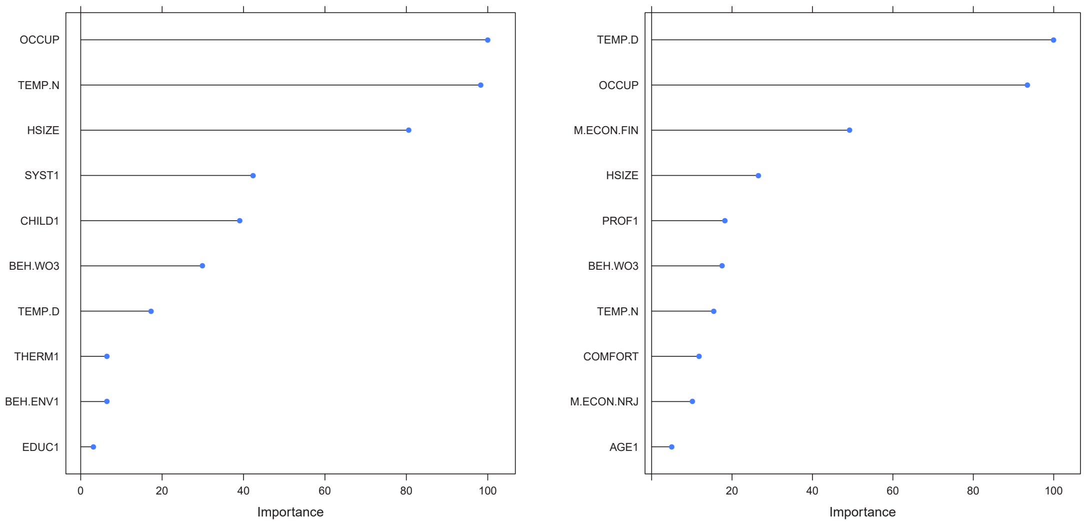
[29] We do not know what the optimal design should be for a given model in the first place, but we want the model to be 'flexible' by examining a range of possibilities. By 'flexible', we mean that the model is not tied to strong assumptions like, for instance, normality of the distribution, or homogeneous standard errors.

either Net Losing or Net Gaining Energy Savings. Cause and effect relationships between individual characteristics and EPG might be substantially different in both situations. Our data-driven approach allows us to identify the most useful features (i.e. used as control variables) to predict the variable of interest. Figures 1.13 to 1.15 portray the variable ranking based on the contribution of predictors made to the learning models in both situations, Net Losing and Net Gaining Energy Savings. The variable importance is measured by the mean decrease of node impurity (i.e. reduction of misclassification) when split by variable. A simple explanation would be that variables with the highest importance scores are those giving the best predictions and thus contributing most to the model. Leaving out the top predictors would dramatically decrease the overall predictive power of the model, while removing the one from the bottom would not much impact prediction. It can been seen from Figures 1.13 to 1.15 that the variable ranking varies within the energy performance situation (i.e. NLS or NGS) and between the learning models. In most of the models, the variable *temperature setting difference during the day* (i.e. difference between the prescribed 19°C and the actual temperature setting) (*TEMP.D*) and *temperature setting gap at night* (*TEMP.N*) are ranked as the top predictors. Other strong predictors are *household size* (*HSIZE*) in the situation of Net Losing Energy Savings, while the *hours of occupation* (*OCCUP*) and *motivation to reduce energy costs* (*M.ECON.FIN*) are most dominant for households exhibiting Net Gaining Energy Savings.



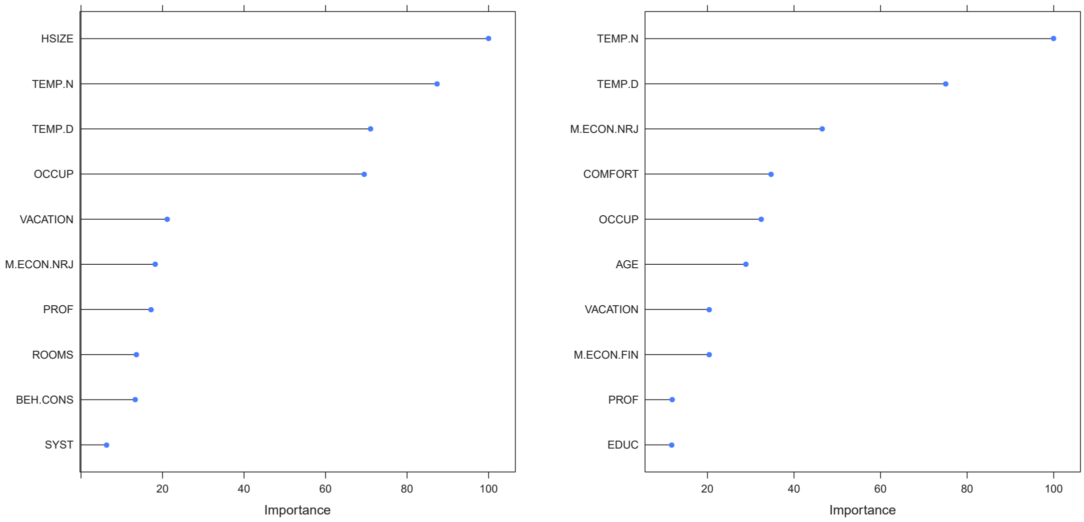
(a) Net Losing Energy Savings (b) Net Gaining Energy Savings

Figure 1.13: Feature Ranking using Decision Tree Classifier (Random Forest)



(a) Net Losing Energy Savings (b) Net Gaining Energy Savings

Figure 1.14: Feature Ranking using Decision Tree Classifier (Gradient Tree Boosting)

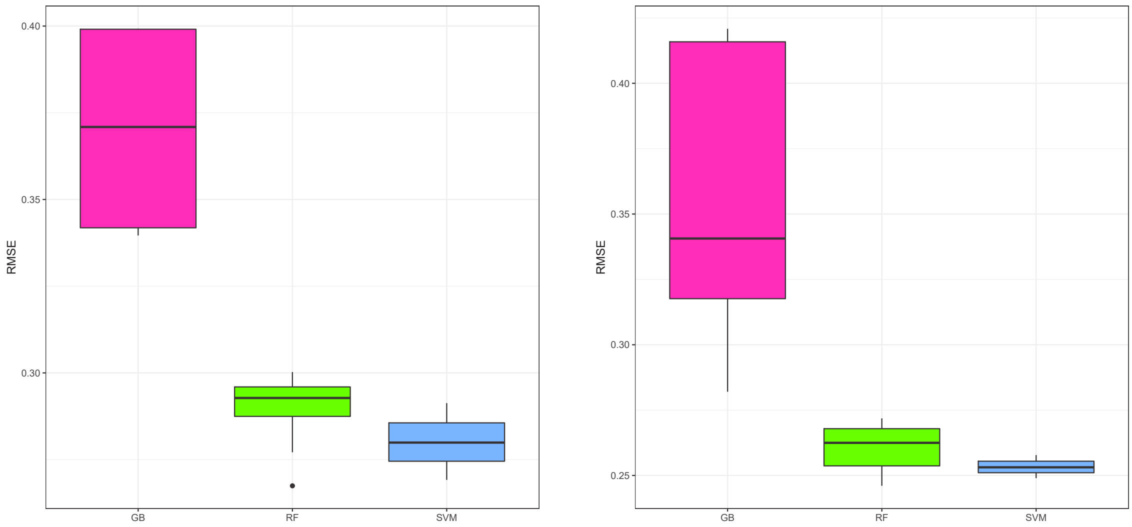


(a) Net Losing Energy Savings (b) Net Gaining Energy Savings

Figure 1.15: Feature Ranking using Support Vector Machine (Non-Linear)

The comparison of the three model performances with the RMSE is displayed in Figure 1.16. In both situation (i.e. NLS and NGS), SVM is the best model with, respectively, a median of 0.2805799 (i.e. variance of 1.27 kWh_{EP}/m^2y) and 0.253127 (i.e. variance of 1.36 kWh_{EP}/m^2y). Based upon the ranking displayed in Figure 1.15 and the degrees of freedom, we thus choose *HSIZE* and *TEMP.N* in the situation of *Net Losing Energy Savings*, and *TEMP.N*, *TEMP.D*, *M.ECON.NRJ* and *COMFORT* in the situation of *Net*

Gaining Energy Savings.



(a) Net Losing Energy Savings (b) Net Gaining Energy Savings

Figure 1.16: Comparison of Model Performance

1.6.2 Modeling approach

To explain the systematic variations of the EPG, we apply a multiple linear regression analysis by running eight different model specifications (i.e. four for Net Losing and Net Gaining Energy Savings, respectively). The econometric model for a household i is:

$$log\left(\frac{E_i^A}{E_i^P}\right) = \alpha + \gamma Z_i + \beta_K X'_{iK} + \varepsilon_i$$

where the logarithmic ratio between E_i^A and E_i^P is the dependent variable (with E_i^A the actual, and E_i^P the predicted *ex-post* energy consumption), α represents the intercept, γ is the estimated coefficient of the independent variable Z, β_K captures the estimated coefficient for the vector X_K which includes K exogenous control variables and ε_i the error term. Since we restrict the data analysis to NLS and NGS, we run four model specifications for each to assess our hypotheses independently. For each model specification, control variables have been selected based on the feature ranking of predictive modeling.

It is very challenging to accurately model the effect of individuals' cognitive biases on the EPG due to low sample size occurring from missing values. Complete information about the variable of interest is available for a total of 95 households (73.64% of the interrogated households), and missing values account for less than 7%. Missing values are ubiquitous in surveys and stem from multiple sources. Respondents may have left items blank because they were not able or did not want to answer the questions. Concerning observations about energy consumption, there may be missing values about the predicted energy consumption due to the prediction method[30] or on the actual consumption due to missing energy bills. They account for nearly 30% of the missing values. The bias associated with the occurrence of missing values can dramatically reduce the explanatory power and may lead to biased and inefficient estimates (Barnes et al., 2006; Graham et al., 2007; Roderick and Fraser, 2008; Higgins et al., 2008; Azur et al., 2011; Grund et al., 2016). Omitting missing values is only an efficient approach when these values are Missing Completely At Random (MCAR). We conduct Little's MCAR test (Little, 1988) with all our selected variables, which rejects the null hypothesis that missing values are missing completely at random ($p_{\text{value}} < 0.01$). We thus assume that the missing values are missing at random (MAR)[31]: the probability that a variable is missing only depends on observed variables.

Hence, we perform the *predictive mean matching* method, which is a multiple imputation method to replace missing values with the observed value close to the predicted mean of the missing values (Vink et al., 2014; Morris et al., 2014). This imputation method is the most popular imputation algorithm.[32] The main idea is that the predictive values are calculated by using a regression model. It then picks the five closest elements based on Euclidean distance to the predictive value. These five elements are named the 'donor pool', from which the final value is randomly chosen (Morris et al., 2014). We provide additional information about the missing data pattern and distribution of imputed and original values in Appendix A.7.

[30]Predicted energy consumption may be missing because, for the JRBBC renovation program, owners and project managers had the choice between calculating the predictions with the *TH-C-E ex* software (which is a regulatory thermal analysis), or use a technical benchmark (specific to the program). We only used the predictions stemming from the thermal analysis. The issue with the technical benchmark predictions is that the assumption was made of the installation of a condensing boiler. However, the owners did not necessarily changed their existing heating system for a condensing boiler. Predictions may thus be biased.

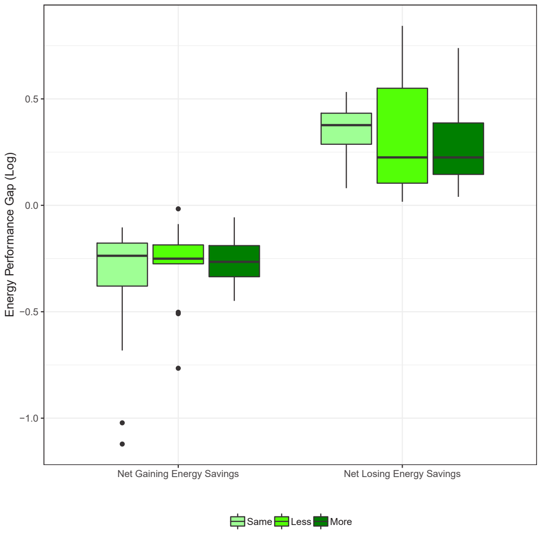
[31]Using data alone does not allow to prove or falsify MAR assumption.

[32]Interested readers can find in Lampach et al. (2017) a small tutorial elucidating the main idea of multiple imputation method.

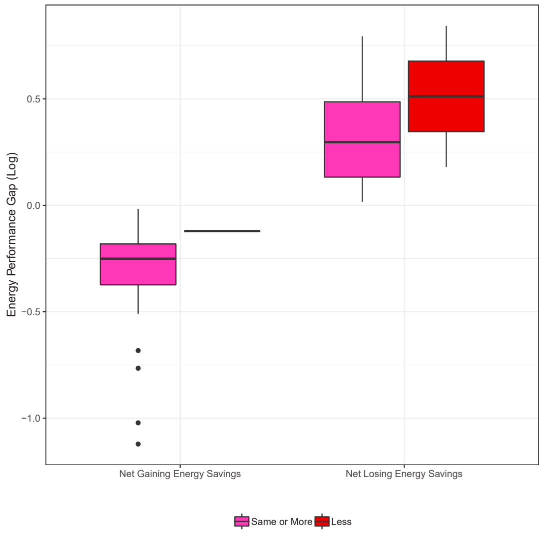
1.7 Empirical analysis

1.7.1 Parametric and non-parametric statistical tests

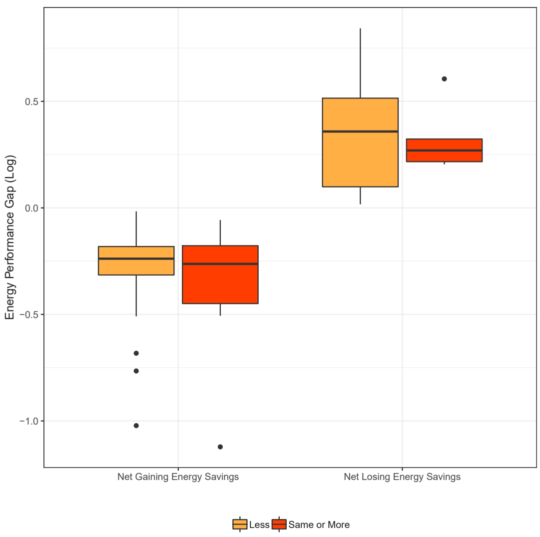
Figure 1.17 presents the relationship between individuals' cognitive biases and the EPG. At first glance, our four hypotheses tend to point in the direction of the results given by Figure 1.17, for households having an EPG greater than zero (i.e. NLS).



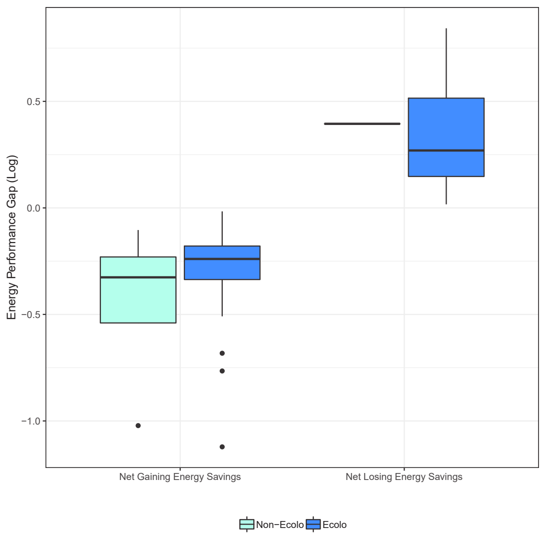
(a) Status Quo Bias



(b) Optimism Bias



(c) Attitude-Behavior Gap



(d) Intention-Behavior Gap

Figure 1.17: Relationship between Cognitive Biases and Energy Performance Gap

However, performing non-parametric tests (i.e. Mann Whitney U test, Moods median test) and parametric statistical tests (i.e. student's t-test) yield no significant differences between groups ($p_{\text{value}} > 0.1$).[33] For households who consume less than predicted (i.e. NGS), almost no divergence is found between groups[34].

1.7.2 Results

Figures 1.18-1.21, hereafter, plot the mean estimates and the 95% confidence intervals[35] of the regression analysis in the situations of Net Losing and Net Gaining Energy Savings respectively.[36] We compute bootstrap standard errors by re-sampling the data 10,000 times for (1) NLS *without* imputed values, (2) NLS *with* imputed values, (3) NGS *without* imputed values, and (4) NGS *with* imputed values. It has been shown that bootstrapping is an efficient method to calculate accurate and valid confidence intervals after multiple imputation (Efron, 1994). In comparison, the confidence intervals of the estimates obtained by applying the *predictive mean matching* method (i.e. (2) and (4) *with* imputed values) are smaller than those for (1) and (3) *without* imputes values. This makes sense, since the variability decreases with a larger sample size, implying more narrow confidence intervals.

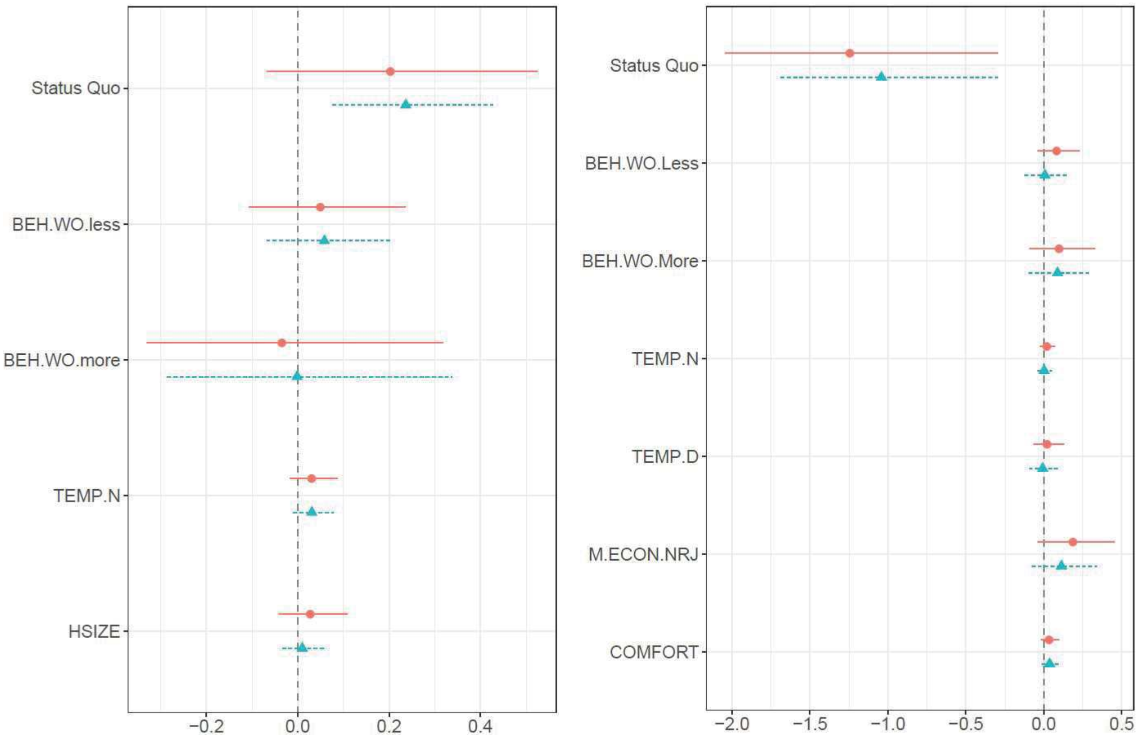
[33] Detailed information on the parametric and non-parametric statistical tests are in Appendix A.8.

[34] For instance, by testing the cognitive bias 'status quo on manual ventilation', there is nearly no difference between households declaring to open *less*, *equally* or *more* than before renovation.

[35] For those which are not familiar with the interpretation of plots using mean estimates and confidence intervals, variables are significant when the confidence intervals are not crossing the vertical dotted line in Figure 1.18-1.21.

[36] We provide tables and more information about the estimation results in Appendix A.9. The estimations were conducted with the open source software R (R Core Team, 2015).

Status Quo Bias Let us first analyze the empirical results with respect to the *Status Quo bias*, displayed in Figure 1.18.



(a) Net Losing Energy Savings (b) Net Gaining Energy Savings

Note: Solid C.I. = model without imputation ; Dotted C.I. = model with imputation

Figure 1.18: Mean Estimates and 95% Confidence Interval: *Status Quo Bias*

Considering the model with imputation for households consuming more than predicted (see Panel 1.18a), results indicate that those who did not change their window opening behavior (i.e. Status Quo) consume significantly more than predicted, and more precisely 26.74% ($= 1 - e^{\beta_{\text{Status Quo}}=0.237}$) more than predicted. However, there is no significant difference between occupants opening less and more their windows, and those keeping the *status quo*.

The *status quo bias* thus substantially deters the achievement of the predicted *ex-post* energy consumption for households yielding NLS after renovation. However, households realizing NGS are not impeded by the *status quo effect* (see Panel 1.18b). In other words, the fact that these households consume less than predicted is not due to keeping the status quo on manual ventilation, since these households have a significantly smaller EPG (−71%) ventilating more and less than before. This means that they make more savings than the others. This effect may be explained by other factors.

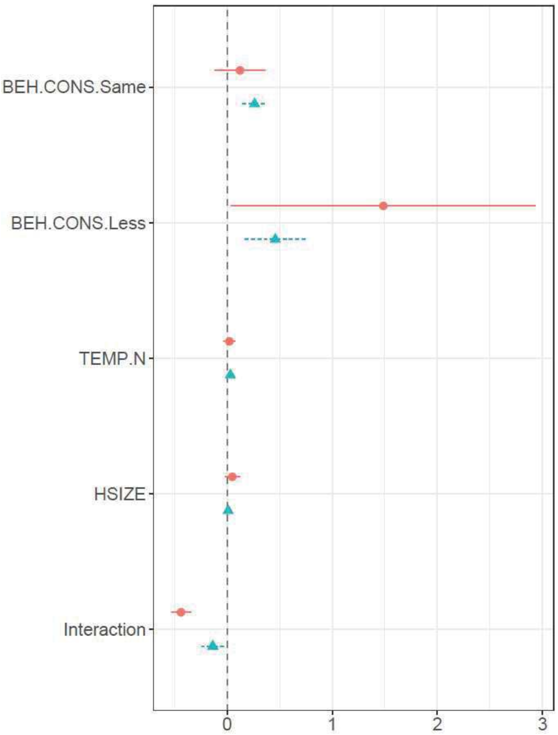
This brings us to a first result, corroborating *Hypothesis* 1 for households consuming more than predicted.

Result 1 *The 'status quo bias' related to manual ventilation behavior positively affects Net Losing Energy Savings, and thus negatively impacts the Energy Performance Gap.*

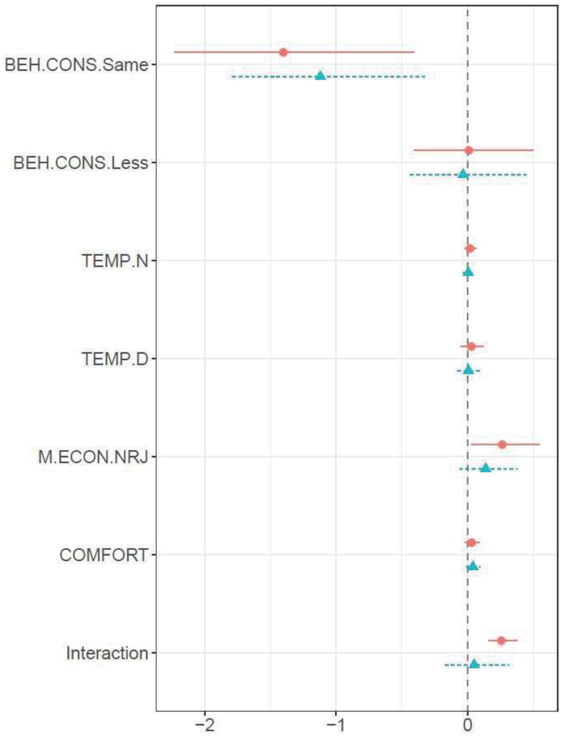
Prevention efforts were made through the distribution of leaflets by the EDF (i.e. the energy utility company involved in the renovation program), explaining the occupants how to modify their behavior in a low energy dwelling. Unfortunately, the basic information communication had no important impact, since the majority of the occupants (85%) reported no behavioral change of their manual ventilation behavior. Their preference toward comfort[37] and the power of their habits (Maréchal, 2009) may play a role in this behavioral inertia. Addressing the excessive energy consumption due to long window opening periods is thus key in preventing the EPG, especially in presence of a mechanical ventilation system.

[37] 94% of the households found it important or very important to increase their comfort as a renovation motive. See question A.1.

Optimism Bias Let us now analyze the empirical results with respect to the *Optimism bias*, displayed in Figure 1.19.



(a) Net Losing Energy Savings



(b) Net Gaining Energy Savings

Note: Solid C.I. = model without imputation ; Dotted C.I. = model with imputation

Figure 1.19: Mean Estimates and 95% Confidence Interval: *Optimism Bias*

For households heating at the prescribed 19°C at night, those reporting to pay less attention to their energy consumption after renovation (BEH.CONS.Less) exhibit much higher NLS than those keeping in mind their energy consumption (BEH.CONS.Same)[38] (thus a larger EPG). Moreover, the estimated parameter for the interaction term (Interaction ≡ BEH.CONS.Less·TEMP.N) is negative and significant, indicating that the effect of paying less attention to energy consumption is distinct for different values of temperature setting at night: heating, at night, under the 19°C used in the prediction, lowers the negative effect of paying less attention to energy consumption, and thus of the *optimism bias* (see Panel 1.19a)[39]. In other words, while occupants' behavioral patterns are not fully considered in current energy analysis tools and thermal studies (Delzendeh et al., 2017), our finding

[38] +343% according to the model without imputation, and +58.25% according to the model with imputation.

[39] −35.34% per degree less, according to the model without imputation, and −12.63% per degree less, according to the model with imputation.

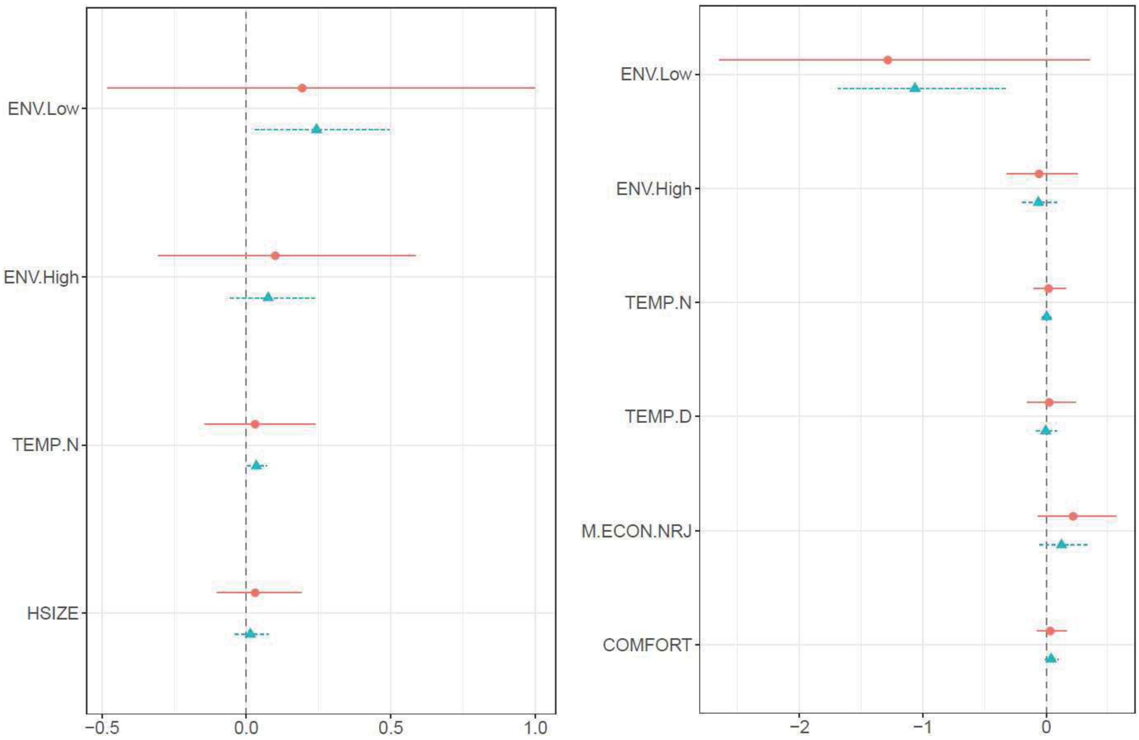
shows that the presence of an *optimism bias* leads to increase the EPG for households consuming more than predicted.

This brings us to a second result corroborating *Hypothesis* 2 for households consuming more than predicted.

Result 2 *There is an 'optimism bias' from households reporting to pay less attention to their energy consumption than before renovation and heating at the prescribed* 19°C *at night, such that it has a negative effect on the EPG. Heating less lowers this effect.*

We cannot confirm thus result for households consuming less than predicted (i.e. NGS). They are not impacted by an *optimism bias*, in the sense that the fact of paying less attention to energy consumption does not explain their NGS (see Panel 1.19b). However, those paying equally attention to their energy consumption than before achieve 75.37% higher savings (thus a larger EPG) than those paying less attention. This finding is very encouraging since higher energy savings in low energy buildings could be achieved by raising awareness about the attenuating effect of paying attention to its energy consumption behavior.

Attitude-Behavior Gap Let us now analyze the empirical results with respect to the *Attitude-Behavior Gap*, displayed in Figure 1.20.



(a) Net Losing Energy Savings (b) Net Gaining Energy Savings

Note: Solid C.I. = model without imputation ; Dotted C.I. = model with imputation

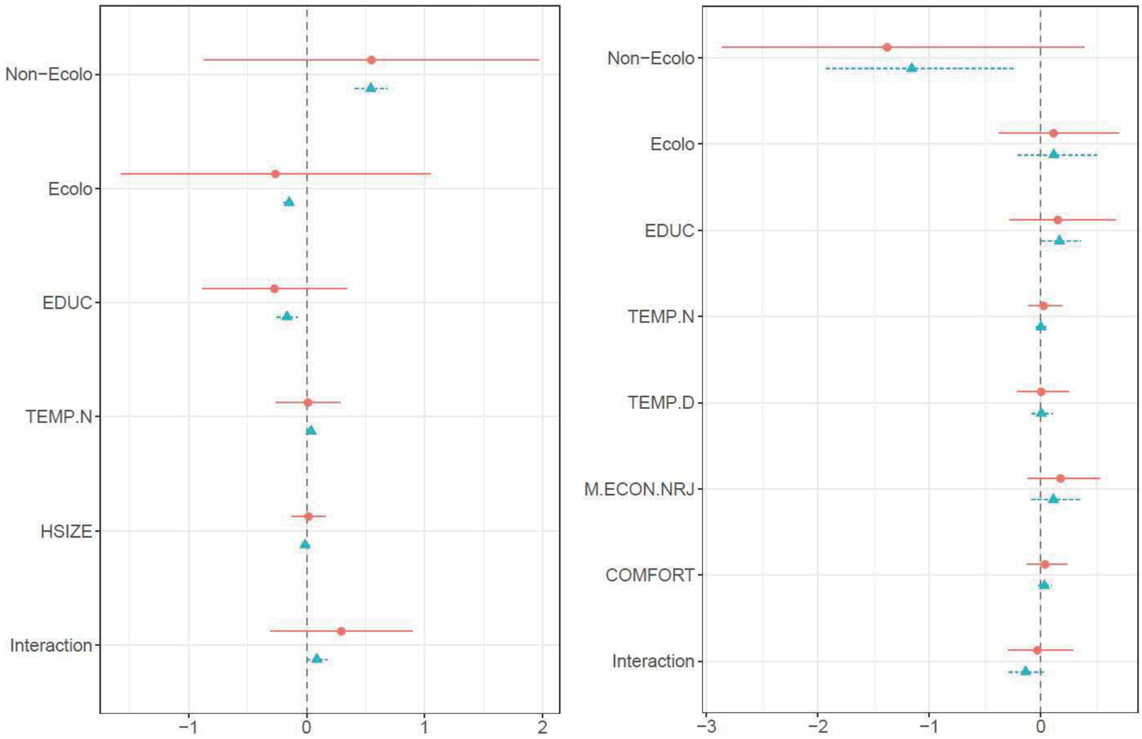
Figure 1.20: Mean Estimates and 95% Confidence Interval: *Attitude-Behavior Gap*

It can be seen from Panels 1.20a and 1.20b that occupants with higher pro-environmental attitudes (ENV.High) do not significantly differ from those with lower pro-environmental attitudes (ENV.Low). In other words, those declaring high pro-environmental attitudes do not consume significantly less than the others. This is true regardless whether households consumes more or less than predicted.

This brings us to a third result, confirming *Hypothesis* 3.

Result 3 *There is evidence for an 'attitude-behavior gap' related to households declaring high pro-environmental attitudes.*

Intention-Behavior Gap Let us finally analyze the empirical results with respect to the *Intention-Behavior Gap*, displayed in Figure 1.21.



(a) Net Losing Energy Savings (b) Net Gaining Energy Savings

Note: Solid C.I. = model without imputation ; Dotted C.I. = model with imputation

Figure 1.21: Mean Estimates and 95% Confidence Interval: *Intention-Behavior Gap*

Recall that the Interaction term includes the revenue level (REV=1 if >4000€, REV=0 otherwise), such that Interaction≡M.Ecolo·EDUC·REV.[40]

Let us first analyze the results for households consuming less than predicted (see NGS on Panel 1.21b). We notice that whether "rich" and more educated, or not, environmentally motivated[41] households do not have a significantly different EPG compared to non environmentally motivated households. This indicates the presence of an *intention-behavior gap* for these households.

Now regarding households consuming more than predicted (see NLS on Panel 1.21a). On the one hand, for lower educated and "less rich" households, we observe that there are significant differences between occupants stimulated by sustainable motives and those who

[40]We do not include REV as a control variable since it did not appear among the top predictors in the SVM ranking.

[41]Recall that an intention is a motivation toward a goal-directed behavior. This is why we account for an intention-behavior gap through analyzing occupants' sustainable motivations.

are not, when considering the model with imputation (i.e. Ecolo vs. Non-Ecolo), such that the EPG decreases by 23.13%, all other variables held constant. This result rejects *Hypothesis* 4 for these households. On the other hand, we see that higher educated and "richer" households reporting pro-environmental motivations (i.e. Interaction) manifest a significantly higher EPG than others (+7%). This manifests the presence of an *intention-behavior gap* for these households. Moreover, it tends to corroborate a former result of Belaid and Garcia (2016), who find that occupants having a higher social status (i.e. occupying at a socio-professional position[42] requiring higher education, and thus being paid more) seem to have stronger desire for comfort than for making energy related savings. Belaid and Garcia (2016) call this phenomenon a "*social status effect*".

This brings us to a last result, corroborating Hypothesis 4 for households consuming less than predicted, and higher educated and "richer" households consuming more than predicted.

Result 4 *There is evidence for an 'intention-behavior gap' related to occupants consuming less than predicted, and to high educated and wealthier occupants consuming more than predicted, expressing ecological motives.*

1.7.3 Model selection

Let us now, for every model specification we run, select the most efficient model (between the one *without* and the one *with* imputed values), in terms of explanatory power. The log-likelihood used on our endogenous variable is not well suited to easily compare model performance of different sample sizes, through the adjusted R^2. We thus have to find a different way to compare our model specifications. One possibility would be to use the *information criterion* (AIC and BIC) to provide means for model selection. However, they also depend on a likelihood function and are sensitive to the number of observations. An alternative way for model selection is thus to use *cross-validation method* by comparing the corresponding *Root-Mean-Square Errors* (RMSE) (Myung et al., 2009). A lowest RMSE indicates the best model. Table 1.4, hereafter, reports RMSE based on the *Leave One Out Cross Validation* method (LOOCV).

[42]Note that only 33% of the lower educated households in our database have a managerial or higher intellectual professional position, compared to 58% of the higher educated ones.

Table 1.4: Model Comparison based on LOOCV

Cognitive Bias	Without Imputed Values	With Imputed Values	Without Imputed Values	With Imputed Values
	Net Losing Energy Savings		*Net Gaining Energy Savings*	
Status Quo	0.297	**0.275**	**0.264**	0.328
Optimism	**0.338**	0.361	**0.255**	0.348
Attitude-Behavior Gap	0.283	**0.270**	**0.258**	0.324
Intention-Behavior Gap	0.289	**0.278**	**0.272**	0.332

Note: The lowest RMSE (corresponding to the best model) are indicated in bold.

Based on the computed LOOCV-RMSE, the model with imputed values represents the best absolute model fit in the situation of NLS, except for the *optimism bias*. This confirms our results.

On the other hand, the *multiple imputation method* does not yield better absolute model fit in the situation of NGS, though the empirical results do not significantly differ between the models without and with imputed values. However, in this case, the model without imputed values is preferred as the corresponding LOOCV-RMSE are the lowest for these models.

1.8 Robustness Analysis

A self-reported energy-behavior (or attitude, or motivation, ...) – as a measurement for a cognitive bias – might potentially suffer from an 'omitted variable bias'. This is problematic to some extend: households' energy behavior might indeed be affected by cognitive biases, yet, this behavior also constitutes a *choice* from them, conditional on observable and unobservable factors. For instance, the presence of a thermostat in the renovated building might increase the likelihood to adopt an *optimism bias*, and therefore pay less attention to their energy consumption. This is problematic with respect to the identification strategy, as the presence of thermostat would affect not only our independent variable (i.e. the proxy related to 'optimism bias'), but also the dependent variable (i.e. the EPG). This problem is known as an *endogeneity bias*.

To validate this measurement method and to rule out potential endogeneity problems, we implement the *inverse probability of treatment weighting* (IPTW) strategy (Austin, 2011; Stuart et al., 2014), a method estimating causal effects.

To obtain the predicted probability, for a given household, to be assigned in the treatment[43] (i.e. *propensity score*) conditional on observed characteristics, we used predictive modeling tools (i.e. the Random Forest algorithm) instead of using a logistic regression (as is usually done). Aside from relaxing basic assumptions, these methods have demonstrated greater accuracy than logistic regression (Lee et al., 2010; Westreich et al., 2010). Applying the Random Forest algorithm permitted to obtain a classification of the variables (and thus the characteristics) having the highest influence on the treatment group.[44] The relative importance of the various characteristics per bias are displayed in Section A.10 of the Appendix.

Once the propensity scores obtained, we implemented the IPTW strategy. The main intuition of this approach is to compare groups having the same characteristics, where the first group (i.e. treatment group) declares a behavior corresponding to the analyzed bias, and the second group (i.e. control group) declares the opposite behavior. The IPTW assigns greater weights[45] to households in the control group which resembles those in the treatment group (Austin, 2011). Since these groups have now more weight, running our regressions with the "new" database permits to obtain more robust results and less likely to suffer from an endogeneity bias. Indeed, the fact of declaring a given behavior or the opposite cannot anymore be suspected to be caused by the common characteristics.

A further advantage of the IPTW method is that it does not eliminate observations in our database[46], compared to the *propensity score matching* method. This latter approach indeed forms matched sets of treated and control units sharing a similar propensity score, and eliminates the remaining observations. As our original sample is relatively small, this method was not appropriate.

To shorten this section, we present solely the robustness of the empirical results obtained in the situation of *Net Losing Energy Savings* and rely on the imputed data set. Recall that the RMSE based on the LOOCV indicates that the data set with imputed

[43]'Treatment assignment' refers to the assignment of a household in a group where all the households reported a specific energy behavior related to a cognitive bias. For example, for measurement of the optimism bias, households declaring to pay less attention to their energy consumption than before, are assigned to the treatment.

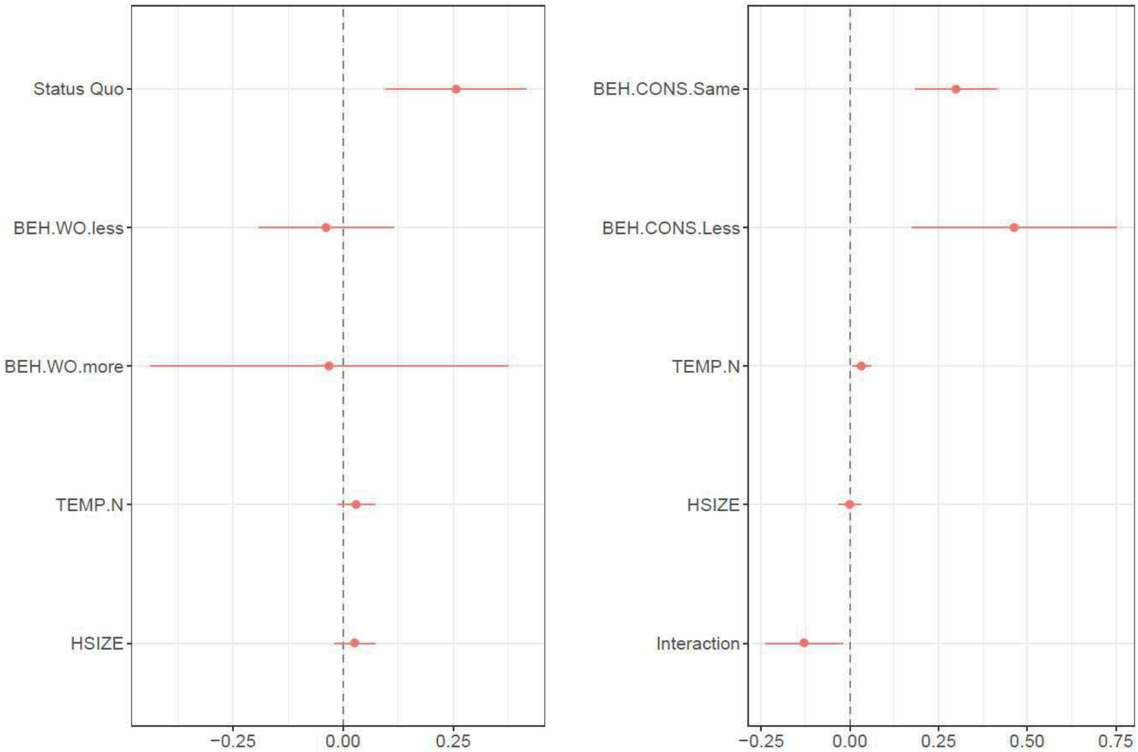
[44]The bagging approach in the *random forest* algorithm solves the problem of overfitting more effectively than the *support vector machine* or the *gradient boost* algorithms.

[45]In case of a *binary endogenous variable*, the IPTW can be expressed as: $w_i = \frac{1}{ps_i} E_i + \frac{1}{(1-ps_i)}(1 - E_i)$, where E_i denotes the treatment assignment of household i, and ps_i the propensity score of the treatment assignment.
In the case of *categorical endogenous variable*, the weight for a household i can be written: $w_i = \frac{ps_1(X_i)}{ps_g(X_i)}$, where $ps_1(X_i)$ is the probability of being in the pre-treatment group, and g denotes the group that household i was actually in.

[46]This method just assigns greater weight on the groups of interest.

values represents the best absolute model fit in the situation of NLS.

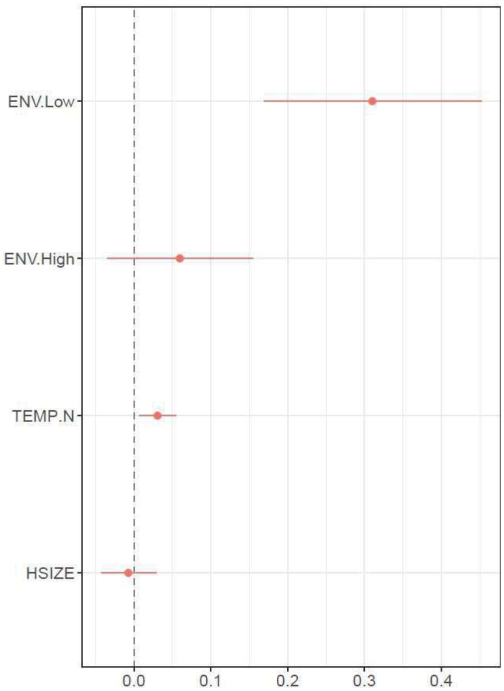
Due to our relatively small sample size, we bootstrap the standard errors by re-sampling 10 000 times the data for each imputed data set (m=100). The results of the weighted regression with inverse probabilities on the imputed data set, in the situation of NLS, are depicted in Figure 1.22.



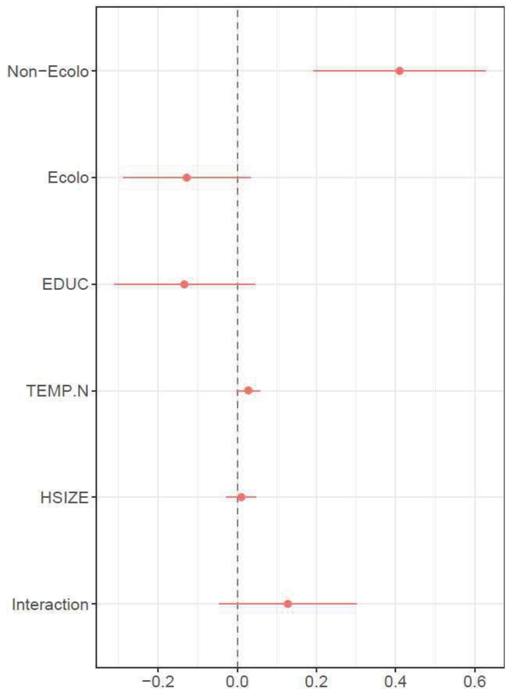
(a) Status Quo Bias (b) Optimism Bias

Note: Mean estimates and 95% confidence intervals

Figure 1.22: Regression with Inverse Probability Weighting on imputed dataset in *Net Losing Energy Savings* situation (part 1)



(c) Attitude-Behavior Gap



(d) Intention-Behavior Gap

Note: Mean estimates and 95% confidence intervals

Figure 1.22: Regression with Inverse Probability Weighting on imputed dataset in *Net Losing Energy Savings* situation (part 2)

These empirical results are similar than those obtained without IPTW for the status quo bias, the optimism bias and the attitude-behavior gap. The declarations measuring these biases may thus not be affected by an endogeneity problem: Results 1 to 3 are robust.

However, the empirical results analyzing the *intention-behavior gap* yield a loss of significance for the coefficient capturing higher pro-environmental motivations and the interaction term. The present results being more robust than before, we now find the following. First, regarding less wealthier and less educated households, the results show that pro-environmentally motivated households do not have a significantly lower EPG than non pro-environmentally motivated ones. Second, regarding wealthier and more educated households, pro-environmentally motivated households do not have a significantly different EPG then non pro-environmentally motivated ones. This indicates that, regardless of being "rich" and educated or not, pro-environmentally motivated households may present an *intention-behavior gap*. However, concerning the wealthier and more educated ones, contrary to before, we find that they may not suffer from a ‘social status effect’.

Globally, the robustness of our previous results may indicate that self-reported energy-behavior can be a valid measurement for households’ cognitive biases.

1.9 Policy implications and conclusion

We explore the effect of individual's cognitive biases on the Energy Performance Gap (EPG) – ratio of the actual and predicted total energy consumption – of buildings renovated up to the level of low energy performance. Using self-collected survey data, energy bills and audits of 129 households, from a pilot energy conservation program located in northeastern France, we assess four hypotheses stemming from the behavioral energy and psychology literature. To avoid the problem of overfitting, we apply learning models to select most relevant covariates as control variables. We run a multiple regression analysis for households consuming more energy than predicted (i.e. Net Losing Energy Savings) and for those consuming less than predicted (i.e. Net Gaining Energy Savings). Our database having 7% of missing values, we run each regression with the original database in the first place, and with the database where missing values have been imputed (with the multiple imputation method) in the second place. We controlled for a potential endogeneity bias from our proxy variables by applying the Inverse Probability of Treatment Weighting approach. The empirical results confirm our four hypotheses. An important contribution of our analysis may thus be the fact that self-reported energy behaviors and attitudes can actually represent a valid measurement instrument to analyze household's cognitive biases.

Furthermore, our findings suggest that the *status quo bias* related to manual ventilation behaviors negatively affect the EPG (i.e. the gap increases) of households consuming more than predicted. It became apparent that leaflets may not be very effective instruments in preventing the excessive energy consumption through window opening.

A second result shows significant differences for occupants reporting to pay less attention to their energy consumption in the renovated building compared to others and consuming more than predicted. This corroborates the hypothesis of an *optimism bias*. Our results indicate, however, that heating less than 19°C at night decreased the gap, and thus lowers the negative effect of the optimism bias. This finding stresses the relevance of full automatic temperature control, setting lower temperatures at night. The energy conservation program may have neglected to inform participants about the efficient temperature settings during the day or at night in low energy buildings. Occupants' knowledge acquisition on managing efficiently the temperature settings during and beyond occupation time might be suitable to achieve higher energy performance.

The idea behind the *optimism bias* is closely associated with the *"technological optimism"* of Mitchell (2012): the direct rebound effect experienced by occupants may be stronger than the positive effect of the technological improvement achieved by renovating the dwelling. It would be beneficial to further elaborate whether the *optimism bias* drives the direct rebound effect. In this study we have so far neglected the existence of rebound effects as we do not have fully available information on all energy prices, and not enough information about ex-ante consumption. The main problems are twofold. First, occupants have no energy bills for specific combustible (e.g. wood, pellets and fuel). Second, there are multiple data sources with heterogeneous definitions on energy prices at regional, national and supranational level, which may produce noise in the analysis.

Our last results show evidence for an *attitude-behavior gap* related to occupants reporting a high pro-environmental attitude, and an *intention-behavior gap* referring to occupants expressing ecological motivations to renovate. In other words, pro-environmental attitudes and motivations did not permit households to achieve a smaller EPG than the others.

What are the lessons learned from the energy conservation program *"Je Rénove BBC"* and to what extent are the gained insights relevant to design and foster effective policy measures? Key policy implications can be deduced from our findings and can be classified into two categories.

First, our findings point out the importance to design effective tools to inform occupants about the risk that can emerge when not adapting their energy related behaviors in low energy buildings. Raising awareness about cognitive biases is key to narrow the EPG in low energy buildings. How can occupants be incentivized to adopt "optimal" energy behaviors? One possibility to inform occupants about the risk related to cognitive biases would be through the engagement of the prime contractor who is in a close relationship with the occupants during the renovation period. During our discussion with participants of the energy conservation program, we noticed that a large majority of occupants strongly trust the prime contractor, for instance, by using their advice to modify the heating systems. The role of the prime contractor might be significant to spur occupants to adopt different behaviors in low energy buildings in order to reduce the risk of not achieving the required energy performance. An alternative instrument to incentivize occupants to adapt their energy behavior would be to introduce energy conservation nudges. The use of descriptive, injunctive messages (i.e. emoticons) or instructive energy-saving tips represent helpful tools to sustain and encourage pro-conservation behavior (see, for instance, Rasul and Hollywood, 2012). These nudges might be most effective directly after the renovation works as many occupants expressed their motivation to pay more attention to their energy consumption during the interviews, but that this ambition diminishes after a year.

Second, our findings provide valuable insights to improve the predicted energy consumption by integrating underlying occupant habits that influence the EPG. As such, we recommend energy consulting firms, operating in the assessment of the feasible improvement of the energy performance through renovating measures, to include information based on a general behavior profile that could be established before calculating the savings predictions. For instance, at an individual project level, thermal energy auditors could meet the households before estimating a savings prediction, to ask them about their habits (e.g. heating, airing, attention to energy consumption). However, as we detected an *Attitude-Behavior Gap* and an *Intention-Behavior Gap*, information about the tendency to be concerned about environmental issues, or the willing to live in an environmental friendly house, may not be an indicator about a less energy consuming household. Further efforts would be needed to determine to what extent these behaviors may impact the energy consumption. Yet, such information could make the energy consumption predictions more reliable, and consequently reduce the risk of non-achievement of the predicted energy performance. For banks and insurance companies to be able to rely on predictions would allow them to avoid ethical issues that could arise by using household information to estimate the risk per individual behavior profile, which may be considered as "discriminating". Better rely on predictions and taking into account the average likelihood to consume more than predicted (based on our database, the likelihood of attaining Net Losing Energy Savings is 38%) will permit them to improve and develop insurance contracts and leverage bank loans.

Although our empirical results are valid and robust, our sample size is relatively small. To validate the formulated policy implications, our findings should be replicated and extended by using a national representative and large sample. Nevertheless, our empirical approach and the resulted findings ground a baseline setting for the elaboration of the impact of cognitive biases on the EPG at sub-national level. While our results hold for the region Alsace located in northeastern France, it might be beneficial to identify the determinants affecting the EPG in low energy buildings on large national or EU wide scale.

Future research should also aim to gather homogeneous energy prices for different types of energy sources such as wood and pellets. This would allow to measure the direct rebound effect and assess its relationship with the *optimism bias*. Our result indicates that self-reported behavior on energy behavior (as, for instance, declaring to pay less attention to daily its energy behavior, to measure an optimism bias) can be an efficient metric to capture and quantify cognitive biases.

Nowadays, a range of other initiatives have emerged to convince people to undertake energy efficiency measures. For instance, the common platform Oktave[47] established in the Region Alsace reflects the relationship between certified renovation firms and governmental services helping households to access relevant information for thermal renovation. Similar than in our energy conservation pilot program, a contractor is assigned to households' willing to carry out renovation works on their house. The role of the contractor is twofold: supporting households throughout the renovation works and helping them to apply for available financial aids. An important question, however, is how efficient are these platforms, and do such initiatives sufficiently incentivize households to renovation their individual buildings? Further research is necessary to answer these questions and to fill the void. Meanwhile, Chapter 3 of the thesis gives an idea about the global efficiency of the craftsman intervening in the context of the Oktave platform.

[47]For further information, refer to Oktave (Oktave).

Appendix A

A.1 "*Je rénove BBC*" survey questions in English

Table A.1: Part A - Motivation

A.1. What motivated you to participate in an energy renovation project?	Own an environmentally friendly house	1. not important at all 2. little important 3. quite important 4. very important
	Make energy savings	
	Make financial savings	
	Increase comfort	
	Facilitate resale / renovate a recently acquired house	
	Rehabilitate an uninhabitable house	
	Enhance the value of your assets	
	Enter the JRBBC program	
A.2. You have heard about the *"Je rénove BBC"* program thanks to...	advertisement	1. yes 2. no
	presence of the JRBBC stand at an exhibition / open house	
	other recommendations	
	internet	
	local community / town hall	
	information booklet	
	Region Alsace / Energivie / energy info	
	EDF / ES	
	architect / project manager / craftsman / client in the building industry	
	other	
A.3 What benefits have you gained from the *"Je rénove BBC"* program?	financial assistance from the program	1. yes 2. no
	engineering to achieve final performance	
	other	
A.4.1. Would you have done all this work without the *"Je rénove BBC"* program?		1. yes; 2. no
A.4.2. If yes, would you have gone to BBC level in energy performance?		1. yes; 2. no
A.4.3. If no, what would have stopped you?	lack of funds	1. yes 2. no
	lack of energy performance expertise	
	lack of assistance and advice	
	lack of knowledge of providers	

Table A.2: Part B - Renovation financing

B.1. With regard to obtaining financial aid from the "*Je rénove BBC*" program, according to you, were the administrative formalities simple and clear?		1. yes 2. no
B.2.1. What other financial assistance did you receive outside the program?	tax credit	1.yes 2. no
	financial support from the municipality	
	zero-rate loan	
	other	
B.2.2. Did you have any problems getting these aids?		1. yes; 2. no

Table A.3: Part C - Choice of companies and materials/equipment and prime contractor

C.1 Have you chosen the project manager among several proposed or has he been suggested to you?	Among several proposed by EDF/ES	1. yes 2. no
	Suggested by an acquaintance/	
	your own choice	
C.2 How important were the following criteria for you in choosing the project manager on a scale of 1 to 5?	energy renovation mastery / quality of work	1. yes 2. no
	its price	
	seniority / notoriety	
	knowing the project manager	
	its proximity	
C.3 How important were the following criteria in the choice of materials for you?	performance and quality	1. not important at all 2. little important 3. quite important 4. very important
	price	
	environmental friendliness	
C.4 If you were advised in the choice of materials, who advised you?	EDF/ES	1. yes 2. no
	project manager	
	firms	
	acquaintance	
	thermal engineering office	
	other	
	has not been advised	

Table A.4: Part D - "Je Rénove BBC" program satisfaction

D.1.1. Are you satisfied...	of the global work of the project manager?	1. yes 2. no
	of the global work of the companies?	
	of the JRBBC program in general?	
	of the final works?	
D.2 Did you live in your house during the renovation work?		1. yes; 2. no
D.3.2. Are you satisfied with your project manager's performance?	client-trade relationship	1. not at all 2. a little 3. quite 4. very
	quality of global coordination	
	total cost of the delivery	
	adequacy between estimate and invoice	
	respect of work deadlines	

Table A.5: Part E1 - Energy consumption before renovation

E.1.1. Indicate your total electricity consumption on a bill dated before the renovation (in kWh).		
E.1.2. What is the period covered by the invoice used above?		
E.1.3. Heating system BEFORE renovation (to complete with consumption units and heating period if "yes")	condensing gas	1. yes 2. no
	atmospheric gas	
	oil-fired boiler	
	pellet boiler	
	pellet stove	
	wood boiler	
	wood stove	
	heating network	
	electric boiler	
	electric radiators	
	air/water heat pump	
	water/water heat pump	
	geothermal heat pump	
E.1.4. How old was the heating system before renovation?		1. 0-5 years 2. 6-10 years 3. 11-15 years 4. more than 15 years
E.1.5. Sanitary hot water consumption before renovation (to complete with consumption in kWh and heating period if "yes")	thermodynamic water heater	1. yes 2. no
	electric water heater	
	solar system	
	heating network	
	other	
E.1.6. Fully electric system before renovation?		1. yes 2. no

Table A.6: Part E2 - Energy consumption after renovation

E.2.1. Indicate your total electricity consumption on a bill dated after the renovation (in kWh).		
E.2.2. What is the period covered by the invoice used above?		
E.2.3. Did you change your heating system during the renovation?		1. yes; 2. no
E.2.4. Heating system after renovation (to complete with consumption units and heating period if "yes")	condensing gas	1. yes 2. no
	atmospheric gas	
	oil-fired boiler	
	pellet boiler	
	pellet stove	
	wood boiler	
	wood stove	
	heating network	
	electric boiler	
	electric radiators	
	air/water heat pump	
	water/water heat pump	
	geothermal heat pump	
E.2.5. Did you change your domestic hot water (DHW) system during the renovation?		1. yes; 2. no
E.2.6. Sanitary hot water consumption after renovation (to complete with consumption in kWh and heating period if "yes")	thermodynamic water heater	1. yes 2. no
	electric water heater	
	solar system	
	heating network	
	other	
E.2.7. Fully electric system after renovation?		1. yes; 2. no

Table A.7: Part F - Habits and behaviors in the dwelling

F.1.1 What type of temperature control did you have before renovation and what type do you have after renovation?	Before: thermostatic valve	1. yes 2. no
	Before: room thermostat	
	Before: nothing	
	Before: other	
	After: thermostatic valve	
	After: room thermostat	
	After: nothing	
	After: other	
F.2.1.1. At what temperature did you usually heat before renovation...	...during daytime with occupation ?	*answer*
	...during daytime without occupation?	*answer*
	...during the night?	*answer*
	I don't know	
F.2.1.2. At what temperature do you usually heat since renovation...	...during daytime with occupation ?	*answer*
	...during daytime without occupation?	*answer*
	...during the night?	*answer*
	I don't know	
F.3.1.1.1. Were there any unused rooms in your house before renovation?		1. yes; 2. no
F.3.1.1.2. If yes, were they heated like the others?		1. yes; 2. no
F.3.1.2.1. Are there any unused rooms in your house since renovation?		1. yes; 2. no
F.3.1.2.2. If yes, are they heated like the others?		1. yes; 2. no
F.4.1. What was your occupancy time of the house on an average weekday before renovation?		
F.4.2. What is your occupancy time of the house on an average weekday since renovation?		
F.5.1. Were you often in the renovated house during the weekend before renovation?		1. yes 2. no
F.5.2. Are you often in the renovated house during the weekend since renovation?		1. yes 2. no
F.6. On average, how many weeks per year are you away from your home (holidays, etc.)?		1. < 1 week 2. 1-2 weeks 3. 2-3 weeks 4. 3-4 weeks 5. > 4 weeks
F.7. Compared to before renovation you	open [...] your windows.	1. less
	have the tendency to consume [...] d. hot water.	2. same/equally
	have the tendency to pay [...] attention to your energy consumption.	3. more
	are [...] concerned about ecol. and env. issues.	

Table A.8: Part G - Comfort before and after renovation

G.1. On a scale of 1 to 10, how would you rate the comfort inside your home before renovation?		
G.2. On a scale of 1 to 10, how would you rate the comfort inside your home after renovation?		
G.3.1 Were there sources of discomfort in your home before renovation?		1. yes; 2. no
G.3.2. If yes, in your opinion, what caused the discomfort?	Sensation of drought	1. yes 2. no
	Cold wall feeling	
	Indoor temperature too low during winter	
	Indoor temperature too high during summer	
	Lack of air renewal	
	Presence of dust in the air	
	Water infiltration / molds	
G.4.1. Are there still sources of discomfort in your home after renovation?		1. yes 2. no
G.4.2. If yes, in your opinion, what causes the discomfort?	Sensation of drought	1. yes 2. no
	Cold wall feeling	
	Indoor temperature too low during winter	
	Indoor temperature too high during summer	
	Lack of air renewal	
	Presence of dust in the air	
	Water infiltration / molds	

Table A.9: Part H - Client

H.1. Name and surname of the respondent		
H.2. Gender of the respondent		1. man; 2. woman
H.3. Family status	1. couple; 2. divorced; 3. single; 4. widow	
H.4. How many people live in the house on a daily basis?	girl 0-5 years old	1. 0
	girl 6-9 years old	2. 1
	girl 10-17 years old	3. 2
	woman 18+	4. 3
	boy 0-5 years old	5. 4
	boy 6-9 years old	
	boy 10-17 years old	
	man 18+	
H.5. Are there the same number of people living in the house on a daily basis before and after renovation?		1. same number 2. more inhabitants 3. less inhabitants
H.6. How old are you and your spouse?	18-24 years old	1. respondent?
	25-34 years old	2. spouse?
	35-44 years old	
	45-59 years old	
	60-69 years old	
	70+	
H.7. What is your and your spouse's socio-professional situation?	Farmer operator	1. respondent?
	Craftsman, trader, company manager	2. spouse?
	Executive, liberal/intellectual profession	
	Intermediate occupation	
	Employee	
	Worker	
	Retired	
	At home (nursery assistant, home work, ...)	
	No professional activity, student	
	other	
H.8. What is your and your spouse's education level?	Without diploma	1. respondent?
	Certificate, CAP, BEP	2. spouse?
	Baccalaureate	
	Bac+1, +2	
	Bac+3, +4	
	Bac+5 et +	

Table A.10: Parts H and I - Client

H.9. The renovated dwelling is your...	main residence	1. yes
	vacation home	2. no
	rented residence	
	other	
H.10. You are...	landlord	1. yes
	tenant	2. no
I.1.1. What are the monthly resources of your entire household?		
I.1.2. If you do not want or cannot give a precise amount of the net resources of the whole household, how much do you estimate them to be for an ordinary month (in Euros)?		1. <= 1000 2. 1000-2000 3. 2000-3000 4. 3000-4000 5. 4000-5000 6. 5000-6000 7. 6000-7000 8. 7000-8000 9. 8000-9000 10. 9000-10000 11. > 10000
Were you already living in the house before renovation?		1. yes; 2. no
In what department do you live?		1. Bas-Rhin 2. Haut-Rhin

A.2 "*Je rénove BBC*" original questionnaire in French

Questionnaire à l'attention des propriétaires ayant rénové leur maison dans le cadre du programme « Je rénove BBC »

Ce questionnaire a pour objectif de réaliser un retour d'expérience sur le programme « Je rénove BBC » auquel vous avez participé, ainsi que d'étudier les habitudes des ménages vivant dans une maison BBC.

Cette étude est menée conjointement par EDF et l'Université de Strasbourg. Nous souhaitons encore améliorer l'évaluation de la performance énergétique qu'un ménage peut attendre de la rénovation de sa maison. Votre participation à cette enquête nous permettra de récolter des données précieuses, et anonymisées, sur l'avant-après rénovation.

EDF, ES et l'Université de Strasbourg s'engagent à ce que vos réponses restent entièrement anonymes et soient utilisées dans les seuls buts expliqués ci-dessus.

EDF, ES et l'Université de Strasbourg vous remercie pour votre participation.

Lucie, étudiante en master, et Nicolas, étudiant en doctorat à l'Université de Strasbourg.

A. MOTIVATIONS de rénovation et du choix du programme « Je rénove BBC »

A.1. Qu'est ce qui vous a essentiellement motivé à vous lancer dans des **travaux de rénovation BBC**?

Laisser le client répondre spontanément :

____

____

S'il ne sais pas trop, lui proposer les motifs suivants en demandant l'importance qu'il y accorde :

	Pas du tout important	Peu important	Assez important	Très important
• Posséder une maison respectueuse de l'environnement	☐	☐	☐	☐
• Réaliser des économies d'énergies	☐	☐	☐	☐
• Réaliser des économies financières	☐	☐	☐	☐
• Avoir un meilleur confort	☐	☐	☐	☐
• Rénover une maison récemment acquise/ Faciliter la revente de mon bien	☐	☐	☐	☐
• Réhabiliter une maison inhabitable, voire insalubre	☐	☐	☐	☐
• Valoriser mon patrimoine immobilier	☐	☐	☐	☐
• Entrer dans le programme « Je rénove BBC »	☐	☐	☐	☐
• *Autre :* ____________________	☐	☐	☐	☐

1

A.2. Vous avez eu connaissance du programme « Je rénove BBC » grâce à…
Plusieurs réponses possibles

☐ Une publicité dans la presse
☐ Un spot radio / spot télé
☐ Internet (Quel site ? ___________________________)
☐ La plaquette d'info (récupérée où ?________________)
☐ *Autre* : ____
☐ La présence du stand JRBBC à un salon
☐ Recommandation (Qui ?____________)
☐ Collectivité locale
☐ Région Alsace

A.3. Quels avantages vous a apporté le **programme « Je rénove BBC »** ?
Plusieurs réponses possibles

☐ Les aides financières du programme
☐ L'ingénierie pour l'atteinte de la performance finale
☐ *Autre*:____

A.4.1. Auriez-vous réalisé tous ces travaux **sans** le programme « Je rénove BBC » ?

☐ Oui (Répondre à A.4.2.) ☐ Non (Répondre à A.4.3.)

A.4.2. **Si oui**, seriez-vous allé jusqu'au niveau BBC dans la performance énergétique ? ☐ Oui ☐ Non

A.4.3. **Si non**, qu'est ce qui vous en aurait empêché ?
Plusieurs réponses possibles

☐ Manque de moyens financiers
☐ Manque d'assistance et de conseils
☐ *Autre* : ____
☐ Manque d'expertise BBC
☐ Méconnaissance des prestataires

B. FINANCEMENT DE LA RENOVATION

B.1. Concernant l'obtention d'aides financières du programme « Je rénove BBC », d'après vous …

- Les formalités administratives étaient-elles simples et claires ? ☐ oui ☐ non

Si non, pourquoi ?
____

____

B.2.1. De quelles autres aides financières avez-vous pu bénéficier en dehors du programme ?

☐Crédit d'impôt
☐Prêt à taux zéro
☐Aides financières de la communauté d'agglomération (commune, …)
☐Autre aide financière : ______________________________________

B.2.2. Avez-vous rencontré des difficultés (obtention d'un prêt bancaire, formalités administratives, délais d'obtention, …) pour l'une ou l'autre aide ?
☐ oui ☐ non

B.2.3. **Si oui**, pourquoi ?
____

____

____

2

C. CHOIX DES ENTREPRISES ET DES MATERIAUX/EQUIPEMENTS

C.1. Avez-vous choisi le maître d'œuvre parmi plusieurs proposés ou vous a-t-il été suggéré?

☐ Parmi plusieurs proposés par EDF/ES ☐ Suggéré par une connaissance/votre propre choix

C.2. Quelle a été l'importance pour vous des critères suivants dans le **choix du maître d'œuvre** ?

Classer les critères suivants de 1 à 5 (1 étant le critère le plus important).

- Sa maîtrise des techniques BBC / Qualité du travail : ________
- Son prix : ________
- Son ancienneté / sa notoriété : ________
- Connaissance du maître d'œuvre : ________
- Sa proximité : ________

C.3. Quelle a été l'importance pour vous des critères suivants dans le **choix des matériaux** ?

	Pas du tout important	Peu important	Assez important	Très important
• Leur performance / qualité	☐	☐	☐	☐
• Leur prix	☐	☐	☐	☐
• *Leur respect de l'environnement*	☐	☐	☐	☐

C.4. **Si** vous avez été conseillé pour le choix des matériaux, qui vous a conseillé ?

☐ EDF / ES
☐ Entreprises (corps de métier)
☐ Bureau d'étude thermique
☐ *Je n'ai pas été conseillé*
☐ Maître d'œuvre
☐ Connaissance
☐ *Autre :* ___________________________

D. SATISFACTION du programme « Je rénove BBC »

D.1.1. Etes-vous satisfait…

• du travail général de la maîtrise d'œuvre ?	☐ oui	☐ non
• du travail général des entreprises ?	☐ oui	☐ non
• du programme « Je rénove BBC » ?	☐ oui	☐ non
• du résultat final des travaux ?	☐ oui	☐ non

D.1.2. **Si** vous avez répondu **non** à l'un des points ci-dessus, pouvez-vous indiquer pourquoi ?

_______________________ ____

____

D.2. Habitiez-vous dans votre maison lors des travaux de rénovation ? ☐ oui ☐ non

D.3.1. Quel est le **nom du maître d'œuvre** qui a encadré l'ensemble de vos travaux de rénovation ?

____

D.3.2. Etes-vous satisfait de sa prestation ?	Pas du tout satisfait	Peu satisfait	Assez satisfait	Très satisfait
• Relation client-corps de métier :	☐	☐	☐	☐
• Qualité de la coordination en général :	☐	☐	☐	☐
• Coût total de la prestation :	☐	☐	☐	☐
• Adéquation devis-facture :	☐	☐	☐	☐
• Respect des délais de travaux :	☐	☐	☐	☐

3

E. CONSOMMATION D'ENERGIE avant et après les travaux de rénovation

E.1. CONSOMMATION D'ENERGIE **AVANT RENOVATION**

E.1.1. Indiquez votre **consommation d'électricité totale** indiquée sur une facture datant d'AVANT la rénovation :

____________kWh

E.1.2. Quelle est la **période** concernée par la facture utilisée ci-dessus ?

____

E.1.3. Complétez les informations suivantes et cochez le **système de chauffage** concerné AVANT RENOVATION **:**

	Système (cocher)	Unité (à titre indicatif)	Energie (à titre indicatif)	Période (MM/AA à MM/AA) ou (MM à MM)	Consom-mation	Unité	Sous-compteur? (cocher si oui)
	Gaz condensation	m^3	GAZ				
	Gaz atmosphérique	m^3	GAZ				
	Chaudière fioul	litres	FIOUL				
	Chaudière granulés	kg, t	GRANULES				
	Poêle à granulés	kg, t	GRANULES				
	Chaudière bois	stères	BOIS				
	Poêle à bois	stères	BOIS				
	Réseau de chaleur	kWh	EAU CHAUDE				
	Chaudière électrique	kWh	ELECTRIQUE				
	Radiateurs électrique	kWh	ELECTRIQUE				
	Pompe A Chaleur (PAC) air/eau	kWh	ELECTRIQUE				
	PAC eau/eau	kWh	ELECTRIQUE				
	PAC géothermie	kWh	ELECTRIQUE				
	Autre						

E.1.4. Quelle était l'ancienneté du système de chauffage AVANT rénovation ?

☐ 0-5 ans ☐ 6-10 ans ☐ 11-15 ans ☐ Plus de 15 ans : Pouvez-vous préciser ? _________

E.1.5. Complétez les informations suivantes et cochez le **système d'eau chaude sanitaire (ECS)** concerné AVANT RENOVATION **:**

	Système (cocher)	Unité (à titre indicatif)	Energie (à titre indicatif)	Période (MM/AA à MM/AA) ou (MM à MM)	Consom-mation	Unité	Sous-compteur? (cocher si oui)
	Chauffe-eau thermodynamique	kWh	ELECTRIQUE				
	Chauffe-eau électrique	kWh	ELECTRIQUE				
	Système Solaire (Panneau solaire)	m^3	EAU CHAUDE				
	Réseau de chaleur	kWh	EAU CHAUDE				
	Autre						

***REMARQUE* : Si vous avez un système entièrement électrique, répondez également à l'annexe s.v.p.**

E.2. CONSOMMATION D'ENERGIE **APRES RENOVATION**

E.2.1. Indiquez votre **consommation d'électricité totale** indiquée sur une facture datant d'APRES la rénovation :

___________kWh

E.2.2. Quelle est la **période** concernée par la facture utilisée ci-dessus ?

____

E.2.3. Avez-vous changé de système de chauffage lors de la rénovation ? ☐ oui ☐ non

E.2.4. Complétez les informations suivantes et cochez le **système de chauffage** concerné APRES RENOVATION **:**

	Système (cocher)	**Unité** (à titre indicatif)	**Energie** (à titre indicatif)	**Période** (MM/AA à MM/AA) ou (MM à MM)	**Consom-mation**	**Unité**	**Sous-compteur?** (cocher si oui)
	Gaz condensation	m^3	GAZ				
	Gaz atmosphérique	m^3	GAZ				
	Chaudière fioul	litres	FIOUL				
	Chaudière granulés	kg, t	GRANULES				
	Poêle à granulés	kg, t	GRANULES				
	Chaudière bois	stères	BOIS				
	Poêle à bois	stères	BOIS				
	Réseau de chaleur	kWh	EAU CHAUDE				
	Chaudière électrique	kWh	ELECTRIQUE				
	Radiateurs électrique	kWh	ELECTRIQUE				
	Pompe A Chaleur (PAC) air/eau	kWh	ELECTRIQUE				
	PAC eau/eau	kWh	ELECTRIQUE				
	PAC géothermie	kWh	ELECTRIQUE				
	Autre						

E.2.5. Avez-vous changé de **système d'eau chaude sanitaire (ECS)** lors de la rénovation ? ☐oui ☐non

E.2.6. Complétez les informations suivantes et cochez le **système d'eau chaude sanitaire (ECS)** concerné APRES RENOVATION **:**

	Système (cocher)	**Unité** (à titre indicatif)	**Energie** (à titre indicatif)	**Période** (MM/AA à MM/AA) ou (MM à MM)	**Consom-mation**	**Unité**	**Sous-compteur?** (cocher si oui)
	Chauffe-eau thermodynamique	kWh	ELECTRIQUE				
	Chauffe-eau électrique	kWh	ELECTRIQUE				
	Système Solaire (Panneau solaire)	m^3	EAU CHAUDE				
	Réseau de chaleur	kWh	EAU CHAUDE				
	Autre						

***REMARQUE* : Si vous avez un système entièrement électrique, répondez également à l'annexe s.v.p.**

5

F. HABITUDES avant et après rénovation

F.1.1. Quel type de contrôle de température possédiez-vous avant rénovation et quel type possédez- vous après rénovation ?

AVANT rénovation :
☐ Robinet thermostatique
☐ Thermostat d'ambiance (répondre à F.1.2.)
☐ Aucun
☐ Autre : ______________________________

APRES rénovation :
☐ Robinet thermostatique
☐ Thermostat d'ambiance (répondre à F.1.2.)
☐ Aucun
☐ Autre : ______________________________

F.1.2. **Si** vous aviez un **thermostat** avant rénovation ou en avez un maintenant après rénovation, dans quelle pièce se situait ou se situe-t-il ?

AVANT rénovation : ____
APRES rénovation : ____

F.2.1. A quelle température aviez-vous l'habitude de chauffer avant rénovation…

a. … en journée lorsque vous étiez dans la maison ? ______________°C
b. … lorsque vous n'étiez pas dans la maison ? ______________°C
c. … la nuit ? ______________°C
☐ *Je ne sais pas*

F.2.2. A quelle température avez-vous l'habitude de chauffer depuis la rénovation…

a. … en journée lorsque vous êtes dans la maison ? ______________°C
b. … lorsque vous n'êtes pas dans la maison ? ______________°C
c. … la nuit ? ______________°C
☐ *Je ne sais pas*

F.3.1.1. Y avait-il des pièces non utilisées dans votre maison avant rénovation ? ☐ oui ☐ non

F.3.1.2. **Si oui**, étaient-elles chauffées comme les autres pièces ? ☐ oui ☐ non

F.3.2.1. Y a-t-il des pièces non utilisées dans votre maison après rénovation ? ☐ oui ☐ non

F.3.2.2. **Si oui**, sont-elles chauffées comme les autres pièces ? ☐ oui ☐ non

F.4.1. Quel était environ votre temps d'occupation de la maison pendant une journée ordinaire en semaine **avant rénovation**? *Marquer les heures où la maison était occupée*

6h	7h	8h	9h	10h	11h	12h	13h	14h	15h
16h	17h	18h	19h	20h	21h	22h	23h	00h	

F.4.2. Quel est environ votre temps d'occupation de la maison pendant une journée ordinaire en semaine **depuis la rénovation**? *Marquer les heures où la maison est occupée*

6h	7h	8h	9h	10h	11h	12h	13h	14h	15h
16h	17h	18h	19h	20h	21h	22h	23h	00h	

6

F.5.1. Etiez-vous souvent dans la maison rénovée pendant le weekend **avant rénovation** ? ☐ oui ☐ non

F.5.2. Etes-vous souvent dans la maison rénovée pendant le weekend **après rénovation** ? ☐ oui ☐ non

F.6. En moyenne, combien de semaines par an êtes-vous absents de votre maison (vacances, …) ?

☐ moins d'1 semaine par an ☐ de 1 à 2 semaines par an
☐ de 2 à 3 semaines par an ☐ de 3 à 4 semaines par an
☐ plus d'1 mois par an : Pouvez-vous préciser ? ________________________________

F.7. Par rapport à avant la rénovation :

	Moins	Autant	Plus
• Ouverture des fenêtres :	☐	☐	☐
• Tendance à consommer de l'eau chaude :	☐	☐	☐
• Tendance à porter attention à la consommation d'énergie :	☐	☐	☐
• Soucieux des problèmes écologiques et environnementaux : *(p.ex. en réalisant des éco-gestes)*	☐	☐	☐

G. CONFORT avant et après rénovation

G.1. Sur un barême de 1 à 10, comment évalueriez-vous le **confort** à l'intérieur de votre maison AVANT rénovation ?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

G.2. Sur un barême de 1 à 10, comment évalueriez-vous le **confort** à l'intérieur de votre maison APRES rénovation ?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

G.3.1. Y avait-il des sources d'**inconfort** dans votre maison avant rénovation ? ☐ oui ☐ non

G.3.2. **Si oui**, à votre avis, par quoi était-il provoqué?

	Oui	Non
• Sensation de courant d'air	☐	☐
• Sensation de paroi froide	☐	☐
• Température intérieure trop basse en hiver	☐	☐
• Température intérieure trop élevée en été	☐	☐
• Manque de renouvellement de l'air	☐	☐
• Présence de poussière dans l'air	☐	☐
• Infiltration d'eau / moisissures	☐	☐

G.4.1. Y a-t-il encore des sources d'**inconfort** dans votre maison après rénovation ? ☐ oui ☐ non

G.4.2. **Si oui**, à votre avis, par quoi est-il provoqué?

	Oui	Non
• Sensation de courant d'air	☐	☐
• Sensation de paroi froide	☐	☐
• Température intérieure trop basse en hiver	☐	☐
• Température intérieure trop élevée en été	☐	☐
• Manque de renouvellement de l'air	☐	☐
• Présence de poussière dans l'air	☐	☐
• Infiltration d'eau / moisissures	☐	☐

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H. CLIENT

H.1. Veuillez s.v.p. indiquer vos nom et prénom :

NOM :____

Prénom :____

H.2. Vous êtes… ☐ un homme ☐ une femme

H.3. Situation familiale :

☐ En couple (marié(e), en concubinage, PACS, …) ☐ Divorcé(e)
☐ Célibataire ☐ Veuf/veuve

H.4. Combien de personnes vivent au quotidien dans la maison rénovée BBC ?

• Filles (0-5 ans) :	☐ 0	☐ 1	☐ 2	☐ 3 et plus
• Filles (6-9 ans) :	☐ 0	☐ 1	☐ 2	☐ 3 et plus
• Filles (10-17 ans) :	☐ 0	☐ 1	☐ 2	☐ 3 et plus
• Femmes (18 ans et plus) :	☐ 0	☐ 1	☐ 2	☐ 3 et plus
• Garçons (0-5 ans) :	☐ 0	☐ 1	☐ 2	☐ 3 et plus
• Garçons (6-9 ans) :	☐ 0	☐ 1	☐ 2	☐ 3 et plus
• Garçons (10-17 ans) :	☐ 0	☐ 1	☐ 2	☐ 3 et plus
• Hommes (18 ans et plus) :	☐ 0	☐ 1	☐ 2	☐ 3 et plus

H.5. Y a-t-il le même nombre de personnes vivant au quotidien dans la maison avant et après rénovation ?

☐ oui ☐ non, il y a **plus** de personnes ☐ non, il y a **moins** de personnes

H.6. Dans quelle tranche d'âge vous et votre conjoint vous situez-vous ?

Vous	Votre conjoint		Vous	Votre conjoint	
☐	☐	18-24 ans	☐	☐	45-59 ans
☐	☐	25-34 ans	☐	☐	60-69 ans
☐	☐	35-44 ans	☐	☐	70 ans et plus

H.7. Quelle profession vous et votre conjoint exercez-vous ?

Vous	Votre conjoint	
☐	☐	Agriculteur exploitant
☐	☐	Artisan, commerçant, chef d'entreprise
☐	☐	Cadre, profession libérale/ intellectuelle supérieure
☐	☐	Profession intermédiaire
☐	☐	Employé
☐	☐	Ouvrier
☐	☐	Retraité
☐	☐	Au foyer (assistante maternelle, travail à domicile, …)
☐	☐	Sans activité professionnelle, étudiant(e)
☐	☐	*Autre* :_______________________________

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H.8. Quel est votre niveau d'étude, ainsi que celui de votre conjoint ?

Vous	Votre conjoint		Vous	Votre conjoint	
☐	☐	Sans diplôme	☐	☐	Bac+1, +2
☐	☐	Brevet, CAP, BEP, certificat d'étude	☐	☐	Bac+3, +4
☐	☐	Baccalauréat	☐	☐	Bac+5 et +

H.9. Le logement que vous avez rénové dans le cadre du programme « Je rénove BBC » est…

☐ votre résidence principale
☐ votre résidence secondaire
☐ une résidence que vous louez
☐ *autre* : ___________________________

H.10. Vous êtes…

☐ **propriétaire** du logement BBC
☐ **locataire** du logement BBC

I. RESSOURCES DU MENAGE

I.1.1. Quelles sont les ressources de l'ensemble de votre ménage ?

____

I.1.2. **Si** vous ne souhaitez ou ne pouvez pas donner un montant précis des ressources nettes de l'ensemble du ménage, à combien environ les estimez-vous pour un mois ordinaire ?

☐ jusqu'à 1000€
☐ entre 1000€ et 2000€
☐ entre 2000€ et 3000€
☐ entre 3000€ et 4000€
☐ entre 4000€ et 5000€
☐ entre 5000€ et 6000€
☐ entre 6000€ et 7000€
☐ entre 7000€ et 8000€
☐ entre 8000€ et 9000€
☐ entre 9000€ et 10000€
☐ plus de 10000€

J. REMARQUES éventuelles

J.1. Avez-vous des suggestions d'amélioration du programme « Je rénove BBC » ou des remarques sur le programme ?

____

____

____

____

____

____

____

____

9

K. ANNEXE – Appareils électroménagers

K.1. Complétez les informations correspondantes aux **appareils électroménagers** que vous possédez :

Appareils électroménagers (cocher)		**Quantité**	**Classe énergétique** (A++, A+, A, B, C, D, E, F, G)	**Capacité** [W]	**Temps d'utilisation pendant une journée** [h]	**Âge approximatif de l'appareil** [a]
	Réfrigérateur					
	Congélateur					
	Lave-vaisselle					
	Cuisinière/four					
	Lave-linge					
	Sèche-linge					
	Equipement de bureau (PC, ordinateur portable)					
	Electronique de loisirs (TV, …)					
	Autre					

K.2. Complétez les informations correspondantes aux **équipements d'éclairage** que vous possédez :

Type (cocher)		**Quantité**	**Classe énergétique** (A++, A+, A, B, C, D, E, F, G)	**Capacité** [W]	**Temps d'utilisation pendant une journée** [h]	**Âge approximatif de l'appareil** [a]
	Ampoule électrique					
	Lampe fluorescente					
	Tube fluorescent (néon)					
	Ampoule à basse consommation					
	Lampe halogène					
	Autre					

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A.3 Conventional data in energy audits: the *TH-C-E ex* software

Table A.11: Conventional data used for generating consumption predictions in case of a dwelling equipped with a mechanical ventilation system

Data used	Additional information
Occupancy time	16h/day during week-days 24h/day during weekend
Temperature	19°C temperature reduction for less than 48h: 16°C temperature reduction for more than 48h: 7°C
Vacation time (where same temperature than during weekends is taken into account)	February: 15 days ; April: 15 days ; July: 31 days ; August: 31 days ; November: 8 days ; December: 15 days
Ventilation (takes into account the flow reduction (Coeff. rdb=1) because a HygroB ventilation system is installed)	24h/7
Artificial lighting (except outdoor lighting, parking lot lighting, emergency lighting and lighting to highlight objects) at $2W/m^2$	5h/day during week-days, 15h/day during weekend
Domestic hot water (DHW) needs and distribution	Hourly energy requirements for (DHW), Gross DHW distribution losses, Recovered losses from DHW distribution, Consumption of DHW distribution aids
Heat loss and input	Losses through the walls, losses by air change, Solar and internal supplies
Heat and cold emission	Spatial and temporal variations of the set-point temperature, Losses at the back of transmitters integrated in the walls
Distribution of heat and cooling: hydraulic networks and refrigerant fluid	Distribution losses and consumption for hydraulic networks, refrigerant distribution, Heat transfer between rooms
Air treatment and distribution	
Thermal behavior of a group and coupling with the system broadcasting and distribution	
Energy required for the production of energy for the heating, cooling and DHW	
Generation, storage and transfer of heat, cold for the heating, cooling and DHW	
Solar photovoltaic system	

A.4 Actual *ex-post* energy consumption

Households' actual (E^A) and predicted (E^P) energy consumption, calculated in primary energy (PE) are measured in $kWh_{PE}/m{\cdot}year$. The households' total actual and predicted energy (E_{tot}) includes four components in Alsace: heating, sanitary hot water, lighting and auxiliaries. Billing data of actual energy consumption are expressed in final energy units. However, the predicted energy consumption is expressed in primary energy units. In order to compare both consumption, we need to convert the actual energy consumption data into primary energy. We also need to correct consumption according to the geographic position of the building and heating period, to standardize consumption among all the households. While no data on the share of electricity of total consumption is available at national level, we use a proxy of 21% of total energy consumption based on a study conducted from the Local Agency in the French department Indre-et-Loire. The share of electricity of total consumption corresponds mainly to lighting and auxiliaries ($E_{lighting+auxiliaries}$). Actual energy consumption can be converted in primary energy as follows:

$$E^A = \frac{E_{tot} - E_{lighting+auxiliaries}}{SHONRT} \cdot \frac{HDD_{30years}}{HDD_{period}} \cdot c + \frac{E_{lighting+auxiliaries}}{SHONRT} \cdot c,$$

with

$HDD_{30years}$: annual heating degree days for a period of 30 years, in $°C.year$,

HDD_{period}: heating degree days for the consumption period, in $°C.year$,

$\frac{HDD_{30years}}{HDD_{period}}$: climate correction per period by geographic location,

$SHON\,RT$: thermal surface[1], in m^2,

c: transformation coefficient from final to primary energy consumption[2].

The heating degree days (HDD) are calculated monthly by the national weather service *Météo France.*

[1]For further information:
https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000022959397\&categorieLien=id

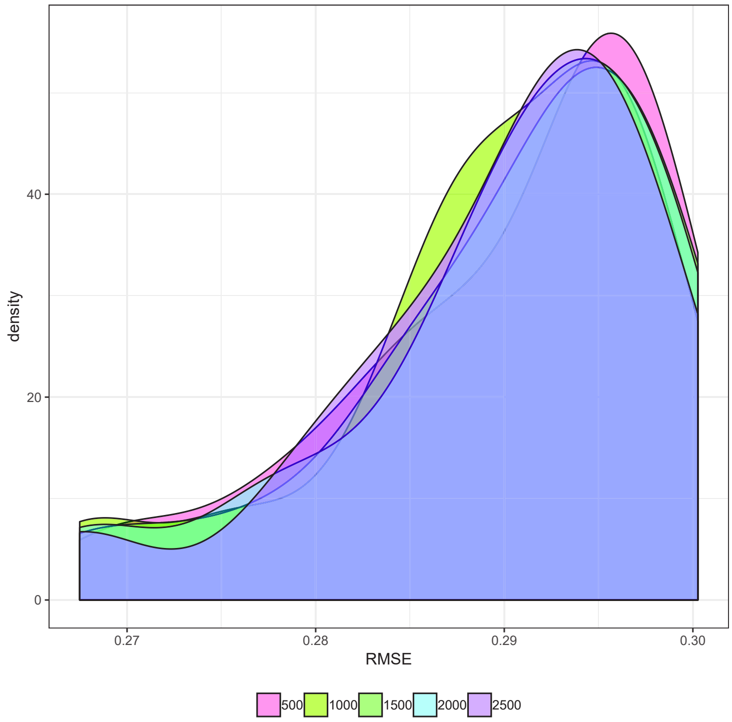
[2]2.58 for electricity, 1 for gas, fuel and coal, 0.6 for wood, 0 for solar energy

A.5 Variable Definitions

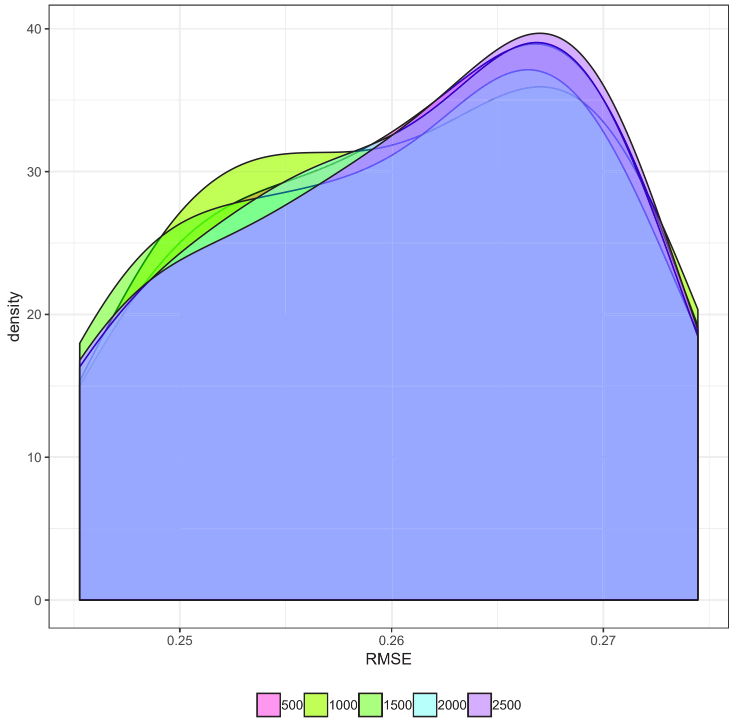
Table A.12: Definition of the variables used in the analysis

Variables	Definitions	Nature
	Ex-post energy consumption	
Y	Energy Savings (Ratio of real and predicted energy consumption)	continuous
	Technical variables	
SYST	*Ex-post* heating system (1 if conventional (≡ reference level), 2 if mixed, 3 if renewable energy)	category
THERM	Presence of room thermostat in the dwelling *ex-post* (1 if yes, 0 otherwise)	dummy
	Socio-demographic variables	
HSIZE	Number of inhabitants in the dwelling	continuous
CHILD	Presence of children in the dwelling (1 if yes, 0 otherwise)	dummy
AGE	Respondent is more than 45 years old (1 if yes, 0 otherwise)	dummy
EDUC	Bachelor's degree and above (1 if yes, 0 otherwise)	dummy
PROF	Liberal profession or top manager (1 if yes, 0 otherwise)	dummy
REV	Net monthly household income of at least 4000 EUR (1 if yes, 0 otherwise)	dummy
	Energy related behavior and determinants of behavior	
BEH_WO	Window opening habits with respect to the *ex-ante* situation (1 if less, 2 if equally (≡ reference level), 3 if more)	category
BEH_ENV	Level of environmental concern with respect to the *ex-ante* situation (1 if more, 0 otherwise)	dummy
BEH_CONS	Tendency to pay attention to energy consumption with respect to the *ex-ante* situation (1 if less, 0 if equally)	dummy
TEMP.N	Household's temperature setting gap at night with the recommended $19°C$ (0 if heated at $19°C$)	continuous
TEMP.D	Household's temperature setting gap during the day with the recommended $19°C$ (0 if heated at $19°C$)	continuous
M.ECOLO	Renovation motivation: Have an environmental friendly dwelling (1 if important or very important, 0 otherwise)	dummy
M.ECON.NRJ	Renovation motivation: Save energy (1 if not important at all, 2 if not important, 3 if important, 4 if very important)	continuous
M.ECON.FIN	Renovation motivation: Save money (1 if not important at all, 2 if not important, 3 if important, 4 if very important)	continuous
OCCUP	Number of hours of occupation per day in a weekday	continuous
VACATION	4 weeks or more of absence per year	dummy
COMFORT	Perception of comfort after renovation (from 1 to 10, where 0 means 'no comfort at all', and 10 means 'very high comfort')	continuous
ROOMS	Presence of unheated rooms in the dwelling (1 if yes, 0 otherwise)	dummy

A.6 Tuning Plots

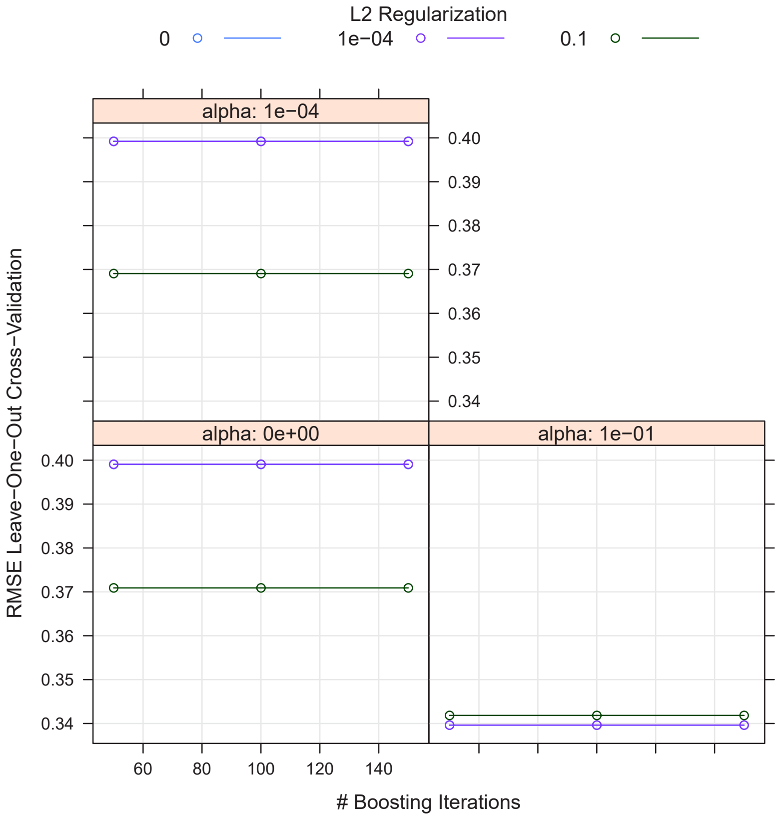


(a) Net Losing Energy Savings

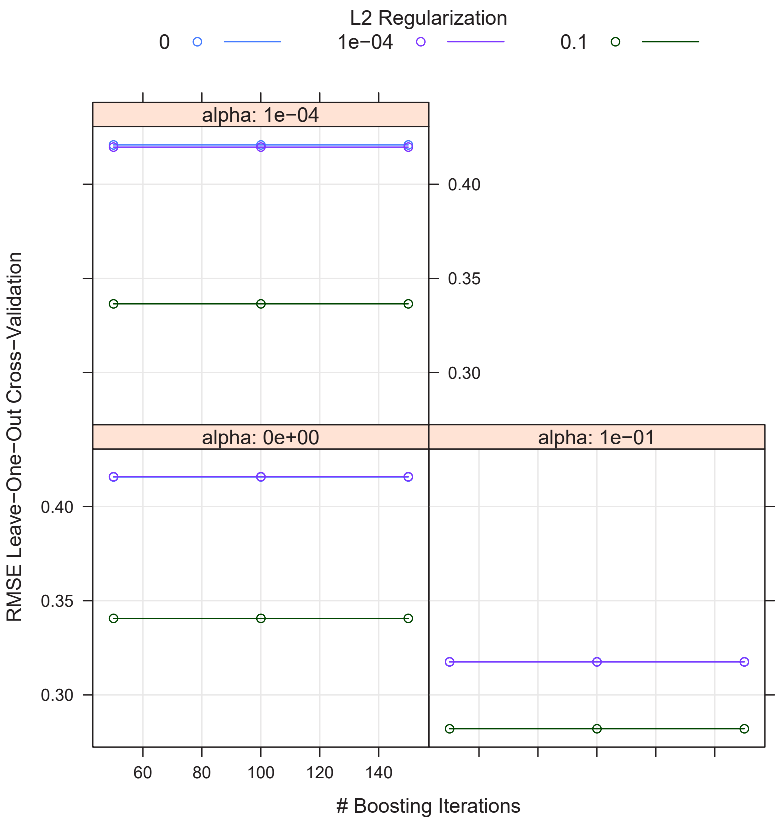


(b) Net Gaining Energy Savings

Figure A.1: Random Forest Model Performance with a Sequence Number of Trees

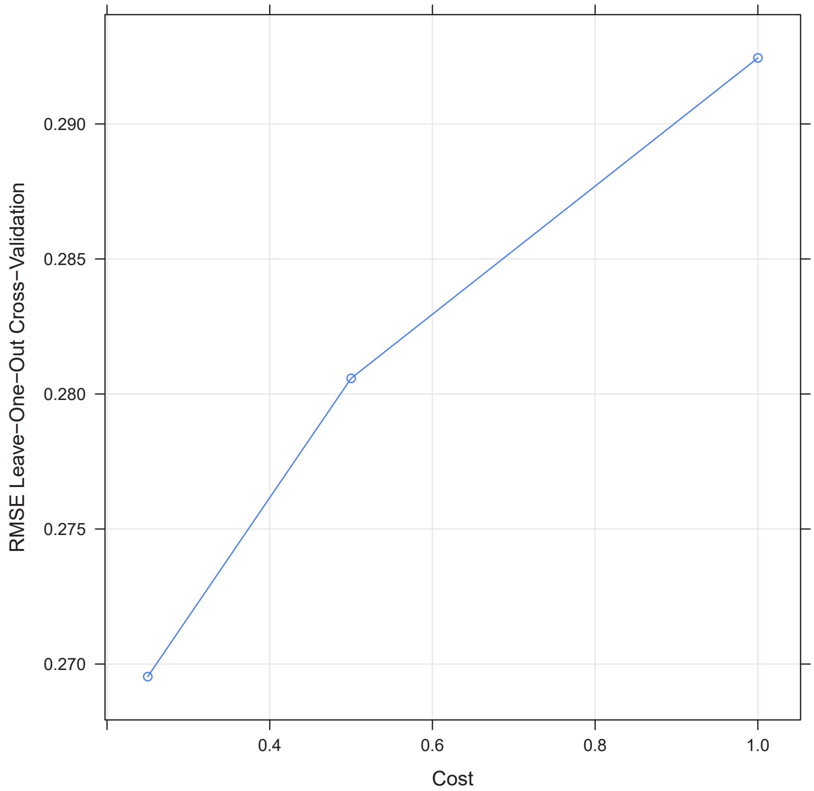


(a) Net Losing Energy Savings

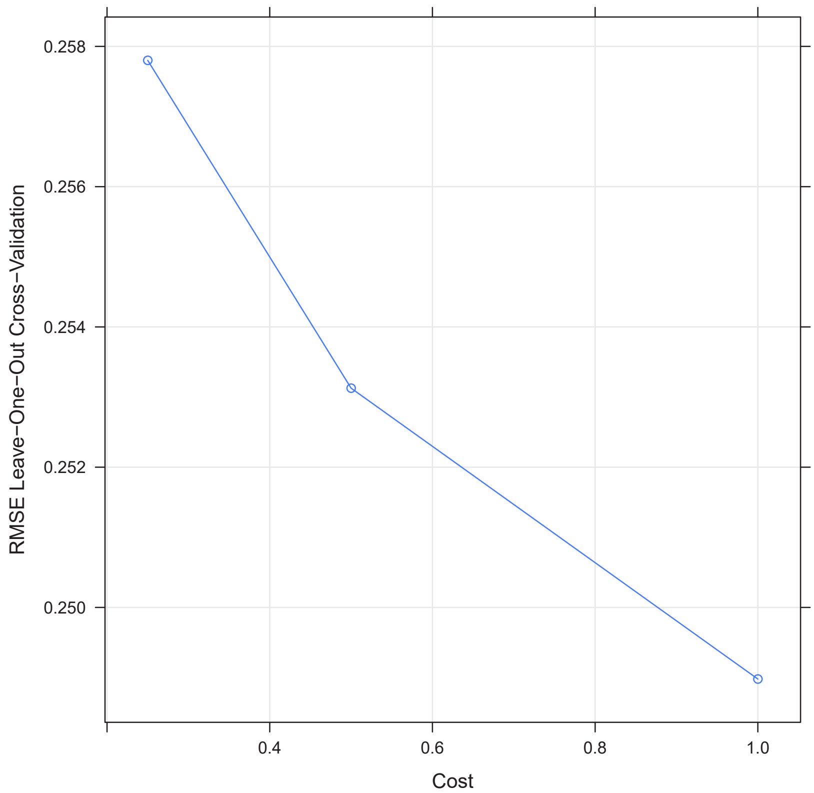


(b) Net Gaining Energy Savings

Figure A.2: Gradient Boost Tree Model Performance



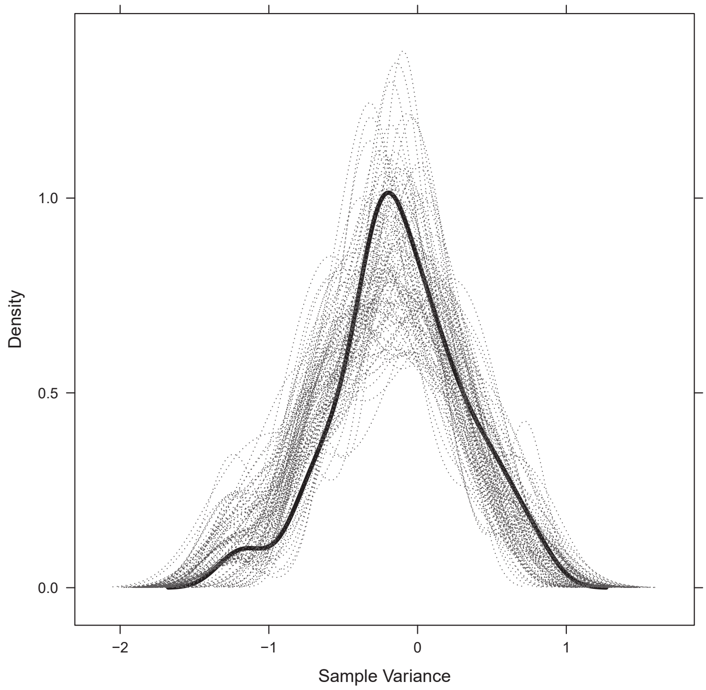
(a) Net Losing Energy Savings



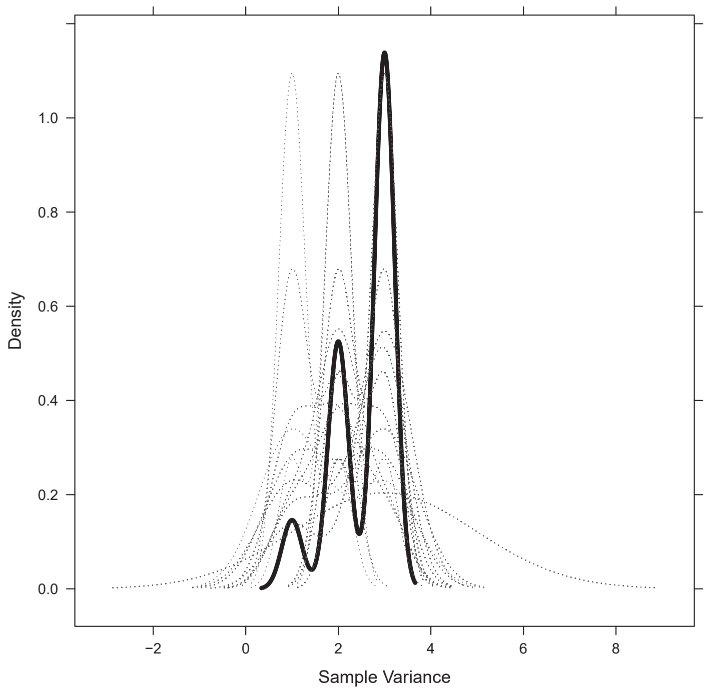
(b) Net Gaining Energy Savings

Figure A.3: Support Vector Machine Model Performance

A.7 Missing values imputation

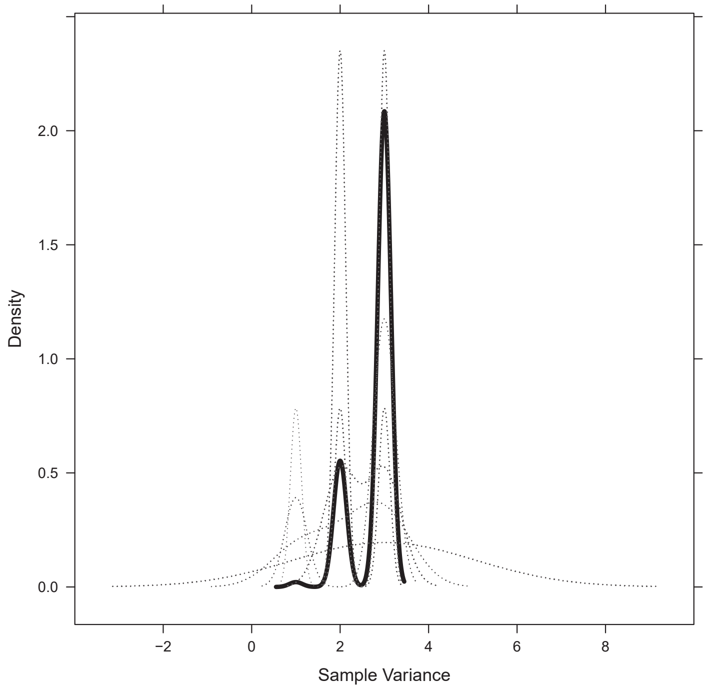


(a) Energy Performance Gap

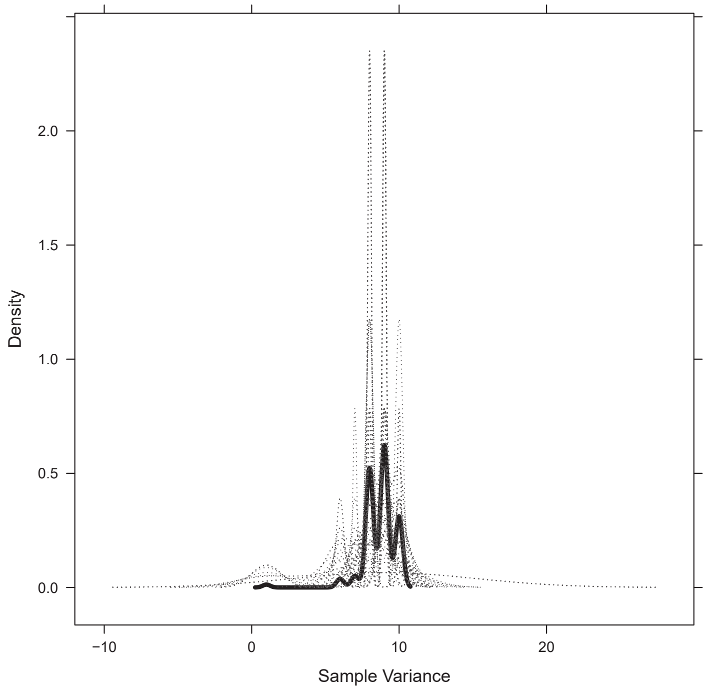


(b) Motivation to Save Energy Costs

Figure A.4: Distribution of original and imputed values (part 1)

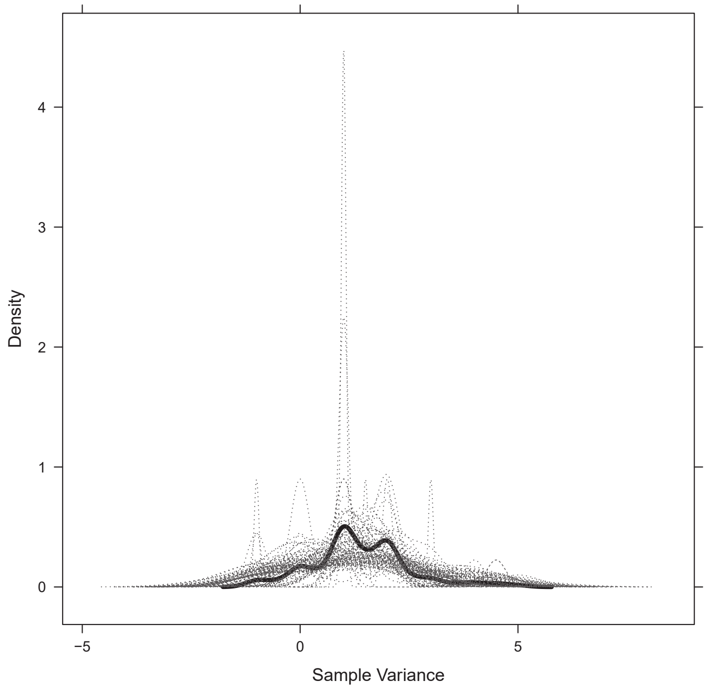


(c) Motivation to Reduce Energy Consumption

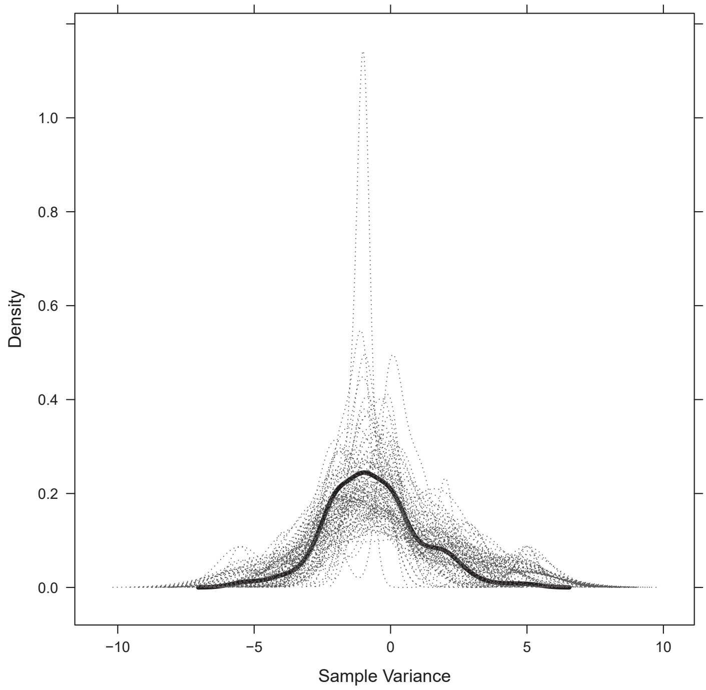


(d) Perceived Comfort

Figure A.4: Distribution of original and imputed values (part 2)

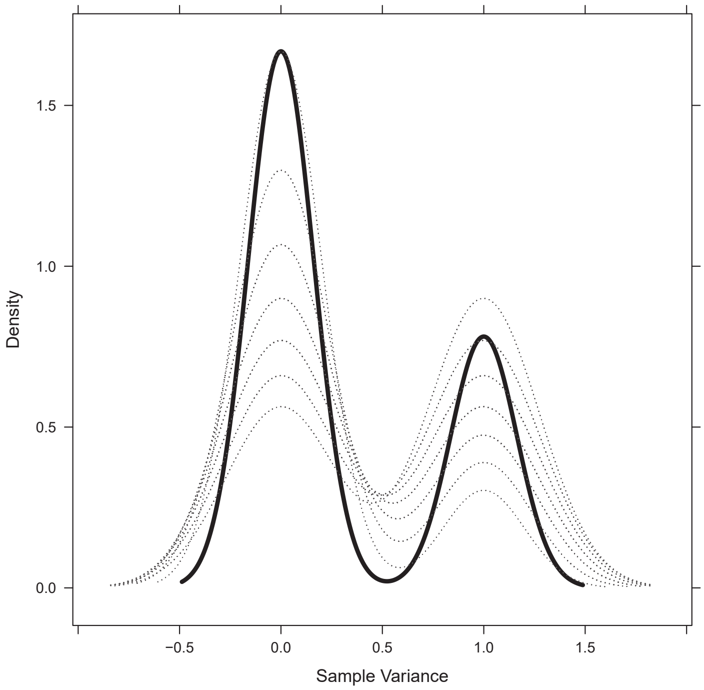


(e) Temperature Setting During Day

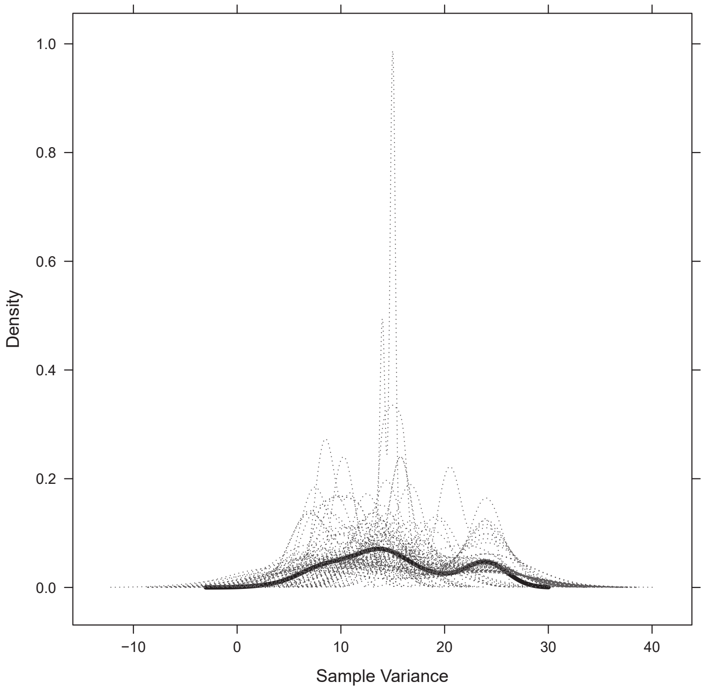


(f) Temperature Setting at Night

Figure A.4: Distribution of original and imputed values (part 3)

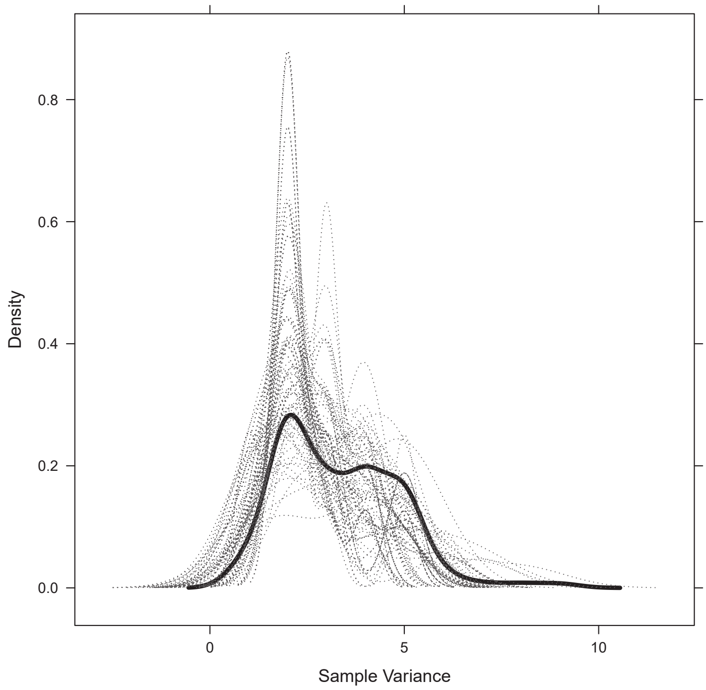


(g) Additional Rooms Heated



(h) Hours of Occupation

Figure A.4: Distribution of original and imputed values (part 4)



(i) Household Size

Figure A.4: Distribution of original and imputed values (part 5)

A.8 Statistical Tests

Table A.13: Comparison of Group Differences Using Non-Parametric and Parametric Statistical Tests

Cognitive Bias	Mann Whitney U		Mood Median		Student's t-test	
			Net Losing Energy Savings			
Status Quo	$W = 98$	$p_{\text{Value}} = 0.463$	$Z = -.147$	$p_{\text{Value}} = 0.883$	$t = -1.105$	$p_{\text{Value}} = 0.278$
Optimism	$W = 45$	$p_{\text{Value}} = 0.444$	$Z = -.178$	$p_{\text{Value}} = 0.859$	$t = 0.608$	$p_{\text{Value}} = 0.650$
Attitude-Behavior Gap	$W = 136$	$p_{\text{Value}} = 0.491$	$Z = -.160$	$p_{\text{Value}} = 0.873$	$t = 0.323$	$p_{\text{Value}} = 0.749$
Intention-Behavior Gap	$W = 42$	$p_{\text{Value}} = 0.760$	$Z = -.175$	$p_{\text{Value}} = 0.861$	$t = -0.096$	$p_{\text{Value}} = 0.925$
			Net Gaining Energy Savings			
Status Quo	$W = 354$	$p_{\text{Value}} = 0.666$	$Z = 0.000$	$p_{\text{Value}} = 1.000$	$t = 0.046$	$p_{\text{Value}} = 0.963$
Optimism	$W = 67$	$p_{\text{Value}} = 0.569$	$Z = 0.000$	$p_{\text{Value}} = 1.000$	$t = -0.542$	$p_{\text{Value}} = 0.637$
Attitude-Behavior Gap	$W = 375$	$p_{\text{Value}} = 0.818$	$Z = 0.000$	$p_{\text{Value}} = 1.000$	$t = -0.385$	$p_{\text{Value}} = 0.702$
Intention-Behavior Gap	$W = 113$	$p_{\text{Value}} = 0.787$	$Z = -.414$	$p_{\text{Value}} = 0.678$	$t = 0.359$	$p_{\text{Value}} = 0.741$

Non-Parametric Tests: Mann Whithney U and Mood Median ; *Parametric Test*: Student's t-test

A.9 Regression Results

A.9.1 Status quo bias

Table A.14: Status Quo Bias - Regression results for Net Losing Energy Savings

Variable	**Coefficient**	**SE**	**Lower**	**Upper**	**Model**
Status Quo	0.203	0.164	-0.066	0.472	Without Imputation
BEH.WO.less	0.050	0.095	-0.106	0.206	Without Imputation
BEH.WO.more	-0.034	0.179	-0.329	0.261	Without Imputation
TEMP.N	0.031	0.029	-0.017	0.078	Without Imputation
HSIZE	0.028	0.041	-0.040	0.095	Without Imputation
Status Quo	0.237	0.097	0.076	0.397	With Imputation
BEH.WO.less	0.058	0.077	-0.068	0.185	With Imputation
BEH.WO.more	-0.001	0.173	-0.285	0.283	With Imputation
TEMP.N	0.031	0.024	-0.009	0.071	With Imputation
HSIZE	0.010	0.026	-0.033	0.054	With Imputation

Table A.15: Status Quo Bias - Regression results for Net Gaining Energy Savings

Variable	**Coefficient**	**SE**	**Lower**	**Upper**	**Model**
Status Quo	-1.244	0.485	-2.194	-0.294	Without Imputation
BEH.WO.Less	0.083	0.073	-0.061	0.227	Without Imputation
BEH.WO.More	0.099	0.116	-0.129	0.327	Without Imputation
TEMP.N	0.020	0.027	-0.032	0.073	Without Imputation
TEMP.D	0.023	0.054	-0.084	0.129	Without Imputation
M.ECON.NRJ	0.188	0.136	-0.078	0.454	Without Imputation
COMFORT	0.034	0.031	-0.028	0.096	Without Imputation
Status Quo	-1.041	0.392	-1.810	-0.273	With Imputation
BEH.WO.Less	0.008	0.078	-0.144	0.160	With Imputation
BEH.WO.More	0.089	0.112	-0.131	0.308	With Imputation
TEMP.N	0.003	0.025	-0.047	0.052	With Imputation
TEMP.D	-0.007	0.052	-0.109	0.095	With Imputation
M.ECON.NRJ	0.114	0.115	-0.112	0.339	With Imputation
COMFORT	0.038	0.029	-0.019	0.095	With Imputation

A.9.2 Optimism bias

Table A.16: Optimism Bias - Regression results for Net Losing Energy Savings

Variable	Coefficient	SE	Lower	Upper	Model
BEH.CONS.Same	0.124	0.123	-0.077	0.326	Without Imputation
BEH.CONS.Less	1.488	0.738	0.274	2.702	Without Imputation
TEMP.N	0.024	0.027	-0.020	0.069	Without Imputation
HSIZE	0.053	0.035	-0.005	0.111	Without Imputation
Interaction	-0.436	0.047	-0.513	-0.358	Without Imputation
BEH.CONS.Same	0.261	0.058	0.166	0.356	With Imputation
BEH.CONS.Less	0.459	0.146	0.219	0.698	With Imputation
TEMP.N	0.032	0.014	0.009	0.055	With Imputation
HSIZE	0.011	0.015	-0.014	0.036	With Imputation
Interaction	-0.135	0.056	-0.227	-0.044	With Imputation

Table A.17: Optimism Bias - Regression results for Net Gaining Energy Savings

Variable	Coefficient	SE	Lower	Upper	Model
BEH.CONS.Same	-1.401	0.505	-2.391	-0.411	Without Imputation
BEH.CONS.Less	0.009	0.252	-0.485	0.503	Without Imputation
TEMP.N	0.017	0.025	-0.032	0.066	Without Imputation
TEMP.D	0.028	0.048	-0.067	0.122	Without Imputation
M.ECON.NRJ	0.263	0.145	-0.020	0.546	Without Imputation
COMFORT	0.031	0.031	-0.030	0.092	Without Imputation
Interaction	0.257	0.060	0.140	0.373	Without Imputation
BEH.CONS.Same	-1.120	0.406	-1.915	-0.325	With Imputation
BEH.CONS.Less	-0.036	0.245	-0.515	0.443	With Imputation
TEMP.N	0.004	0.025	-0.045	0.053	With Imputation
TEMP.D	0.005	0.051	-0.096	0.106	With Imputation
M.ECON.NRJ	0.136	0.121	-0.100	0.373	With Imputation
COMFORT	0.040	0.029	-0.017	0.096	With Imputation
Interaction	0.049	0.136	-0.217	0.316	With Imputation

A.9.3 Attitude-Behaviour gap

Table A.18: Attitude-Behaviour Gap - Regression results for Net Losing Energy Savings

Variable	Coefficient	SE	Lower	Upper	Model
ENV.Low	0.194	0.410	-0.480	0.868	Without Imputation
ENV.High	0.100	0.247	-0.307	0.507	Without Imputation
TEMP.N	0.030	0.106	-0.144	0.205	Without Imputation
HSIZE	0.030	0.081	-0.103	0.164	Without Imputation
ENV.Low	0.243	0.129	0.031	0.455	With Imputation
ENV.High	0.076	0.081	-0.057	0.208	With Imputation
TEMP.N	0.034	0.019	0.004	0.065	With Imputation
HSIZE	0.014	0.032	-0.039	0.067	With Imputation

Table A.19: Attitude-Behaviour Gap - Regression results for Net Gaining Energy Savings

Variable	Coefficient	SE	Lower	Upper	Model
ENV.Low	-1.282	0.832	-2.650	0.087	Without Imputation
ENV.High	-0.056	0.158	-0.317	0.204	Without Imputation
TEMP.N	0.021	0.072	-0.098	0.139	Without Imputation
TEMP.D	0.025	0.109	-0.154	0.203	Without Imputation
M.ECON.NRJ	0.221	0.173	-0.065	0.506	Without Imputation
COMFORT	0.034	0.067	-0.077	0.145	Without Imputation
ENV.Low	-1.063	0.381	-1.690	-0.437	With Imputation
ENV.High	-0.063	0.077	-0.190	0.064	With Imputation
TEMP.N	0.004	0.024	-0.037	0.044	With Imputation
TEMP.D	-0.004	0.046	-0.080	0.072	With Imputation
M.ECON.NRJ	0.124	0.109	-0.054	0.303	With Imputation
COMFORT	0.040	0.029	-0.007	0.088	With Imputation

A.9.4 Intention-Behaviour gap

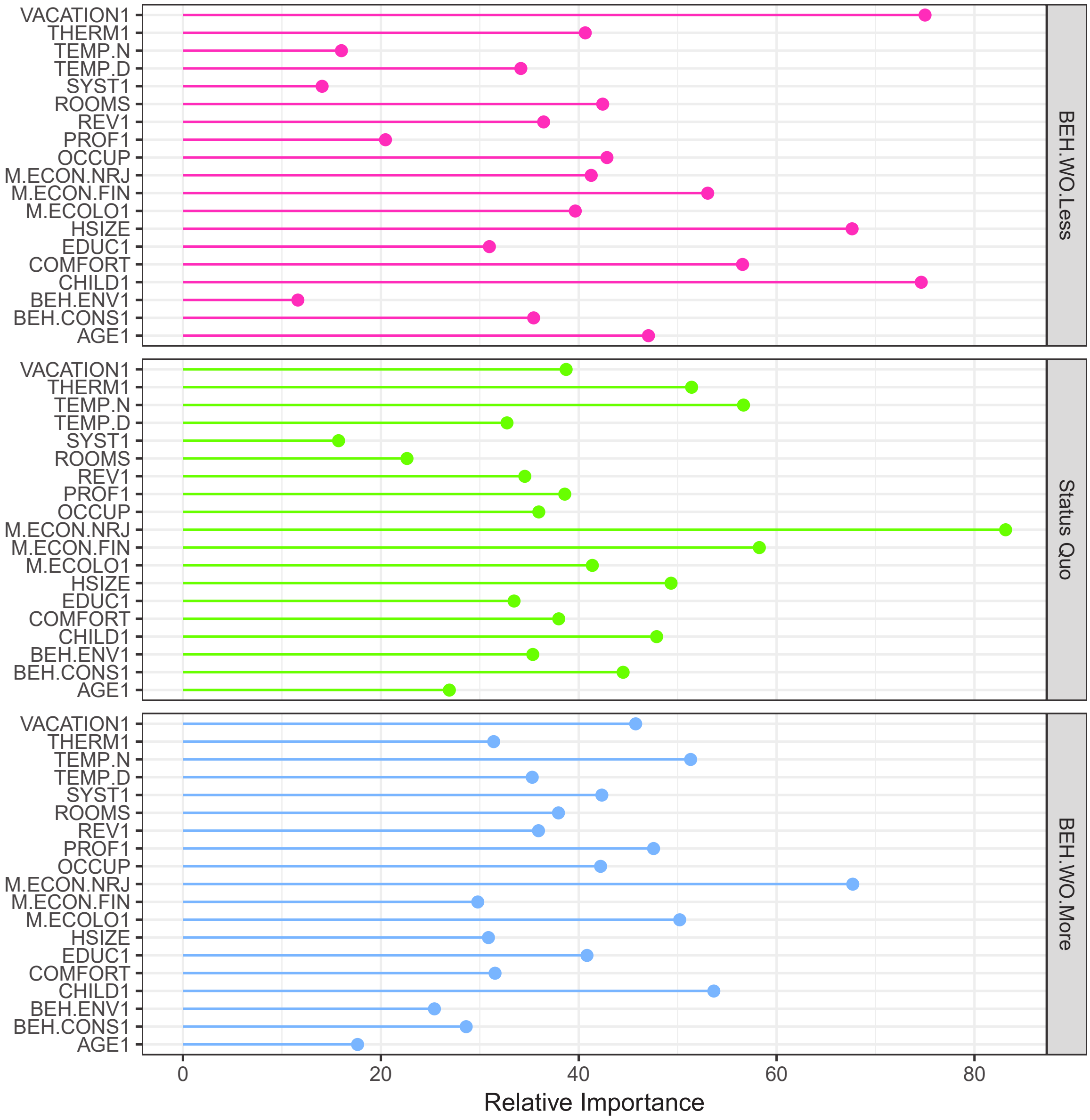
Table A.20: Intention-Behaviour Gap - Regression results for Net Losing Energy Savings

Variable	Coefficient	SE	Lower	Upper	Model
Non-Ecolo	0.551	0.863	-0.869	1.971	Without Imputation
Ecolo	-0.263	0.797	-1.574	1.048	Without Imputation
EDUC	-0.271	0.374	-0.886	0.344	Without Imputation
TEMP.N	0.014	0.167	-0.261	0.288	Without Imputation
HSIZE	0.018	0.087	-0.125	0.160	Without Imputation
Interaction	0.295	0.365	-0.305	0.894	Without Imputation
Non-Ecolo	0.545	0.082	0.409	0.680	With Imputation
Ecolo	-0.148	0.029	-0.195	-0.100	With Imputation
EDUC	-0.166	0.053	-0.253	-0.080	With Imputation
TEMP.N	0.039	0.014	0.016	0.061	With Imputation
HSIZE	-0.013	0.019	-0.044	0.017	With Imputation
Interaction	0.087	0.052	0.001	0.173	With Imputation

Table A.21: Intention-Behaviour Gap - Regression results for Net Gaining Energy Savings

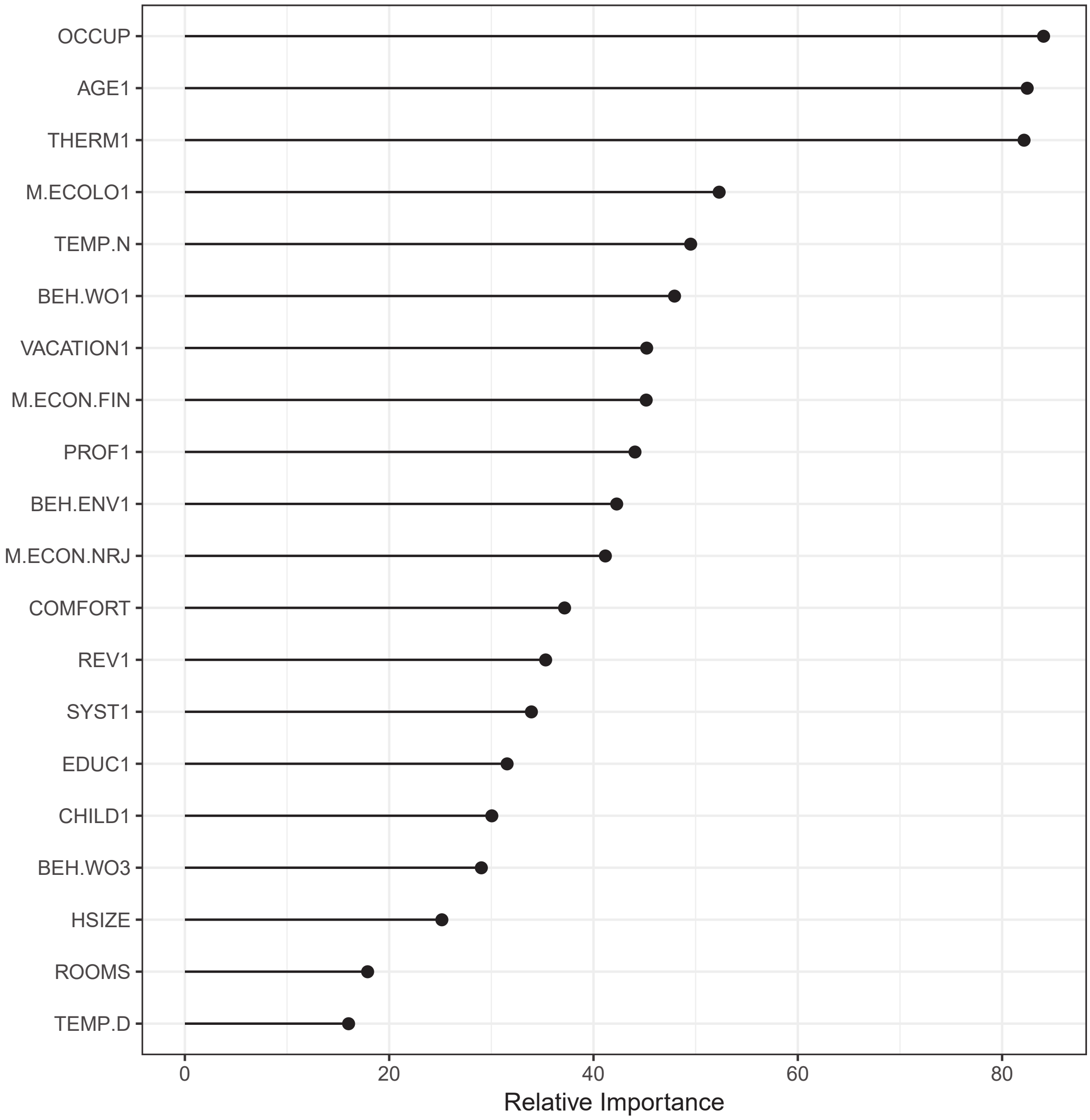
Variable	Coefficient	SE	Lower	Upper	Model
Non-Ecolo	-1.378	0.902	-3.145	0.389	Without Imputation
Ecolo	0.115	0.296	-0.465	0.696	Without Imputation
EDUC	0.155	0.264	-0.362	0.671	Without Imputation
TEMP.N	0.026	0.084	-0.139	0.190	Without Imputation
TEMP.D	0.005	0.126	-0.242	0.251	Without Imputation
M.ECON.NRJ	0.179	0.179	-0.172	0.530	Without Imputation
COMFORT	0.039	0.100	-0.157	0.236	Without Imputation
Interaction	-0.028	0.161	-0.343	0.286	Without Imputation
Non-Ecolo	-1.158	0.465	-2.069	-0.247	With Imputation
Ecolo	0.117	0.195	-0.265	0.498	With Imputation
EDUC	0.167	0.095	-0.020	0.355	With Imputation
TEMP.N	0.002	0.025	-0.048	0.052	With Imputation
TEMP.D	0.005	0.050	-0.093	0.102	With Imputation
M.ECON.NRJ	0.114	0.119	-0.120	0.347	With Imputation
COMFORT	0.032	0.032	-0.031	0.095	With Imputation
Interaction	-0.136	0.092	-0.316	0.044	With Imputation

A.10 Feature ranking



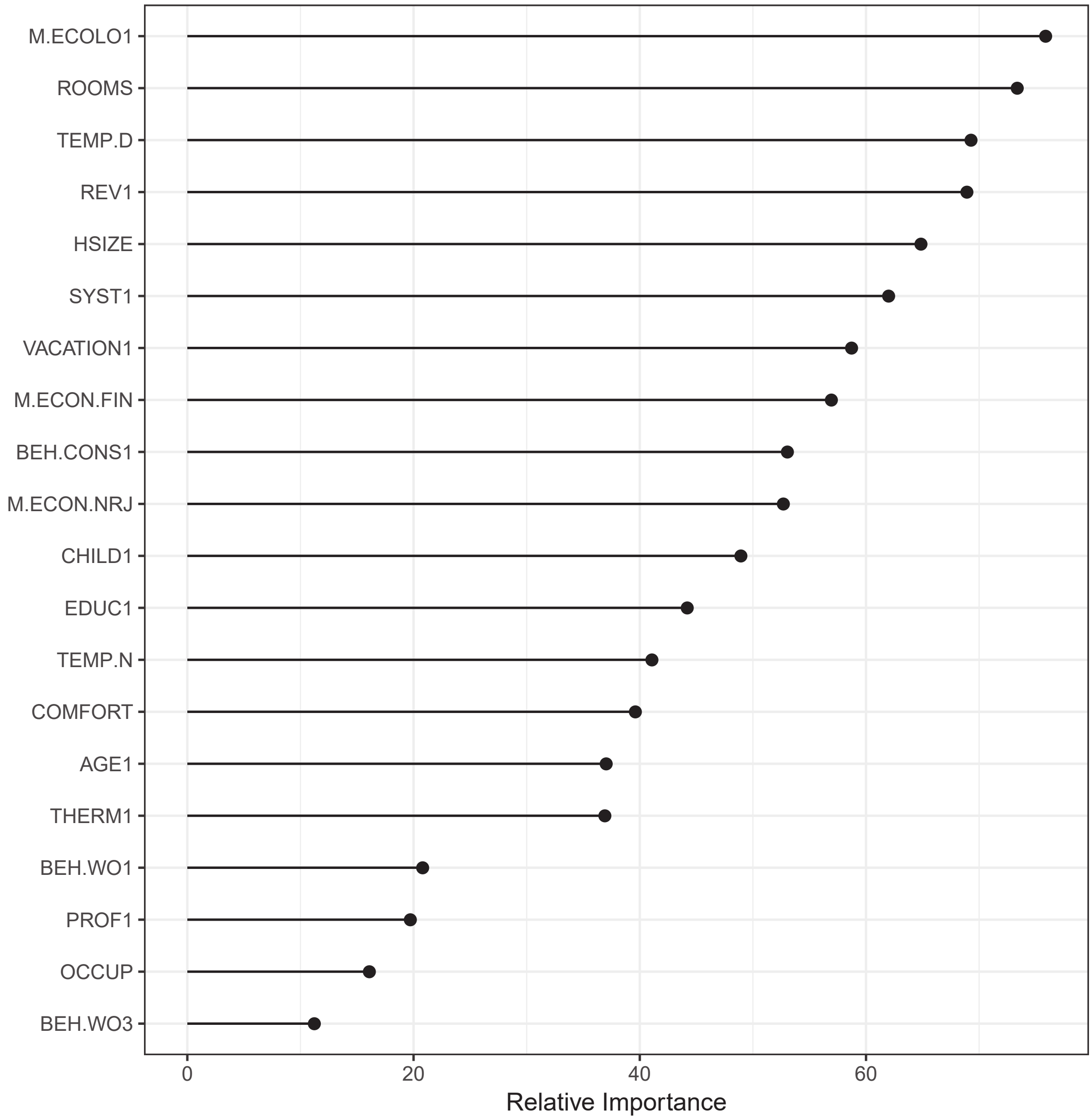
Measurement variable: 'declaring to open its windows as often as before renovation'.

Figure A.5: Relative Importance of Features: Status Quo Bias



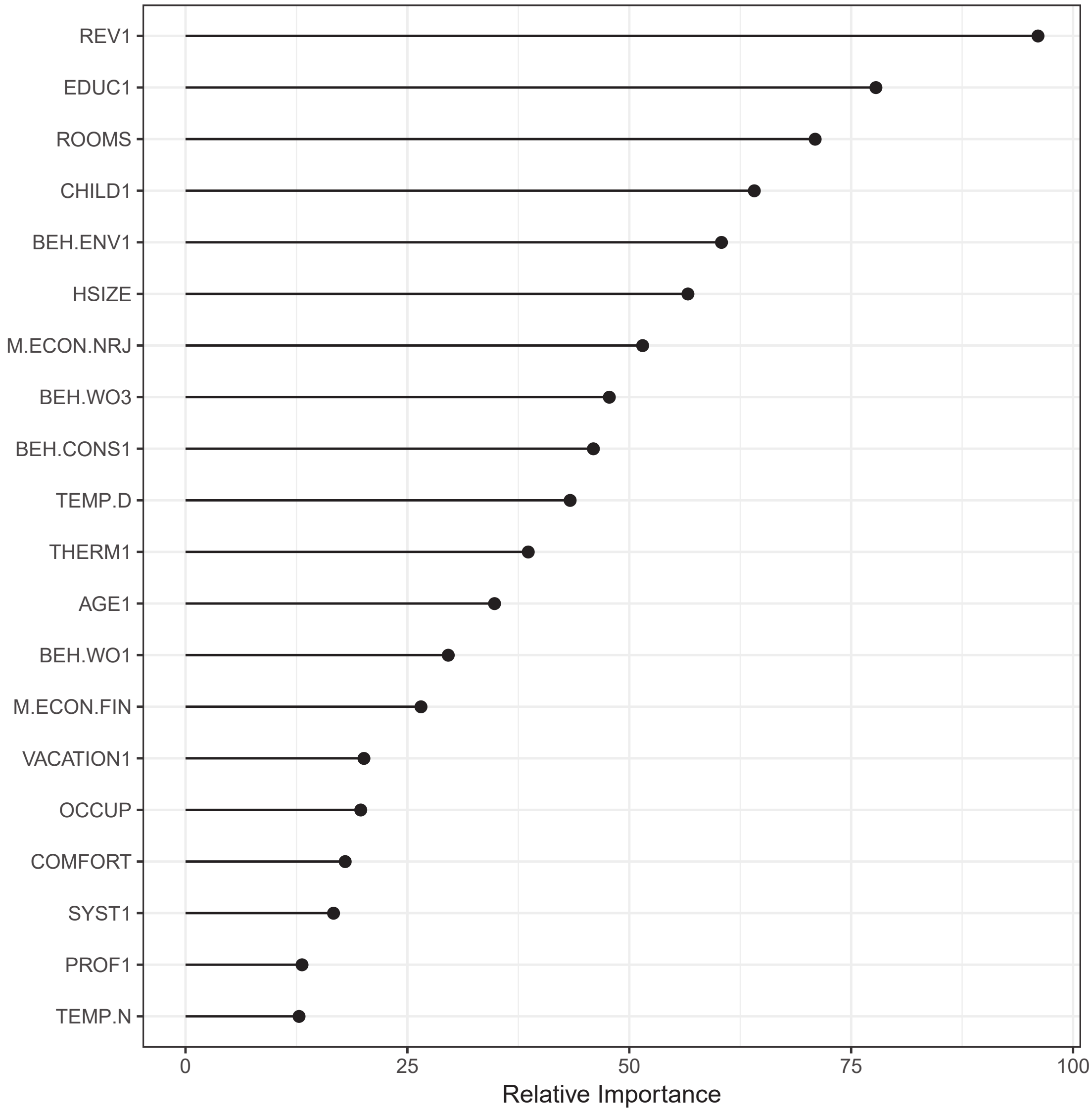
Measurement variable: 'declaring to pay less attention to its energy consumption than before renovation'.

Figure A.6: Relative Importance of Features: Optimism Bias



Measurement variable: ‘declaring to be more concerned about ecological and environmental issues than before renovation’.

Figure A.7: Relative Importance of Features: Attitude-Behavior Gap



Measurement variable: 'declaring to renovate because of finding it (very) important to own an environmental friendly house'.

Figure A.8: Relative Importance of Features: Intention-Behavior Gap

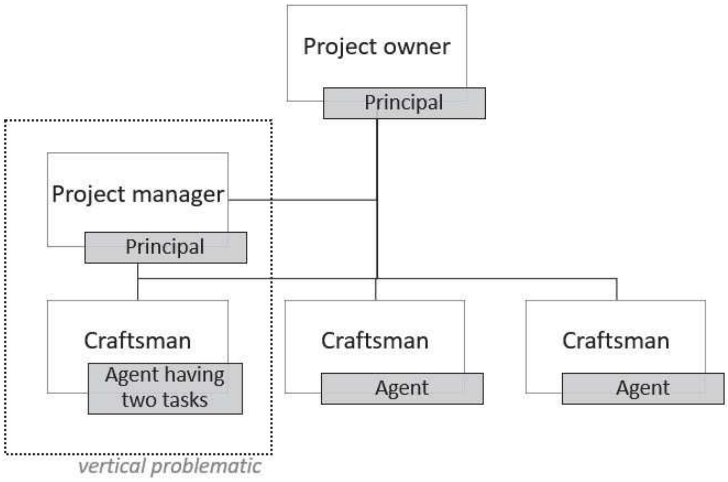
Chapter 2

Optimal incentives for a multi-task Agent with possible unawareness

2.1 Introduction

Chapter 1 analyzed ex-post (to renovation) cognitive and behavioral biases from households that are not taken into account in the energy consumption prediction models, thus leading to the emergence of an Energy Performance Gap. However, factors inherent to the renovation stage may also cause non optimally renovated buildings, resulting in intensifying the gap. In Chapters 2 and 3 we thus focus on optimal contracts for craftsmen permitting to enhance the quality of the renovation works.

In the present chapter, we aim at studying what we call the *vertical problematic* as displayed in Figure 2.1.



Note: Both the project owner and the project manager can have the role of the Principal.

Figure 2.1: Vertical problematic between a project manager and a craftsman

We determine the optimal contract between a project manager (or a project owner) and a craftsman which has *two* tasks to execute. The craftsman's first task can be seen as the actual renovation of the building[1]. His associated effort is the effort level he puts into his work: more conscientiously, or faster and without caution. His second task can be considered as the participation in a low-energy training to learn new effective renovation techniques. Her associated effort is the effort level he puts into such a specific training[2]. We assume, in this chapter, that if he exerts a positive effort on his second task, he also *actually applies* low-energy techniques during renovation works[3]. Optimally, the project manager

[1] He works only on her trade specialty. For example, if he is a drywall worker, he installs insulation boards, if he is a carpenter, he installs windows, etc.

[2] A larger number of hours spent on the training and the review of its lessons, or a lower number of hours on it.

[3] The case where he is trained but does not apply the new techniques is not considered.

wants the craftsman to exert high effort levels for both tasks: working conscientiously and having spent many hours on the training (and thus applying the learned techniques during work). Yet, the craftsman is not necessarily aware about the impact his second task may have on the building's final performance. More specifically, craftsmen working on renovation sites are nowadays more and more often trained to new efficient renovation techniques (mostly for competitive reasons), but they may underestimate how the rightful application of these techniques actually affect the energy performance of a building.

Let us analyze the optimal contract from a theoretical perspective, where the project manager is a Principal, and the craftsman is an Agent, as mentioned in Figure 2.1.

The standard moral hazard problem seeks to determine the optimal compensation scheme a Principal (he) should propose to an Agent (she) when she hides information about her real effort level. This optimal contract must give the right incentives to bring the Agent to exert the optimal effort level that maximizes the Principal's expected utility. The underlying assumption of the standard model is that both parties are completely aware of all the possible outcomes of a given action, and that the Agent's efforts impact their distribution.

However, this fully-awareness assumption may be challenged. One of the parties may not necessarily be aware of every possible outcome so that (s)he conceives the world in a simplified form. Galanis (2013) presents a model of unawareness where the Agent can make errors, because she is unaware of certain dimensions of her surroundings. Namely, the author's *unawareness of theorems* says that the Agent may be aware of the activities composing a given action, but be unaware of their consequences on performance (i.e. outcome). Alternatively, as Auster (2013) explains it, there may be relevant contingencies affecting performance (and thus the Agent's payoff) that have never crossed her mind. The Agent is also unaware of her unawareness, so that she believes to have in mind a true and complete description of the world. As formally defined by Modica and Rustichini (1994), the Agent is unaware about something, and she ignores that she ignores it.

This chapter presents a static theoretical model in a stochastic approach, which introduces possible asymmetric awareness in the moral hazard model with one Principal and one two-task Agent. Asymmetric awareness means that both parties do not have the same awareness level, such that the Agent underestimates the impact of her tasks on the outcome's distribution. The particularity of our model is the introduction of a parameter representing the Agent's awareness level. The main objective of our research is to determine the optimal compensation the Principal should offer the Agent. In other words, we determine how the Agent's compensation should vary with final performance, and how it is impacted by the Agent's awareness level. Our research thus contributes to the literature on contracting problems with unawareness of actions.

We first present a baseline model considering a completely aware Agent (cf. Section 2.3). We determine the Agent's optimal compensation for various risk preferences (i.e. risk aversion and prudence) of both parties. We solve a standard contracting problem, but with two tasks for the Agent. We see that the downside risk aversion (i.e. prudence), as well as the assumption of a concave monotone likelihood ratio[4], play a significant role in the determination of the optimal compensation, as previously demonstrated in a one task setup by Sinclair-Desgagne and Spaeter (2018). We show that for a two-task Agent with additive tasks, their finding holds. When the Principal is not too prudent (i.e. too averse to downside risk), an interesting point is that the more prudent the Agent, the less concave the compensation structure. Indeed, a concave payment in performance is too variable in bad states of natures, and thus too risky for a too downside risk averse Agent. A summary of the optimal compensation schemes for different risk preferences of both parties can be found in Table 2.1.

We then present the *possible unawareness* model (cf. Section 2.4), which considers a possibly unaware Agent, underestimating the impact of her second task on the performance's distribution.[5] She may therefore believe in a smaller impact than it has in reality (i.e. she has mistaken beliefs). We assume that the Principal knows the Agent's awareness level about some contingencies, and more particularly, about the impact of her second task on the performance's distribution. Moreover, when completely unaware, we make the assumption that the Agent exerts no effort on her second task, because she finds it useless. Our analysis shows that the compensation scheme (concavity or convexity) does not vary the with the degree of awareness, but the Principal takes the Agent's lack of awareness into account to adapt the level of her payment. Hence, he pays her less for high performance levels when she underestimates her task's impact on performance. Furthermore, the optimal compensation may less strongly with performance when the Agent has

[4]The concavity of the likelihood ratio entails that a given variation of the performance in its low levels (i.e. in bad states of nature or the downside) procures more information about the Agent's effort levels than the same variation of performance in its high levels (i.e. in good states of nature or the upside).

[5]For simplification reasons, we talk about "the task's impact on performance" in the rest of the chapter.

mistaken beliefs. The interesting point is that the Agent will *not* refuse such a contract, since she is not aware of the complete impact of her second effort on performance. She indeed believes that her payment rightfully corresponds to the actual impact her second task has on final performance.

In the Appendix, we briefly present the particular case of a completely unaware Agent, where the risk averse Agent's second effort level is *observable* by the risk neutral Principal (cf. the *unawareness model* in Section B.2).

The rest of the chapter proceeds as follows. Section 2.2 presents a review about the literature this work is related to. Section 2.3 analyzes the baseline moral hazard model, with two task for the Agent. Optimal compensation schemes are determined according to risk and downside risk aversion of the agents, with a completely aware Agent and unobservable efforts. In Section 2.4 we present a two-task moral hazard model which introduces a measure of the Agent's awareness level. She might be unaware that her second action affects the distribution of performance. We determine the optimal compensation when the Principal is risk neutral and the Agent risk averse. We conclude in Section 2.5.

2.2 Related literature

A first strand of literature related to our work concerns moral hazard in contracting problems, as explained at the beginning of the behavior. This problem has largely been studied in the literature, among others by Holmstrom (1979); Grossman and Hart (1983); Holmstrom and Milgrom (1991); Mirrlees (1999). It is well-known that optimal compensation is a compromise between incentives and risk sharing. It should thus consider preferences (i.e. risk aversion and prudence, also called downside risk aversion) of the involved parties. Including the notion of prudence in an analysis has been proven essential in various applications, as for instance in saving decisions (Leland, 1968; Sandmo, 1968; Kimball, 1990; Etner and Jeleva, 2014), background risk (Gollier et al., 2000; Ligon and Thistle, 2013), contingent monitoring (Fagart and Sinclair-Desgagné, 2007), but also in classical Principal-Agent models (Sinclair-Desgagné and Gabel, 1997; Sinclair-Desgagne, 1999; Hau, 2011; Chaigneau et al., 2017; Sinclair-Desgagne and Spaeter, 2018).

Moreover, the structure of the payment function is shaped by the assumptions on the likelihood ratio of the density function in stochastic models. As stated by Sinclair-Desgagne (1999), the monotonicity of the likelihood ratio is a necessary condition to obtain increasing payoffs in outcome, to incentivize the Agent to choose a high effort level. It allows, for instance, Chaigneau et al. (2017) (who consider a risk neutral Principal), to determine that the optimal reward is convex in outcome, if and only if the Agent is 'very prudent' (in the sense defined in our chapter). Reversely, the optimal reward is concave if and only if the Agent is 'non' or 'weakly prudent'. Our analysis permits to confirm this finding in a two-task setting. Yet, additionally assuming an either concave or convex likelihood ratio may lead to different results. In this chapter, we assume a concave likelihood ratio, leading us to show that when the Agent is not or weakly averse to downside risk (i.e. high wage variations in low outcomes), the optimal reward should be concave in outcome. Yet, assuming a convex likelihood ratio does not allow to clearly conclude on the reward scheme in this case.

Now, when the Principal turns out to be prudent too, both parties' downside risk aversion may enter in conflict. Sinclair-Desgagne and Spaeter (2018) propose a model treating this problematic. They determine the optimal compensation when the Principal is 'more downside risk averse' than the Agent. By adapting the mathematical property of *approximate concavity* developed by Páles (2003), they show that the Principal should offer the Agent a contract that is *approximately concave* in outcome, to transfer downside risk towards the Agent. In particular, Sinclair-Desgagne and Spaeter (2018) consider CRRA utility functions for both parties and obtain convex-concave optimal incentive schemes. This means that for moderate performances, the optimal compensation should be convex, and become concave for higher performances. Our results indicate that their finding holds in the case of multiple additive tasks.

A second strand of literature related to this chapter concerns the agents' unawareness of actions. The notion of *unawareness* of agents is quite intuitive to imagine: it is rather unlikely that policy makers anticipate all the possible consequences their decisions and implemented laws will generate. Yet, modeling unawareness is not so simple. It has been studied in different fields of economics and is formalized in hand of *information structures*. Nermuth (1998) explains that they mathematically formalize the idea of imperfect (incomplete, uncertain, ...) information. Intuitively, the true states (i.e. reality) are transformed into signals, which can be distorted images of reality. An Agent who only observes these 'incomplete' signals, such that her surrounding environment does not reflect reality (i.e. her state-space is incomplete), is unaware of, for instance, some action choices, impacts or consequences on outcome. In her mind, it is however the reality. In our model, the Agent perceives an incomplete signal about the impact of her second task on the distribution of final performance.

The most widely studied model introducing unawareness is the state-space model. An earlier version of this model, commonly known as the "standard state-space model", imposes that the Agent is either completely aware or unaware (see for instance Modica and Rustichini, 1994, 1999; Dekel et al., 1998; Heifetz et al., 2006). Dekel et al. (1998) conclude that it cannot correctly capture and model unawareness, because in these models, if an Agent is unaware of something, then she is automatically unaware of everything and knows nothing. Li (2009) generalizes the standard state-space model by allowing for non-trivial awareness from the Agent. It means that although the Agent is unaware of something, she may be aware of other aspects of the world.[6]

Our study applies the notion of unawareness directly on contracting problems with moral hazard. It is based on the models presented by Von Thadden and Zhao (2012, 2014). In their paper of 2012, they present a stochastic one-task moral hazard model, with an unaware Agent. In their follow-up paper of 2014, they consider *two* tasks, in a deterministic approach. As in our paper, the Agent is unaware of her second effort's impact on the distribution of the outcome. Contrary to us, they assume a linear compensation, and thereupon seek to determine in what cases the Principal should make the Agent aware through incentive pay (i.e. by giving the Agent an appropriate implicit incentive to exert a high effort, which is represented by the incentive constraint in the Principal's program), and thus avoid him an unnecessary cost if it is not in his best interest. They also go further by determining *when* the Principal should make multiple Agents aware, when the firm is composed of aware and unaware Agents.

Similarly, Auster (2013) intents to answer the same question for one Agent. By applying a very simplified version of the generalized state-space model introduced by Heifetz

[6]A wide range of literature studied how to further model the Agent's unawareness, and its impact on the information structures. This is not the subject of this chapter. Interested readers may relate to Geanakoplos (1989) to see one of the first attempts to model unawareness, to Modica and Rustichini (1999) and Li (2008, 2009) who managed to bypass Dekel et al. (1998)'s above mentioned result, to Heifetz et al. (2006) who where the first to study interactive unawareness among multiple Agents, to Board and Chung (2009) who implement a model that makes it possible to distinguish between what an Agent 'does not know' and what she is 'unaware of', and apply it to the case of insurance contracts, to Heifetz et al. (2013) who extend their former model to capture only the Agent's probabilistic beliefs rather than ignorance and knowledge, to Meier and Schipper (2014) who apply these latter belief structures to Bayesian games, to Halpern and Rêgo (2014) who extend these games with awareness about unawareness of other players, to Galanis (2015) who examine the *value* of information, to Li et al. (2016) who study information disclosure from a firm and its disadvantages, and finally to Mengel et al. (2016) and Ma and Schipper (2017) who study, in an economic experiment, how the Agents' unawareness can affect their risk preferences.

et al. (2006), she presents a deterministic theoretical moral hazard model and asymmetric awareness between a risk neutral Principal and a risk averse and unaware Agent. Same as we do, she considers that the Principal knows the Agent's unawareness level, and what she is unaware of. Her main contribution is the characterization of a trade-off between a *participation effect* (coming from the revelation of additional information and "new states") and an *incentive effect* (coming from the presence of moral hazard), to determine in what cases enlarging the Agent's awareness. In other words, there is a trade-off between leaving the Agent unaware and making her aware. She specifies explicitly that making the Agent aware (i.e. enlarging her state-space by adding new dimensions) and transmitting her information in the contract (i.e. narrowing her state-space) have to be distinguished.

Zhao (2008) also studies *when* and *how* to enlarge the Agent's awareness through the contract. They extend the standard model by a model with unawareness of actions in a deterministic approach, based on information structures. In contrast to Auster; Von Thadden and Zhao and us, they assume that the Principal may be (partially) unaware about the Agent's awareness level.

In contrast to these papers, we do *not* intent to answer the question of *when* to enlarge the Agent's awareness. In our model, and by assumption, it is always better for the Principal to leave the Agent unaware, so that we do not modify the Agent's state-space by adapting her information structure. Our contribution is focused on the determination of the optimal compensation *structure* and *level*, given the Agent's awareness level. We show that our Principal adapts the Agent's *level* of compensation by taking into account her awareness level.

A last difference with the previous papers analyzing contracting problems with unawareness, concerns the default effort level[7] adopted by the Agent, on the contingency she is unaware about. Hayek (1967); Mayr (1992); Vanberg (2002); Auster (2013) and Von Thadden and Zhao (2012, 2014) assume that it is *positive*. This permits Von Thadden and Zhao (2012, 2014) to show that the Principal should make the Agent aware if and only if her default effort level is too far away from the one he prefers. In contrast, we assume that when completely unaware, she has a default effort level equal to *zero*. We argue that she finds it useless to exert any effort when being unaware that this action impacts her payoff (through the outcome's distribution). However, an important similarity with these

[7]The default effort level is the one the Agent undertakes for the second task she is unaware of, without having any incentive from the Principal. It corresponds to a routine effort level. The Principal knows this level.

papers, is that the Agent optimizes over the 'dimensions' she is aware about.

2.3 A two-task Principal-Agent model with complete awareness

Before introducing the Agent's unawareness, we first present a baseline multi-task moral hazard model with symmetric and complete awareness. We determine the optimal compensation scheme for different risk preferences of the Principal and the Agent.

2.3.1 The baseline model

The Principal earns a random profit $\tilde{x}$, with realization x in $[\underline{x}, \overline{x}]$, $\underline{x} \leqslant 0$, $\overline{x} > 0$. The Agent chooses two non observable efforts t_1 and t_2 she has to exert, associated with two different tasks. Efforts being non observable by the Principal, he pays a compensation to the Agent which may only depend on the performance x. We denote it $w(x)$. We assume that the Agent's efforts are limited such that $t_i \in [0, \overline{t_i}]$ for $i = 1, 2$. The Principal's net profit is, thus, given by $x - w(x)$. The outcome x is correlated with the Agent's efforts through a conditional probability distribution $F(x|t_1, t_2)$. We denote the likelihood ratio by $\ell_F^i(x|t_1, t_2) \equiv \frac{f_{t_i}(x|t_1,t_2)}{f(x|t_1,t_2)}$, $i = 1, 2$, with $f(x|t_1, t_2)$ the probability density function. To describe the optimal contract under the 'first-order approach' (Rogerson, 1985; Jewitt, 1988; Mirrlees, 1999; Sinclair-Desgagne, 1999; LiCalzi and Spaeter, 2003; Bolton and Dewatripont, 2005, ...), we make the following assumption.

Assumption 1 (*CMLRP*). The Concave Monotone Likelihood Ratio Property holds for $f(x|t_1, t_2)$: $\ell_x^i(x|t_1, t_2) \geqslant 0$, $\ell_{xx}^i(x|t_1, t_2) \leqslant 0$, $i = 1, 2$

The property of CMLR (nondecreasing concave likelihood ratio in x for all t_1 and t_2), says that "(...) *variations in output at higher levels are relatively less useful in providing 'information' on the [A]gent's effort than they are at lower levels of output*" (Jewitt, 1988, p. 1181). Hence, as in Sinclair-Desgagne and Spaeter (2018), but contrary to Chaigneau et al. (2017) who assume a linear likelihood ratio, the likelihood ratio in this paper is increasing and concave in x for any t_i, $i = 1, 2$.

The Principal's (respectively the Agent's) risk preferences are given by $v'(.) > 0$, $v''(.) \leqslant 0$ and $v'''(.) \geqslant 0$ (respectively $u'(.) > 0$, $u''(.) \leqslant 0$ and $u'''(.) \geqslant 0$).

Finally, we assume for now that the Agent is aware about her efforts' impact on the distribution of the outcome x, and that both parties consider the distribution $F(x|t_1, t_2)$.

The Agent knows that exerting higher efforts increases the likelihood of achieving a higher final performance. The maximization program of the Principal is defined as follows:

$$\max_{w} \int v(x-w(x)) \cdot f(x|t_1,t_2)dx \tag{2.1}$$

subject to

$$(t_1,t_2) \in argmax \int u(w(x)) \cdot f(x|t_1,t_2)dx - C(t_1,t_2) \tag{2.2}$$

$$\int u(w(x)) \cdot f(x|t_1,t_2)dx - C(t_1,t_2) \geqslant U_0 \tag{2.3}$$

We assume an increasing, strictly convex and twice-differentiable Agent's cost-of-effort function in both efforts, $C(t_1,t_2) = \frac{1}{2}t_1^2 + \frac{1}{2c}t_2^2$, with $c > 0$. The higher c, the less costly the second effort is to the Agent compared to her first effort. From now on, t_1 and t_2 have been optimally chosen by the Principal (i.e. $t_1 \equiv t_1^*$ and $t_2 \equiv t_2^*$). Condition (2.2) is the Incentive-Compatibility Constraint that gives the Agent an incentive to choose efforts t_1^* and t_2^* (by maximizing her utility function). Condition (2.3) is the Participation Constraint, with U_0 her reservation utility.

Applying the first-order-approach and replacing the Incentive-Compatibility Constraint (2.2) with the adequate first-order conditions[8], the Principal's maximization program becomes:

$$\max_{w} \int v(x-w(x)) \cdot f(x|t_1,t_2)dx \tag{2.4}$$

subject to

$$\int u(w(x)) \cdot f_{t_1}(x|t_1,t_2)dx = t_1 \tag{2.5}$$

$$\int u(w(x)) \cdot f_{t_2}(x|t_1,t_2)dx = \frac{1}{c}t_2 \tag{2.6}$$

$$\int u(w(x)) \cdot f(x|t_1,t_2)dx - \frac{1}{2}t_1^2 - \frac{1}{2c}t_2^2 \geqslant U_0 \tag{2.7}$$

[8] Because (2.2) has an infinity of inequality constraints, we "relax" this constraint by replacing it with a constraint where the Agent's expected utility is stationary at the effort levels t_1 and t_2 (i.e. first-order approach).

The Lagrangian of the maximization problem is

$$\begin{aligned}\mathcal{L}(w,\lambda,\mu,\gamma) = &\int v(x-w(x)).f(x|t_1,t_2)dx \\ &+\lambda[\int u(w(x))\cdot f_{t_1}(x|t_1,t_2)dx - t_1] \\ &+\mu[\int u(w(x))\cdot f_{t_2}(x|t_1,t_2)dx - \frac{1}{c}t_2] \\ &+\gamma[\int u(w(x))\cdot f(x|t_1,t_2)dx - \frac{1}{2}t_1^2 - \frac{1}{2c}t_2^2 - U_0]\end{aligned} \tag{2.8}$$

where the Lagrange multipliers λ, μ and γ of the relaxed Incentive-Compatibility Constraints (2.5) and (2.6), and the Participation Constraint (2.7) are positive.

Computing $\frac{\partial \mathcal{L}}{\partial w} = 0$ leads to the following Kuhn-Tucker condition:

$$\frac{v'(x-w(x))}{u'(w(x))} = \gamma + \lambda\frac{f_{t_1}(x|t_1,t_2)}{f(x|t_1,t_2)} + \mu\frac{f_{t_2}(x|t_1,t_2)}{f(x|t_1,t_2)}, \forall x. \tag{2.9}$$

This condition must be satisfied for any level of x. Computation of Equation (2.9) is detailed in Appendix B.1.

Equation (2.9) (i.e. the Kuhn-Tucker Condition) permits to characterize the optimal compensation $w^*(x)$ the Principal should offer the Agent. The positive Lagrange multipliers and Assumption 1 entail that the right-hand-side term of Equation (2.9) is increasing and concave in the performance signal x. The left-hand-side term of Equation (2.9) must have the same properties at the optimum for the Kuhn-Tucker Condition to be satisfied for any x.

Proposition 1 *Consider that at least one agent (i.e. Principal or Agent) is risk averse. The optimal compensation scheme $w^*(x)$ is strictly increasing in the performance signal x.*

Proof. See Appendix B.1. ♦

Proposition 1 is valid when both parties are risk averse, but also when either the Principal or the Agent are risk neutral (not both). Making an effort increases the likelihood of a high performance x. Thus, the Principal rewards the Agent better in good performance states.[9]

[9] When both the Principal and the Agent are risk neutral, the optimal compensation scheme may have any curvature. Only the mean reward will be meaningful for risk neutral agents.

Result of Proposition 1 is well-known in the one-task agency problem (Milgrom, 1981; Grossman and Hart, 1983; Rogerson, 1985; Jewitt, 1988; Sinclair-Desgagne and Spaeter, 2018; Chaigneau et al., 2017). In a multi-task setup, as Sinclair-Desgagne (1999) stated, the Monotone Likelihood Ratio Property is essential to find that the monetary compensations are increasing in performance signals. The author considers selective audits to show that they permit higher incentives, even though the final performance is difficult to measure. In our model, under the assumptions made, adding tasks with additive properties to the Agent, always leads to the same needed characteristics of Equation (2.9)'s right-hand-side term (i.e. it must be increasing and concave in the performance signal x).

In what follows, we analyze the structure of the optimal contract w^* for different preferences of the Principal and the Agent.

2.3.2 Optimal compensation with a risk neutral Principal

Consider a risk neutral Principal (i.e. $v'(.) > 0, v''(.) = 0$). The Agent is risk averse and may be prudent (i.e. $u'(.) > 0, u''(.) < 0, u'''(.) \geqslant 0$). Let us denote the measures of the absolute risk aversion as $R_u = -\frac{u''(.)}{u'(.)}$ (Pratt, 1964; Arrow, 1971), and the absolute prudence[10] as $P_u = -\frac{u'''(.)}{u''(.)}$ (Kimball, 1990).

To determine the curvature of the optimal compensation w^*, we complete the second derivative of the left-hand-side term of Equation (2.9). It has to be negative to satisfy the characteristics of the Equation's right-hand-side term (i.e. increasing and concave in x):

$$\frac{\partial^2}{\partial x^2}\left(\frac{1}{u'(w(x))}\right) = (2R_u - P_u)\cdot\Big[w'(x)\Big]^2 + w''(x) \leqslant 0 \qquad (2.10)$$

See Appendix B.1 for the details of the computation.

We are looking for the sign of w'', knowing that $w' > 0$ (cf. Proposition 1). From Equation (2.10), it is easy to see that the results depend on the sign of $2R_u - P_u$. In other words, if the Agent's prudence (i.e. downside risk aversion) is sufficiently weak, even nonexistent, such that $2R_u > P_u$, she will accept an increasing and concave compensation in performance. Otherwise, if $2R_u < P_u$, the curvature of the optimal payment cannot be clearly determined without additional information about the Agent's preferences, and more specifically, her degree of prudence.

[10]The prudence is also known under the term of downside risk aversion. When the Agent is downside risk averse, she does not like a very sensitive wage in bad states of nature, i.e. when the performance is bad.

Let us first propose the following definition.

Definition 1 (degree of prudence) The Agent is:

(i) *non prudent* when $2R_u - P_u > 0$ and $P_u = 0$,

(ii) *weakly prudent* when $2R_u - P_u > 0$ and $P_u > 0$,

(iii) *very prudent* when $2R_u - P_u < 0$ and $P_u > 0$.

We thus have Proposition 2.

Proposition 2 *Consider a risk neutral Principal and a risk averse Agent.*

(i) When the Agent is 'non prudent' or 'weakly prudent', the reward function $w^*(x)$ is strictly concave in the performance signal x: $w''(x) < 0$.

(ii) When the Agent is 'very prudent', the optimal reward function $w^*(x)$ is convex in performance (i.e. $w''(x) > 0$) whenever the likelihood ratio is linear. However, the result is undetermined if the likelihood ratio is strictly concave.

As specified by Chaigneau et al. (2017), the curvature of the optimal compensation depends on both the curvature of the likelihood ratio in the performance signal x, and the Agent's risk preferences. In their paper, the optimal contract is more convex (in terms of curvature) than the likelihood ratio if and only if $2R_u - P_u < 0$. Same as in our model, they assume the monotonicity of the likelihood ratio. We furthermore assume its concavity. This means that in our study, a given variation of the performance in its low levels (i.e. in bad states of nature or the downside) procures more information about the Agent's effort levels than the same variation of performance in its high levels (i.e. in good states of nature or the upside). We call this the *likelihood ratio effect*. Thus, without considering the agents' risk preferences, the optimal compensation shall be more sensitive to final performance on the downside than on the upside. This incentive is shaped by the likelihood ratio. We name this the *incentive effect*.

The risk neutral Principal would thus prefer to offer the Agent a strictly increasing and concave compensation in performance. First, the increasing compensation incites the Agent to reach higher performance levels. Second, the concave likelihood ratio implies that, for variation in performance on the downside, her compensation varies more than for the same variation in performance on the upside. Due to this *incentive effect*, the Agent will exert higher effort levels, to "rapidly" increase her compensation (especially on the downside). This incentive property is however balanced by the Agent's prudence.

Indeed, when the Agent is prudent (i.e. downside risk averse), both an *incentive effect* and a *downside risk effect* appear. This latter effect appears when the Agent is downside risk averse. In this case, the Agent is reluctant to bear high variability of her compensation in bad states of nature, and may, hence, refuse a concave compensation. Nevertheless, her *degree* of prudence (i.e. degree of downside risk aversion) may influence this result, as we explain it in the following explanations.

When the **Agent is *very prudent***, the *downside risk effect* is stronger than the *incentive effect*. She might thus be very reluctant to accept a concave contract, and would rather accept one that is less sensitive to performance in bad states of nature. In this case, non concave contracts appear.

For a ***weakly prudent* Agent**, the *incentive effect* prevails over the *downside risk effect*. In this case, the optimal compensation w^* remains therefore concave, as preferred by the Principal.

Finally, when the **Agent is *non prudent***, and thus not averse to downside risk, the *downside risk effect* is nonexistent. In that case, she does not mind bearing risk in bad states of nature. Hence, only the *likelihood ratio effect* matters. For a concave likelihood ratio, the optimal concave reward function gives the maximal *incentive effect*, especially on the downside. The optimal compensation w^* preferred by the risk neutral Principal is therefore accepted by the risk averse and non prudent Agent.

Note that these results are valid whether both effort dimensions have the same or different costs for the Agent, in terms of cost-of-effort. This is because, as mentioned earlier, both efforts are additive and only the total amount of cost-of-effort is taken into account in determining the optimal reward structure.

In what follows, we illustrate our results with three examples.

Examples

The following examples show the case of a prudent (i.e. downside risk averse) Agent.
We present three utility functions, among which two lead to a concave optimal reward (i.e. DARA utility function with $\sigma > 1$, and CARA utility function), and one leads to a convex optimal reward (i.e. DARA utility function with $0 < \sigma < 1$).

The Principal is risk neutral. Consider that the distribution function $F(x|t_1,t_2)$, parameterized by the Agent's discrete effort levels $t_1 \in \{1,2\}$ and $t_2 \in \{0,1\}$, follows a gamma distribution with mean $\kappa(t_1+t_2)$, $\kappa > 0$. We define performance as $\tilde{x} = t_1 + t_2 + \varepsilon$, where ε is normally distributed with mean 0 and variance σ^2. Let us use the notation $t = t_1 + t_2$. With the assumption on $\tilde{x}$, we have $f(x|t_1,t_2) \equiv f(x|t_1+t_2) \equiv f(x|t)$. As the probability distribution function follows a gamma distribution, we have that

$$f(x|t) = \frac{1}{\Gamma(\kappa)}\left(t^{-\kappa}\cdot x^{\kappa-1}\cdot e^{-\frac{x}{t}}\right),$$

and that

$$f_{t_1}(x|t) = f_{t_2}(x|t) = \frac{x^{\kappa-1}}{\Gamma(\kappa)}\left(-\kappa\cdot t^{-\kappa-1}\cdot e^{-\frac{x}{t}} + x\cdot t^{-\kappa-2}\cdot e^{-\frac{x}{t}}\right).$$

We thus have the following likelihood ratios:

$$\frac{f_{t_1}(x|t)}{f(x|t)} = \frac{f_{t_2}(x|t)}{f(x|t)} = \frac{x-\kappa t}{t^2}$$

It is easy to verify that they are increasing and linear in x (i.e. $\left(\frac{f_{t_i}(x|t)}{f(x|t)}\right)' > 0$ and $\left(\frac{f_{t_i}(x|t)}{f(x|t)}\right)'' = 0$, $i = 1,2$). Thus, linearity being a form of concavity, Assumption 1 holds.

The Agent has a DARA utility function

Suppose the Agent has a DARA utility function $u(w(x)) = \frac{w(x)^{1-\sigma}}{1-\sigma}$, $\forall \sigma \in \mathbb{R}^+ \setminus \{0,1\}$. We have the Agent's absolute risk aversion $R_u = \frac{\sigma}{w(x)}$ and her absolute prudence $P_u = \frac{\sigma+1}{w(x)}$, $\forall w > 0, \forall x > 0, \forall \sigma \in \mathbb{R}^+ \setminus \{1\}$ [11]. Thus, $2R_u - P_u = \frac{\sigma-1}{w(x)}$ which is positive when $\sigma > 1$, and negative when $0 < \sigma < 1$. From Proposition 2, we shall have $w'' < 0$ when $\sigma > 1$ (the Agent is *weakly prudent*: $2R_u - P_u > 0$). However, w's concavity is not guaranteed anymore when $0 < \sigma < 1$ (the Agent is *very prudent*: $2R_u - P_u < 0$). The first-order condition (2.9) becomes, with $t = t_1 + t_2$ and $\forall x$,

$$w(x)^{\sigma} = \gamma + \lambda\frac{x-\kappa t}{t^2} + \mu\frac{x-\kappa t}{t^2} = \gamma + (\lambda+\mu)\frac{x-\kappa t}{t^2}.$$

Hence:

$$w^*(x) = \left(\gamma + (\lambda+\mu)\frac{x-\kappa t}{t^2}\right)^{\frac{1}{\sigma}} \tag{2.11}$$

[11] $R_u = -\frac{-\sigma w(x)^{-\sigma-1}}{w(x)^{-\sigma}} = \frac{\sigma}{w(x)}$, and $P_u = -\frac{\sigma(\sigma+1)w(x)^{-\sigma-2}}{-\sigma w(x)^{-\sigma-2}} = \frac{\sigma+1}{w(x)}$

Case 1: A weakly prudent Agent *($\sigma > 1$)*

The **optimal reward function is concave** as expected (i.e. $w''(x) < 0$)[12]. This scheme is depicted on Figure 2.2, using parameters $\sigma = 2$, $\gamma = 0.2$, $\lambda = 0.05$, $\mu = 0.1$ and $\kappa = 2$. We determine the optimal effort levels by introducing $w^*(x)$ in the objective function of the Agent and by solving Program (2.5-2.7). We take into account the cases where it is more or less costly for the Agent to exert t_1 compared to t_2, or where both efforts represent the same cost for her. The optimal effort levels are $(t_1^*, t_2^*) = (1,1)$.

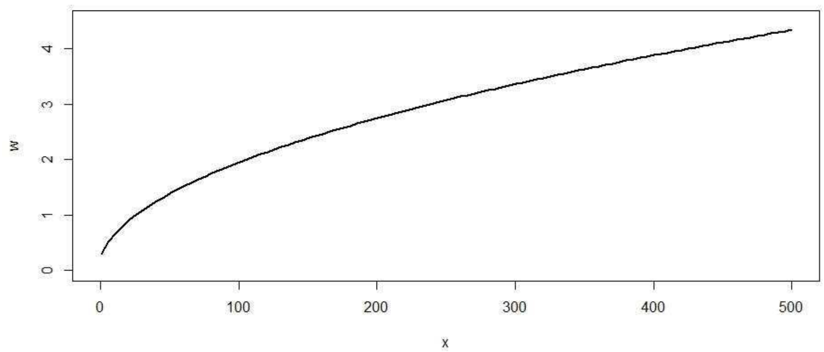


Figure 2.2: $w^*(x)$ for a risk averse and weakly prudent Agent (DARA $u(w(x))$)

Case 2: A very prudent Agent *($0 < \sigma < 1$)*

As predicted by Proposition 2, the **optimal reward function is convex** (i.e. $w''(x) > 0$). This is depicted on Figure 2.3, using the same parameters than before, except that now $\sigma = 0.5$. The optimal effort levels are $(t_1^*, t_2^*) = (1,0)$.

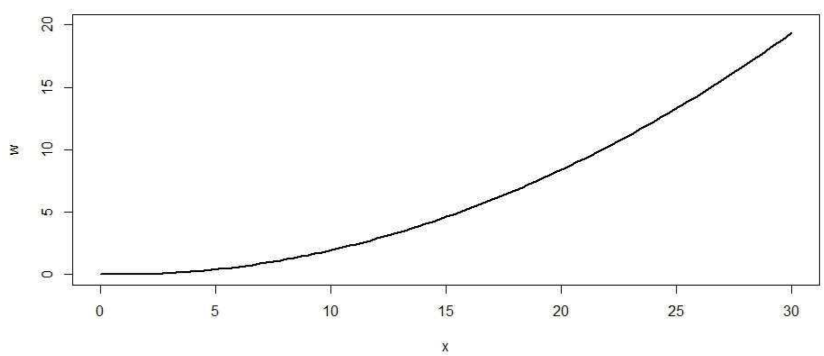


Figure 2.3: $w^*(x)$ for a risk averse and very prudent Agent (DARA $u(w(x))$)

[12] $w^{*\prime\prime}(x) = \left(\frac{\lambda+\mu}{t^2}\right)^2 \frac{1}{\sigma}\left(\frac{1}{\sigma}-1\right)\left[\gamma + \frac{x-\kappa t}{t^2}(\lambda+\mu)\right]^{\frac{1}{\sigma}-2}$

The risk averse Agent has a CARA utility function

Now, suppose that the Agent has a CARA utility function $u(w(x)) = \frac{-1}{t_1+t_2}e^{-(t_1+t_2)w(x)}$, such that she is weakly prudent ($2R_u - P_u > 0$ and $P_u > 0$). The optimal reward function is

$$w^*(x) = \frac{1}{t_1+t_2} \cdot ln\left[\gamma + (\lambda+\mu)\frac{x-\kappa t}{t^2}\right] \tag{2.12}$$

It can be checked that $w^*(x)$ is concave (i.e. $w''(x) < 0$). This is confirmed on Figure 2.4 hereafter. Again, we depict the optimal reward functions, using parameters $\gamma = 0.2$, $\lambda = 0.05$, $\mu = 0.1$ and $\kappa = 2$. The optimal effort levels are $(t_1^*, t_2^*) = (2, 1)$.

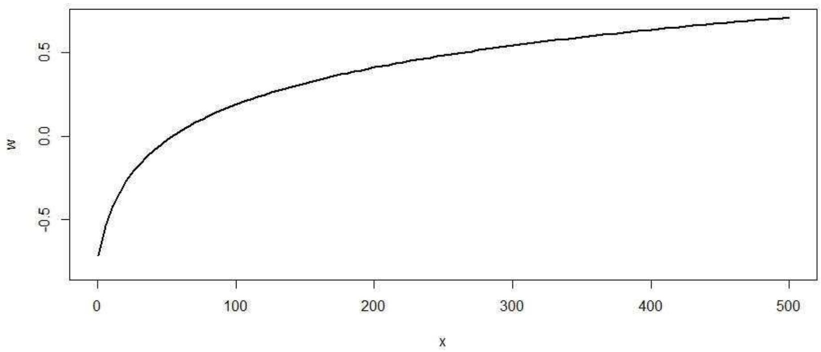


Figure 2.4: $w^*(x)$ for a risk averse and weakly prudent Agent (CARA $u(w(x))$)

Let us in the following Subsection consider the case where the Principal is not risk neutral anymore.

2.3.3 Optimal compensation with a risk averse and prudent Principal

Consider now a risk averse and prudent Principal, whose preferences satisfy $v'(.) > 0$, $v''(.) < 0$ and $v'''(.) > 0$. The Agent is risk averse and may be prudent.

The curvature of the optimal compensation w^* is determined by the second derivative of the left-hand-side term of Equation (2.9). It has to be negative to satisfy the characteristics of the Equation's right-hand-side term. The second derivative can be found by following Theorem 1's proof in Sinclair-Desgagne and Spaeter (2018). It is given in Appendix B.1. Furthermore, when both parties are prudent, we adopt the latter authors' definition of a "more downside risk averse" Principal than the Agent, by a factor k. By denoting Dom(v) and Dom(u) the Principal's and the Agent's utility functions' respective domains, Sinclair-

Desgagne and Spaeter (2018) define that the Principal is more prudent than the Agent by a factor $k \geqslant 0$, when $kP_uR_u \leqslant P_vR_v$, $w(x) \in \mathrm{Dom}(u)$ and $x - w(x) \in \mathrm{Dom}(v)$, for any real number x.[13] P_uR_u and P_vR_v capture the intensity of both parties' prudence (i.e. downside risk aversion) (Modica and Scarsini, 2005; Sinclair-Desgagne and Spaeter, 2018). We thus have the following Proposition:

Proposition 3 *Consider a risk averse and prudent Principal, and a risk averse Agent.*

(i) When the Agent is 'non prudent', the optimal reward function $w^*(x)$ is concave in the performance signal x: $w''(x) < 0$.

(ii) When the Agent is 'prudent', but the Principal is more prudent by a factor $k \geqslant 0$, in the sense defined by Sinclair-Desgagne and Spaeter (2018), the optimal reward function $w^*(x)$ is 'approximately concave' in the performance signal x.

Proof of point *(i)*. See Appendix B.1. ♦

The risk averse and prudent Principal is reluctant to bear the whole risk, in particular the downside risk. Hence, he does not like a high sensitivity of his net profit $x - w(x)$ to final performance in bad states of nature. He would therefore prefer the Agent to "absorb" a part of the net profit's variability in these states. Given that the final performance depends on the Agent's effort levels, and more importantly, that the likelihood ratio is concave, he would like to propose her an increasing and concave compensation[14]. However, in this case, both parties' degrees of downside risk aversion may enter in conflict. The optimal reward thus depends on their respective degrees of prudence.

When the **Agent is *non prudent***, the *downside risk effect* is nonexistent. She accepts downside risk in bad states of nature, and thus, a contract with a concave reward. This is point *(i)* of Proposition 3.

Contrary to Hau (2011) and Sinclair-Desgagne and Spaeter (2018) who obtain this result with one single effort for the Agent, we obtain it with two tasks. Hence, under complete awareness of the Agent, the standard moral hazard problems with one single effort for the Agent can be generalized to cases of multiple *additive* efforts.

[13] Alternatively, the Principal is more prudent than the Agent by a factor k, when $k \cdot \frac{u'''(w(x))}{u'(w(x))} \leqslant \frac{v'''(x-w(x))}{v'(x-w(x))}$, for $w(x) \in \mathrm{Dom}(u)$ and $x - w(x) \in \mathrm{Dom}(v)$.

[14] As seen in Section 2.3.2, a concave compensation gives the maximal *incentive effect*, especially on the downside, when the likelihood ratio is concave.

Now, when the **Agent is *prudent***, she does not like a very sensitive reward in performance in bad states of nature. This is also the case for the prudent Principal, knowing that bad states for him are linked to low levels of his net profit $x - w(x)$. Hence, both parties' degrees of prudence enter in conflict. This is point *(ii)* of Proposition 3.

Sinclair-Desgagne and Spaeter (2018) establish that "*a Principal who is more downside risk averse than the Agent [by a factor k] should set an incentive compensation (...) that is approximately concave ((*$\delta(k)$*,0)-concave) in outcome*", where δ is a non-negative number[15]. They adapt the concept of *approximate concavity* from the mathematical property of *approximate concavity* developed by Páles (2003). The more downside risk averse the Principal is compared to the Agent, the more downside risk is delegated to the Agent, and the more the optimal reward scheme 'approaches some concave function' in performance. This means that, in a contract composed of concave (e.g. capped bonuses, ...) and convex (e.g. stock call options, ...) components in performance, the convex ones become less important in the contract than the concave ones. Hence, if our Principal is more downside risk averse (i.e. prudent) than the Agent by a factor k, we obtain the same result, but with multiple tasks.

Table 2.1 summarizes the six different scenarios (in terms of both parties' risk preferences) studied in this section.

Table 2.1: Optimal compensation schemes according to the parties' preferences, for a completely aware Agent

Agent / **Principal**	*risk averse & non prudent*	*risk averse & weakly prudent*	*risk averse & very prudent*
risk neutral & non prudent	concave	concave	non concave
risk averse & prudent	concave	"approx. cc" *	"approx. cc" *

* "*Approximately concave*" means that the Principal is more prudent than the Agent by a factor k, in the sense of Sinclair-Desgagne and Spaeter (2018).

All these results are valid when the Agent is aware that her second effort has an impact on the final performance level x. Unfortunately, this may no longer be the case when unawareness appears. In the following Section, we study the optimal compensation characteristics when the Agent may be unaware of the impact of her second effort on the distribution of x.

[15] To learn more about this function, see Lemma 2 of Sinclair-Desgagne and Spaeter (2018).

2.4 A two-task Principal-Agent model with possible unawareness

An Agent may not measure all the consequences her multiple tasks have on the final outcome, by underestimating the actual impact of some of them. Hence, she focuses on those she believes to be relatively more significant in impacting her work and salary. Her impact estimation can, however, be more or less accurate, so that she can have different awareness levels, going from completely aware to completely unaware about this impact.

The modeling of the Agent's wrong beliefs can, among others, be found in the literature on exploitative contracting. These models assume that the Principal knows the Agent's tendency to commit (cognitive) mistakes, so that he is more informed about her beliefs than she is (Köszegi, 2014). Likewise, we assume that, contrary to the Agent, the Principal knows her unawareness level. Moreover, the Agent does not make deductions about her awareness level from the offered contract. This allows the Principal to "take advantage" of the Agent's mistaken beliefs by 'adapting' the contract. In Gabaix and Laibson (2006), this "exploitation" occurs as follows. Naive Agents (buyer) underestimate the fact that the product they want to buy needs add-on purchases.[16] The Principal (seller) therefore sells the product cheaper in the first place, so that he can increase his future benefits (if the Agent pays for the add-ons to use the product properly). In our model, the Principal may "use" the fact that the Agent underestimates her action's impact on performance, by adapting the compensation level given the unawareness level. This might allow him to "compensate" a decrease of his profit when the Agent chooses a lower optimal effort level due to her unawareness. In both cases, the Agent does not notice the Principal's "strategy" when accepting the contract.

Adapting the moral hazard model presented in Section 2.3, we introduce a parameter being the Agent's awareness level. Hence, according to the parameter, this model displays symmetric as well as asymmetric awareness about the Agent's second effort's impact on performance. The Agent's second effort being unobservable, the Principal cannot signal t_2^* in the contract when the Agent is unaware. He has to find another way to limit the decrease of his expected profit.

[16] The transaction between the buyer and the seller can be seen as a contract between them, whereas the product's price is apparent to the compensation level.

2.4.1 The possible unawareness model

This section presents a static moral-hazard model with a continuous degree of awareness level of the Agent. We specifically study the case of a risk neutral Principal and a risk averse Agent: $v'(.) = 1$, respectively $u'(.) > 0, u''(.) \leqslant 0, u'''(.) \geqslant 0$. We introduce the Agent's level of awareness with the parameter $\alpha \in [0,1]$, observable by the Principal. $\alpha = 0$ represents a completely unaware Agent, $0 < \alpha < 1$ a partially aware Agent, and $\alpha = 1$ a completely aware Agent about the impact of t_2 on performance x. The Principal is completely aware about t_2's impact on x, such that he considers the conditional probability density distribution $f(x|t_1,t_2)$. The Agent, however, may unconsciously minimize this impact. She believes in a conditional distribution of x that may be less sensitive to t_2 than in reality. We denote $f^{(\alpha)}(x|t_1,t_2)$ the conditional probability density function considered by the Agent. We make the following assumption in the remaining analysis:

Assumption 2 Let $f^{(\alpha)}(x|t_1,t_2)$ be a probability density function.
$\forall t_1, t_2$, $\forall x$, $\forall \alpha \in [0,1]$: $f^{(\alpha)}_{t_1}(x|t_1,t_2) = f_{t_1}(x|t_1,t_2)$ and $f^{(\alpha)}_{t_2}(x|t_1,t_2) = \alpha f_{t_2}(x|t_1,t_2)$

When the Agent underestimates t_2's impact on the distribution of x, she considers a lower sensitivity to a given performance $\hat{x}$, as well as for given efforts t_1 and t_2, than in the case of complete awareness[17]. Intuitively, the probability to achieve a minimal given final performance $\hat{x}$ or more (i.e. Proba$(\hat{x} \leqslant x \leqslant \bar{x})$) is lower when she underestimates t_2's impact, than otherwise.
Let us furthermore consider the following definition of the probability density functions.

Definition 2 Let f and g be conditional probability density functions. We define the following properties, $\forall\, x$ and $\forall\, t_1, t_2$:

(i) $f^{(\alpha)}(x|t_1,t_2) = f(x|t_1,t_2)$, when $\alpha = 1$

(ii) $f^{(\alpha)}(x|t_1,t_2) = g(x|t_1)$, when $\alpha = 0$

When $\alpha = 0$, we infer from point (ii) that $f_{t_1}(x|t_1,t_2) = g_{t_1}(x|t_1)$, $\forall\, x$ and $\forall\, t_1$. We define the likelihood ratio of the probability density function $g(x|t_1)$ by $m^i_G(x|t_1) \equiv \frac{g_{ti}(x|t_1)}{g(x|t_1)}$, $i = 1,2$. Similar to Section 2.3, we assume the following:

Assumption 3 (*CMLRP*). The Concave Monotone Likelihood Ratio Property holds for $g(x|t_1)$: $m^i_x(x|t_1) > 0$, $m^i_{xx}(x|t_1) \leqslant 0$, $i = 1,2$

[17] $Proba^{(\alpha)}(x < \hat{x}) > Proba^{(1)}(x < \hat{x})$, when $0 \leqslant \alpha < 1$

The remaining assumptions of this *possible unawareness model* are similar to those of the *complete awareness model* of Section 2.3. The Agent's unobservable effort levels t_1 and t_2 are limited such that $t_i \in [0, \overline{t_i}]$, for $i = 1, 2$. The Principal pays the Agent with a compensation depending on the performance x, and on the exogenous awareness level α, denoted $w(x, \alpha)$. The Concave Monotone Likelihood Ratio Property (CMLRP) of Assumption 1 holds. Finally, recall from Section 2.3 that the Agent's cost-of-effort function is increasing, strictly convex and twice-differentiable in both efforts, denoted $C(t_1, t_2) = \frac{1}{2}t_1^2 + \frac{1}{2c}t_2^2$, with $c > 0$.

Applying the first-order-approach to the Principal's maximization program, it states that:

$$\underset{w}{max} \int (x - w(x,\alpha)) \cdot f(x|t_1, t_2)dx \tag{2.13}$$

$$subject\, to$$

$$\int u(w(x,\alpha)) \cdot f_{t_1}^{(\alpha)}(x|t_1, t_2)dx = t_1 \tag{2.14}$$

$$\int u(w(x,\alpha)) \cdot f_{t_2}^{(\alpha)}(x|t_1, t_2)dx = \frac{1}{c}t_2 \tag{2.15}$$

$$\int u(w(x,\alpha)) \cdot f^{(\alpha)}(x|t_1, t_2)dx - \frac{1}{2}t_1^2 - \frac{1}{2c}t_2^2 \geqslant U_0 \tag{2.16}$$

Recall that t_1 and t_2 have been optimally chosen by the Principal. Computing $\frac{\partial \mathcal{L}}{\partial w} = 0$ from the Lagrangian of the Principal's program (2.13-2.16) leads to the following Kuhn-Tucker conditions:

$$\frac{1}{u'(w(x,\alpha))} = \frac{f^{(\alpha)}(x|t_1,t_2)}{f(x|t_1,t_2)} \left[\gamma + \lambda \frac{f_{t_1}^{(\alpha)}(x|t_1,t_2)}{f^{(\alpha)}(x|t_1,t_2)} + \mu \frac{f_{t_2}^{(\alpha)}(x|t_1,t_2)}{f^{(\alpha)}(x|t_1,t_2)} \right], \forall x \tag{2.17}$$

Computation of Equation (2.17) is detailed in Appendix B.1.

Following Assumption 2 and Definition 2, Equation (2.17) becomes:

$$\frac{1}{u'(w(x,\alpha))} = \gamma \frac{f^{(\alpha)}(x|t_1,t_2)}{f(x|t_1,t_2)} + \lambda \frac{f_{t_1}(x|t_1,t_2)}{f(x|t_1,t_2)} + \mu\alpha \frac{f_{t_2}(x|t_1,t_2)}{f(x|t_1,t_2)}, \forall x \tag{2.18}$$

Computation of Equation (2.18) is detailed in Appendix B.1. This condition must be satisfied for any level of x, which allows us to characterize the optimal compensation $w^*(x)$ in Subsection 2.4.2.

2.4.2 Optimal compensation

The determination of the optimal compensation scheme depends on the structure of the right-hand-side term of Equation (2.18).

With respect to performance

Let us first analyze the curvature of the optimal compensation with performance x, for given a given awareness level of the Agent. According to this level ($\alpha \in [0,1]$), different Kuhn-Tucker conditions appear:

***Case 1*: The Agent is completely aware ($\alpha = 1$).** Equation (2.18) becomes Equation (2.9) of Section 2.3 with a risk neutral Principal:

$$\frac{1}{u'(w(x,\alpha))} = \gamma + \lambda \frac{f_{t_1}(x|t_1,t_2)}{f(x|t_1,t_2)} + \mu \frac{f_{t_2}(x|t_1,t_2)}{f(x|t_1,t_2)}, \forall x \tag{2.19}$$

We recover the same result as in Subsection 2.3.2 (cf. Propositions 1 and 2).

***Case 2*: The Agent is completely unaware ($\alpha = 0$).** Equation (2.18) becomes:

$$\frac{1}{u'(w(x,\alpha))} = \frac{g(x|t_1)}{f(x|t_1,t_2)} \left[\gamma + \lambda \frac{g_{t_1}(x|t_1)}{g(x|t_1)} \right], \forall\, x. \tag{2.20}$$

We notice that no likelihood ratio related to the Agent's second effort appears in the Kuhn-Tucker condition (2.20). The contract $w(x,\alpha)$ depending directly on the final performance x, the Principal indirectly incentivizes the Agent to exert a positive second effort through x, except that she believes that her second effort is useless for x. Thus, she will only exert a positive effort on her first task.

According to Assumption 3, $\frac{g_{t_1}(x|t_1)}{g(x|t_1)}$ is increasing and concave in x. Yet, the structure of the right-hand-side term of Equation 2.20 depends on $\frac{g(x|t_1)}{f(x|t_1,t_2)}$. There are thus two different scenarios[18].

Scenario *(a)* When $\frac{g(x|t_1)}{f(x|t_1,t_2)}$ is such that the right-hand-side term of Equation 2.20 is increasing and concave in x, the left-hand-side term must also be increasing and concave in x. This means that we recover Equation 2.10. We thus have the same results as in

[18] A third scenario appears when the ratio $\frac{g(x|t_1)}{f(x|t_1,t_2)}$ is such that the right-hand-side term of Equation 2.20 is undetermined. In this case, we cannot conclude on the structure of w.

Subsection 2.3.2 (cf. Propositions 1 and 2). In this scenario, we recover Chaigneau et al. (2017)'s result, saying that the reward is convex if and only if the Agent is 'very prudent', but with two tasks for an unaware Agent.

Scenario *(b)* When $\frac{g(x|t_1)}{f(x|t_1,t_2)}$ is such that the right-hand-side term of Equation 2.20 is increasing and convex in x, the left-hand-side term must also be increasing and convex in x. This means that Equation 2.10 must be positive, as displayed hereafter:

$$\frac{\partial^2}{\partial x^2}\left(\frac{1}{u'(w(x))}\right) = (2R_u - P_u)\cdot\left[w'(x)\right]^2 + w''(x) \geqslant 0 \tag{2.21}$$

Given Proposition 1, we see that when the Agent is very prudent (i.e. $2R_u - P_u < 0$), a necessary condition to satisfy Equation 2.21 is $w''(x,\alpha) > 0$. Hence, the optimal reward is strictly convex in this case.

Recall that Assumption 3 still prevails: performance levels in good states of nature are less informative about the Agent's effort levels, than performance levels in bad states of nature. Furthermore, a very prudent Agent does not like downside risk. Yet, we find that in this case, the optimal reward should be convex in x. This means that a trade-off between the 'likelihood ratio effect' and the strong prudence of the Agent appears. On one hand, the concavity of the likelihood ratio tells us that the reward w should have a strong variability with x in bad states of nature, and a weak variability with x in good states of nature, all other things being equal. On the other hand, the Agent's prudence tells us the contrary. To resolve this trade-off, the Agent's degree of prudence comes into play.

When the **Agent is non or weakly prudent**, the likelihood effect is stronger than the Agent's prudence. Hence, w^* may be concave or convex.

When the **Agent is very prudent**, her downside risk aversion is stronger than the likelihood effect. Hence, w^* is strictly convex.

Contrary to Chaigneau et al. (2017) who find under the assumption of a linear likelihood ratio, that the optimal reward is convex if and only if the Agent is 'very prudent', we find that it is possible to have a convex reward when the Agent is not 'very prudent', when the Agent is unaware. We thus have the following Proposition:

Proposition 4 *Consider a risk neutral Principal and a risk averse and unaware Agent, such that the right-hand-side term of the corresponding Kuhn-Tucker condition is convex in x.*

When the Agent is 'very prudent' (i.e. $2R_u - P_u < 0$), the optimal reward function $w^*(x, \alpha)$ is strictly convex in x: $w''(x, \alpha) > 0$.

In Appendix B.2, interested readers will find a particular case of this model when $\alpha = 0$. We adapt the model to the case where t_2 is *observable* by the Principal, and the Agent is not paid when $t_2 \neq t_2^*$. We recover similar results than in Propositions 1 and 4.

***Case 3*: The Agent is partially unaware ($0 < \alpha < 1$).** The Kuhn-Tucker condition (2.18) stays unchanged. According to Assumption 2, $\frac{f_{t_1}(x|t_1,t_2)}{f(x|t_1,t_2)}$ and $\frac{f_{t_2}(x|t_1,t_2)}{f(x|t_1,t_2)}$ are increasing and concave in x. Hence, the structure of the final compensation depends on $\frac{f^{(\alpha)}(x|t_1,t_2)}{f(x|t_1,t_2)}$. When this ratio is such that the right-hand-side term of Condition 2.20 is increasing and concave in x, we recover the results of Subsection 2.3.2 (cf. Propositions 1 and 2). On the contrary, when this ratio is such that the right-hand-side term of Condition 2.20 is increasing and convex in x, we recover the results of Propositions 1 and 4.

In hand of all these results, we notice that when the Agent is unaware, her optimal reward depends on her degree of downside risk aversion.

With respect to the Agent's awareness level

Let us now analyze the impact of the Agent's awareness level α on the optimal compensation w^*, for a given performance level x.

The more the Agent's awareness level increases, the "more aware" she is about her second effort t_2's impact on the distribution of x. Hence, she knows that when increasing t_2, all other things being equal, she puts more weight on higher performance levels, and less on lower performance levels. Accordingly, we make the following assumption on $F^{(\alpha)}(x|t_1,t_2)$:

Assumption 4 $F^{(\alpha)}(x|t_1,t_2)$ is such that

$$\frac{\partial}{\partial \alpha} \int_0^{\hat{x}} f^{(\alpha)}(x|t_1,t_2)dx < 0 \text{ and } \frac{\partial}{\partial \alpha} \int_{\hat{x}}^{\bar{x}} f^{(\alpha)}(x|t_1,t_2)dx > 0$$

$$\text{and } \frac{\partial^2}{\partial \alpha^2} \int_0^{x} f^{(\alpha)}(x|t_1,t_2)dx = 0.$$

Assumption 4 says that when the performance x is under a given level $\hat{x}$, distribution $f^{(\alpha)}$ decreases when α increases. Then, when performance x reaches a level between $\hat{x}$ and a maximum $\bar{x}$, distribution $f^{(\alpha)}$ increases with α. Graphically, compared to the distribution f of a completely aware Agent (i.e. $\alpha = 1$), an unaware Agent's distribution $f^{(\alpha)}$ is under f when $x \in [0, \hat{x}[$, and above it when $x \in]\hat{x}, \bar{x}]$.

The first derivative of Equation 2.17's right-hand-side term (let us denote it A), with respect to α, is given by:

$$\frac{\partial}{\partial\alpha} A = \gamma \frac{f_\alpha^{(\alpha)}(x|t_1,t_2)}{f(x|t_1,t_2)} + \mu \frac{f_{t_2}(x|t_1,t_2)}{f(x|t_1,t_2)}, \; \forall x, \forall \alpha \in [0,1] \tag{2.22}$$

Furthermore, Equation 2.17's left-hand-side term's first derivative, with respect to α, is given by:

$$\frac{\partial}{\partial\alpha}\left(\frac{1}{u'(w(x,\alpha))}\right) = \left[-u'(w(x,\alpha))^{-2} \cdot u''(w(x,\alpha))\right] \cdot w'(x,\alpha), \; \forall x, \forall \alpha \in [0,1] \tag{2.23}$$

When $x \in [0, \hat{x}[$, according to Assumption 4, $\frac{\partial}{\partial\alpha} f^{(\alpha)} < 0$. In that case, under the condition $\gamma |f_\alpha^{(\alpha)}| > \mu f_{t_2}$, Equation (2.22) is negative. Hence, when this condition is satisfied (which we assume), Equation (2.23) must be negative too. A necessary condition to satisfy this, is $w'(x,\alpha) < 0$, $\forall x \in [0, \hat{x}]$.

Now when $x \in]\hat{x}, \bar{x}]$, according to Assumption 4, $\frac{\partial}{\partial\alpha} f^{(\alpha)} > 0$. In this case, Equation (2.22) is always positive. Hence, Equation (2.23) must be positive too. A necessary condition to satisfy this, is $w'(x,\alpha) > 0$, $\forall x \in]\hat{x}, \bar{x}]$.

The second derivative of Equation 2.17's right-hand-side term, with respect to α, is $f_{\alpha\alpha}^{(\alpha)}$, which is zero according to Assumption 4. Hence, the second derivative of Equation 2.17's left-hand-side, with respect to α, must also be zero. $\forall x, \forall \alpha \in [0,1]$, it is given by:

$$\begin{aligned}&\frac{\partial^2}{\partial\alpha^2}\left(\frac{1}{u'(w(x,\alpha))}\right)\\ &= \left[\frac{2}{u'(w)^3} \cdot w' \cdot u''(w) - \frac{1}{u'(w)^2} \cdot u'''(w) \cdot w'\right] \cdot w' + \left[\frac{-1}{u'(w)^2} \cdot u''(w)\right] \cdot w''\end{aligned} \tag{2.24}$$

A necessary condition for Equation (2.24) to be zero, is $w''(x,\alpha) > 0$.

All this permits us to state the following Proposition:

Proposition 5 *Consider a risk neutral Principal and a risk averse Agent, and let* $\alpha \in [0,1]$ *be the Agent's awareness level about her second effort's impact on performance* x.

(i) The higher α*, the lower the Agent's reward level when* $x \in [0,\hat{x}]$ *(i.e.* $w_\alpha(x,\alpha) < 0$*), and the higher her reward level when* $x \in]\hat{x},\bar{x}]$ *(i.e.* $w_\alpha(x,\alpha) > 0$*).*

(ii) The higher α*, the higher the incentive effect, that is, the more variable the optimal reward function* $w^*(x,\alpha)$ *with* x*,* $\forall x$ *(i.e.* $w_{\alpha\alpha}(x,\alpha) > 0$*).*

Point *(i)* of Proposition 5 tells us that the Principal strategically takes the Agent's awareness level into account. For two given awareness levels, the Agent will receive an equal average reward. However, the more aware the Agent is, the more the Principal will pay her, but not at any performance levels: he will pay her more at higher performance levels. Indeed, he wants to incentivize her to exert higher t_2 levels to achieve higher x levels. On the contrary, when the Agent is less aware, the Principal finds it useless to pay her more at higher performance levels (i.e. performance levels that can be reached by combining high effort levels on both tasks t_1 and t_2), since she will not increase her second effort level t_2. Hence, he can "use" the Agent's lack of awareness and pay her at the level she believes to be rightful according to her awareness level on t_2's impact on x.

Point *(ii)* of Proposition 5 can be explained as follows. When the Agent's belief is such that $0 \leqslant \alpha < 1$, she will always choose a lower t_2 level than the optimal one wanted by the Principal[19]: she will choose a t_2 level corresponding to the belief she has on t_2's impact on performance x. The Principal thus finds it useless to propose her a reward with a strong *incentive effect*. It is, however, possible to incentivize a more aware Agent to exert higher t_2 levels, in order to reach higher performance levels. To do so, he will increase her downside risk to increase the *incentive effect*.

For concreteness, we now illustrate our results in hand of two examples. We consider a DARA utility function for the Agent.

Examples

Consider a risk neutral Principal and a risk averse and prudent Agent. Recall the examples of Subsection 2.3.2 with a DARA utility function (i.e. $u(w(x)) = \frac{w(x)^{1-\sigma}}{1-\sigma}, \forall \sigma \in \mathbb{R}^+ \setminus \{0,1\}$) for the Agent. Consider the distribution function $F(x|t_1,t_2)$ following a gamma distribution with mean $\kappa(t_1+t_2)$, $\kappa > 0$, and parameterized by the Agent's discrete effort levels

[19] Moreover, when $\alpha = 0$, she will exert $t_2 = 0$

$t_1 \in \{1,2\}$ and $t_2 \in \{0,1\}$. We define performance as $\tilde{x} \equiv t_1 + t_2 + \varepsilon$, where ε is normally distributed with mean 0 and variance σ^2. Given the assumption on $\tilde{x}$, we denote the probability density function of a completely aware agent $f(x|t_1,t_2) \equiv f(x|t_1+t_2)$. Additionally, we define a density function, denoted $f^{(\alpha)}(x|t_1,t_2)$, which corresponds to the probability density function an Agent considers when she underestimates t_2's impact on x. We have that $f^{(\alpha)}(x|t_1,t_2) \equiv f(x|t_1+\alpha t_2)$. As the distribution function follows a gamma distribution, we have that

$$f(x|t_1+t_2) = \frac{1}{\Gamma(\kappa)}(t_1+t_2)^{-\kappa} \cdot x^{\kappa-1} \cdot e^{-\frac{x}{t_1+t_2}} \tag{2.25}$$

and

$$f(x|t_1+\alpha t_2) = \frac{1}{\Gamma(\kappa)}(t_1+\alpha t_2)^{-\kappa} \cdot x^{\kappa-1} \cdot e^{-\frac{x}{t_1+\alpha t_2}} \tag{2.26}$$

Differentiating (2.25) with respect to t_1 and t_2 respectively, we determine that

$$f_{t_i}(x|t_1+t_2) = \frac{x^{\kappa-1}}{\Gamma(\kappa)} \cdot \left(\frac{x}{(t_1+t_2)^{\kappa+2}} - \frac{\kappa}{(t_1+t_2)^{\kappa+1}}\right) \cdot e^{-\frac{x}{t_1+t_2}},\ i=1,2 \tag{2.27}$$

The likelihood ratios of f are the following:

$$\frac{f_{t_i}(x|t_1+t_2)}{f(x|t_1+t_2)} = \frac{x-\kappa(t_1+t_2)}{(t_1+t_1)^2},\ i=1,2 \tag{2.28}$$

It is easy to verify that the likelihood ratio is increasing and linear in x[20]. Thus, Assumption 1 holds. From (2.25) and (2.26), we have

$$\frac{f^{(\alpha)}(x|t_1,t_2)}{f(x|t_1,t_2)} = \frac{f(x|t_1+\alpha t_2)}{f(x|t_1+t_2)} = \left[\frac{t_1+t_2}{t_1+\alpha t_2}\right]^{\kappa} \cdot e^{\frac{(\alpha-1)xt_2}{(t_1+\alpha t_2)(t_1+t_2)}} \tag{2.29}$$

Given (2.28) and (2.29), the first-order condition (2.18) becomes, $\forall x$:

$$w(x)^{\sigma} = (\lambda+\mu\alpha)\frac{x-\kappa(t_1+t_2)}{(t_1+t_2)^2} + \gamma\left[\frac{t_1+t_2}{t_1+\alpha t_2}\right]^{\kappa} \cdot e^{\frac{(\alpha-1)xt_2}{(t_1+\alpha t_2)(t_1+t_2)}} \tag{2.30}$$

[20] $\frac{\partial}{\partial x}\left(\frac{f_{t_i}(x|t)}{f(x|t)}\right) > 0$ and $\frac{\partial^2}{\partial x^2}\left(\frac{f_{t_i}(x|t)}{f(x|t)}\right) = 0$, $i=1,2$

The optimal reward level $w^*(x)$ is thus

$$w^*(x) = \left[(\lambda+\mu\alpha)\frac{x-\kappa(t_1+t_2)}{(t_1+t_2)^2} + \gamma\left[\frac{t_1+t_2}{t_1+\alpha t_2}\right]^\kappa \cdot e^{\frac{(\alpha-1)xt_2}{(t_1+\alpha t_2)(t_1+t_2)}}\right]^{\frac{1}{\sigma}} \tag{2.31}$$

In the following two cases, we determine the optimal effort levels for three levels of awareness of the Agent (i.e. $\alpha = 1, \alpha = 0.5$ and $\alpha = 0$). We then depict the optimal reward functions, given the Agent's awareness level, to see how the optimal reward depends on the Agent's awareness.

Case 1: A weakly prudent Agent ($\sigma > 1$)

As in Subsection 2.3.2, it can be checked that when $\sigma > 1$, the **optimal reward function is concave** as expected ($w''(x) < 0$). The optimal effort levels are determined by introducing (2.31) in the Agent's objective function, and by solving Program (2.14)-(2.16). Table 2.2 gives the Agent's optimal effort levels (from the effort levels considered) for different awareness levels.

Table 2.2: Optimal effort levels for a weakly prudent Agent (DARA utility function), given her awareness level α

	$\alpha = 1$	$\alpha = 0.5$	$\alpha = 0$
$\sigma > 1$	$(t_1^*, t_2^*) = (1,1)$	$(t_1^*, t_2^*) = (2,0)$	$(t_1^*, t_2^*) = (2,0)$

Parameters: $\sigma = 2$, $\gamma = 0.2$, $\lambda = 0.05$, $\mu = 0.1$ and $\kappa = 2$

Figure 2.5 depicts the optimal rewards w^*. Note that when the Agent is completely aware ($\alpha = 1$, black curve) the optimal reward is the same than in the example of Section 2.3.

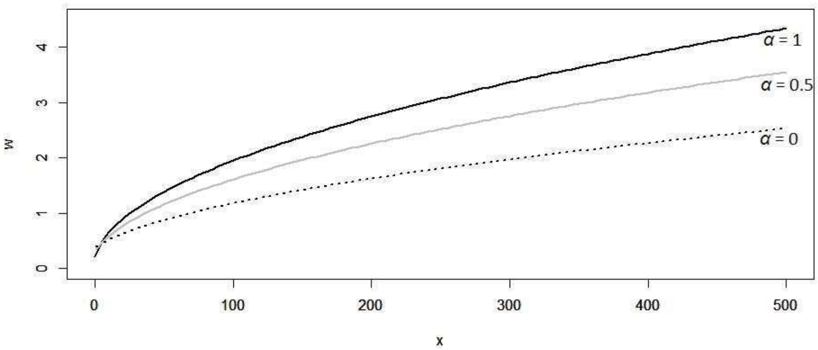


Figure 2.5: $w^*(x,\alpha)$ for a weakly prudent Agent and different α levels (DARA $u(w(x,\alpha))$)

By scaling Figure 2.5 on lower performance levels, we confirm Point *(i)* of Proposition 5, with $\hat{x} = 4$. This is depicted hereafter, where condition $\gamma|f_\alpha^{(\alpha)}| > \mu f_{t_2}$ is satisfied for $x \in [0,4]$, with $\kappa = 2$, $\gamma = 0.2$, $\mu = 0.1$, and the effort levels determined in Table 2.2.

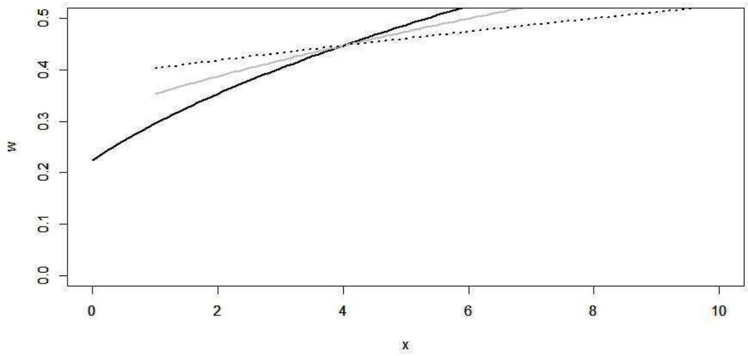


Figure 2.5: $w^*(x,\alpha)$ for a weakly prudent Agent and different α levels (DARA $u(w(x,\alpha))$)

Case 2: A very prudent Agent $(0 < \sigma < 1)$

When $0 < \sigma < 1$, the **optimal reward function is convex** $(w''(x) > 0)$. The optimal effort levels, from $t_1 \in \{1,2\}$ and $t_2 \in \{0,1\}$, are presented in Table 2.3 hereafter.

Table 2.3: Optimal effort levels for a very prudent Agent (DARA utility function), given her awareness level α

	$\alpha = 1$	$\alpha = 0.5$	$\alpha = 0$
$0 < \sigma < 1$	$(t_1^*, t_2^*) = (1,0)$	$(t_1^*, t_2^*) = (1,0)$	$(t_1^*, t_2^*) = (1,0)$

Parameters: $\sigma = 0.5$, $\gamma = 0.2$, $\lambda = 0.05$, $\mu = 0.1$ and $\kappa = 2$

The optimal rewards for the Agent's different levels of awareness are depicted in Figure 2.6. Again, when the Agent is completely aware ($\alpha = 1$, black curve) the optimal reward is the same than in the example of Section 2.3.

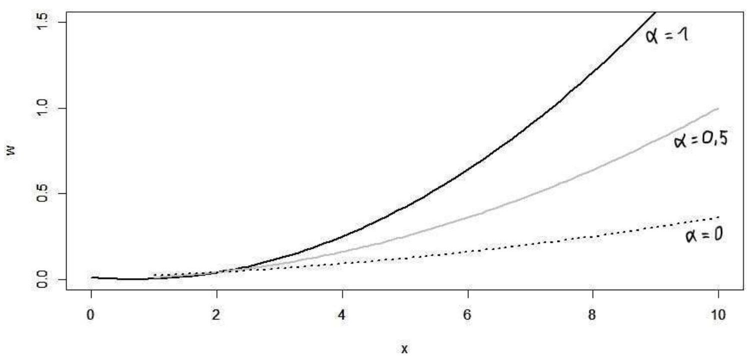


Figure 2.6: $w^*(x,\alpha)$ for a very prudent Agent and different α levels (DARA $u(w(x,\alpha))$)

As shown in hand of these examples, the optimal reward function has always the same structure (e.g. concavity, convexity, ...) for given utility functions and distribution, regardless of the Agent's awareness level toward t_2's impact on x. However, the reward *level* depends on the Agent's awareness level.

2.5 Discussion and concluding remarks

This chapter incorporates possible asymmetric awareness in a standard two task principal-agent model with moral hazard. We assume that the Principal is equally or more aware than the Agent about her second effort's impact on the outcome's distribution. This means that, when less aware than the Principal, the Agent has an *information structure* with missing or incomplete information concerning her second task, such that she has mistaken beliefs about the true environment. In this context, we determine the optimal compensation scheme the Principal should offer the Agent. We do not intent to make the Agent aware by modifying her information structure. Our basic assumption is that it is in the interest of the Principal to leave the Agent unaware when she is.

We show that, when both parties have symmetric awareness levels, the optimal compensation is impacted by (1) the assumption of the Monotone Concave Likelihood Ratio Property, and (2) the degree of downside risk aversion (i.e. prudence) of both parties. The Agent refuses a strictly concave reward in performance when being too prudent, because such a contract is too risky (i.e. variable) on the downside. The shape of the optimal reward in this case depends on the Principal's risk preferences, who has to make a trade-off between *incentive effect* and *downside risk effect*.

When asymmetric awareness emerges, under the assumption of a zero default effort level of the Agent, we show that the previous trade-off still prevails. An interesting finding is that the Principal takes the Agent's awareness level into account when proposing the contract: although the average reward is the same regardless of the awareness degree, the less aware the Agent, the less the Principal will pay her for good performance levels, in addition to decrease the incentive effect of the reward. Making the reward less variable with performance adds risk for the Principal, but being risk neutral, this is not an issue.

Let us end this chapter with a brief application of our results, and consider the case of a renovation work, as mentioned in the introduction of this chapter. The Principal is a project manager, the Agent is a craftsman and the performance observed by the project

manager represents the renovated building's final energy performance. The craftsman's first task can be seen as the actual renovation of the building. Her associated effort is the effort level she puts into her work: more conscientiously, or faster and without caution. Her second task can be considered as the participation in a low-energy training to learn new effective renovation techniques. Her associated effort is the effort level she puts into such a specific training.
The craftsman's degree of risk aversion plays an important role in the incentive effect the project manager can give: when too prudent (i.e. downside risk averse), the craftsman will be reluctant to accept a concave contract. Hence, she will be more difficult to incentivize to spend a high number of hours in a low-energy training. Now, when the craftsman additionally *underestimates* the impact of learning efficient techniques (and applying them correctly), on the building's performance, she will be very difficult to incentivize to simply participate in a training. Indeed, as she finds it less important or useless, she will less or not participate in a training, and thus be unable to apply these efficient techniques on the renovation work. Such a behavior is likely to have a negative impact on the building's final performance. Given this situation, the project manager will nevertheless try to increase his benefit out of this project. Knowing the craftsman's awareness level, he will propose her a contract incentivizing her to exert the highest possible effort level corresponding to the impact she believes the training may have on the buildings performance.

The main limit of our model, if the main purpose of energy renovation is to achieve a high energy performance of the building (i.e. high levels of performance), is that it does not make the Agent aware about the importance of being trained to achieve the highest possible performance levels. Determining models making Agents aware about it and incentivizing them to choose the best effort levels could be the purpose of a future research.

In another future extension of this research, it would be interesting to analyze the impact of the contract's shape (concavity, convexity) given the Agent's participation constraint. Considering the application on the renovation works, this would allow to determine which contracts may "attract" trained or non trained craftsmen. Knowing this is interesting since the participation of trained craftsmen may positively impact the building's final energy performance.

Appendix B

B.1 Proofs of Propositions and equation computations

Computation of Equation (2.9) Differentiating the Lagrangian (2.8) with respect to w gives, $\forall x$:

$$\frac{\partial \mathcal{L}}{\partial w} = 0$$
$$\Leftrightarrow - v'(x - w(x)).f(x|t_1, t_2) + \lambda[u'(w(x)).f_{t_1}] + \mu[u'(w(x)).f_{t_2}] + \gamma[u'(w(x)).f(x|t_1, t_2)] = 0, \forall x$$
$$\Leftrightarrow \frac{v'(x - w(x))}{u'(w(x))} = \gamma + \lambda \frac{f_{t_1}(x|t_1, t_2)}{f(x|t_1, t_2)} + \mu \frac{f_{t_2}(x|t_1, t_2)}{f(x|t_1, t_2)}, \forall x \ \blacklozenge$$

Proof of Proposition 1 Since the right-hand-side term of Equation (2.9) is increasing in the performance signal x (given the positive Lagrange multipliers and Assumption 1), the left-hand-side term must present the same characteristics for any x.

$$\frac{\partial}{\partial x}\left(\frac{v'(x - w(x))}{u'(w(x))}\right) > 0$$
$$\Leftrightarrow \frac{v''(x - w(x)) \cdot (1 - w'(x)) \cdot u'(w(x)) - v'(x - w(x)) \cdot u''(w(x)) \cdot w'(x)}{[u'(w(x))]^2} > 0$$
$$\Leftrightarrow \frac{-w'(x) \cdot \Big[v''(x - w(x)) \cdot u'(w(x)) + v'(x - w(x)) \cdot u''(w(x))\Big] + v''(x - w(x)) \cdot u'(w(x))}{[u'(w(x))]^2} > 0$$
$$\Leftrightarrow - \frac{1}{u'(w(x))} \left[-w'(x) \cdot [v''(x - w(x)) - v'(x - w(x)) \cdot R_u(x)] + v''(x - w(x))\right] > 0 \tag{B.1}$$

where R_u is the Agent's absolute risk aversion ratio of Arrow-Pratt (Pratt, 1964). Given the risk preferences $v' > 0$, $u' > 0$, $v'' \leqslant 0$, $u'' \leqslant 0$, a necessary condition to satisfy Equation (B.1), when either $v'' < 0$ or $u'' < 0$, is $w'(x) > 0$. $\blacklozenge$

Computation of Equation (2.10) Differentiating the right-hand-side term of Equation (2.9), where the Principal is risk neutral entails the following Equation:

$$
\begin{aligned}
&\frac{\partial^2}{\partial x^2}\left(\frac{1}{u'(w(x))}\right) \leqslant 0\\
\Leftrightarrow & -u'''(w(x))\cdot\Big[w'(x)\Big]^2\cdot\Big[u'(w(x))\Big]^{-2} - u''(w(x))\cdot w''(x)\cdot\Big[u'(w(x))\Big]^{-2}\\
&+2\Big[u''(w(x))\Big]^2\cdot\Big[w''(x)\Big]^2\cdot\Big[u'(w(x))\Big]^{-3}\leqslant 0\\
\Leftrightarrow & \frac{1}{u'(w(x))}\left[-\frac{u'''(w(x))}{u''(w(x))}\cdot\frac{u''(w(x))}{u'(w(x))}\cdot\Big[w'(x)\Big]^2-\frac{u''(w(x))}{u'(w(x))}\cdot w''(x)+2\left(\frac{u''(w(x))}{u'(w(x))}\right)^2\cdot\Big[w''(x)\Big]^2\right]\leqslant 0\\
\Leftrightarrow & \frac{1}{u'(w(x))}\left[-P_uR_u\cdot\Big[w'(x)\Big]^2+R_u\cdot w''(x)+2R_u\Big[w''(x)\Big]^2\right]\leqslant 0\\
\Leftrightarrow & \frac{R_u}{u'(w(x))}\left[(2R_u-P_u)\cdot\Big[w'(x)\Big]^2+w''(x)\right]\leqslant 0\\
\Leftrightarrow & (2R_u-P_u)\cdot\Big[w'(x)\Big]^2+w''(x)\leqslant 0
\end{aligned}
\tag{B.2}
$$

It is easy to see from Equation (B.2), that when $2R_u > P_u$, the optimal compensation $w^*(x)$ is concave (i.e. $w''(x) < 0$). In other words, if the Agent's prudence is sufficiently weak, even nonexistent, the Agent will accept a concave compensation in the performance x. ♦

Proof of Point *(i)* of Proposition 3 When the Principal is risk averse and prudent, the second derivative of the left-hand-side term of Equation (2.9) (calculated in the proof of Theorem 1 in Sinclair-Desgagne and Spaeter (2018)) is given by

$$
\begin{aligned}
&2w'(x)\cdot R_u\cdot\frac{\partial}{\partial x}\left[\frac{v'(x-w(x))}{u'(w(x))}\right]\\
&+\frac{v'(x-w(x))}{u'(w(x))}\cdot\left[w''(x)\cdot(R_v+R_u)+(1-w'(x))^2P_vR_v-\Big[w'(x)\Big]^2\cdot P_uR_u\right]
\end{aligned}
\tag{B.3}
$$

The sign of Expression (B.3) depends on the sign of

$$
w''(x)\cdot(R_v+R_u)+(1-w'(x))^2P_vR_v-\Big[w'(x)\Big]^2\cdot P_uR_u \tag{B.4}
$$

For a risk averse and *non prudent* Agent, we have $R_u > 0$ and $P_u = 0$. Thus, as Expression (B.4) has to be negative (i.e. Assumption 1, CMLRP), we can solve:

$$
w''(x)\cdot(R_v+R_u)+(1-w'(x))^2\cdot P_vR_v\leqslant 0 \tag{B.5}
$$

For a risk averse and *prudent* Principal, we have $R_v > 0$ and $P_v > 0$. A necessary condition to satisfy Equation (B.5), is to have $w''(x) > 0$, i.e. the optimal compensation has to be concave in the performance signal x. ♦

Computation of Equation (2.17) The Lagrangian of maximization program (2.13-2.16) is

$$\begin{aligned}\mathcal{L}(w,\lambda,\mu,\gamma) = &\int (x - w(x,\alpha)) \cdot f(x|t_1,t_2)dx \\ &+ \lambda\left[\int u(w(x,\alpha)) \cdot f_{t_1}^{(\alpha)}(x|t_1,t_2)dx - t_1\right] \\ &+ \mu\left[\int u(w(x,\alpha)) \cdot f_{t_2}^{(\alpha)}(x|t_1,t_2)dx - \frac{1}{c}t_2\right] \\ &+ \gamma\left[\int u(w(x,\alpha)) \cdot f^{(\alpha)}(x|t_1,t_2)dx - \frac{1}{2}t_1^2 - \frac{1}{2c}t_2^2 - U_0\right]\end{aligned} \tag{B.6}$$

Differentiating Lagrangian (B.6) with respect to w gives, $\forall x$:

$$\begin{aligned}&\frac{\partial \mathcal{L}}{\partial w} = 0 \\ \Leftrightarrow &-1 \cdot f(x|t_1,t_2) \\ &+ \lambda[u'(w(x,\alpha)) \cdot f_{t_1}^{(\alpha)}] \\ &+ \mu[u'(w(x,\alpha)) \cdot f_{t_2}^{(\alpha)}] \\ &+ \gamma[u'(w(x,\alpha)) \cdot f^{(\alpha)}(x|t_1,t_2)] = 0, \forall x \\ \Leftrightarrow &\frac{1}{u'(w(x,\alpha))} = \lambda\frac{f_{t_1}^{(\alpha)}}{f} + \mu\frac{f_{t_2}^{(\alpha)}}{f} + \gamma\frac{f^{(\alpha)}}{f}, \forall x \\ \Leftrightarrow &\frac{1}{u'(w(x,\alpha))} = \frac{f^{(\alpha)}(x|t_1,t_2)}{f(x|t_1,t_2)}\left[\lambda\frac{f_{t_1}^{(\alpha)}(x|t_1,t_2)}{f^{(\alpha)}(x|t_1,t_2)} + \mu\frac{f_{t_2}^{(\alpha)}(x|t_1,t_2)}{f^{(\alpha)}(x|t_1,t_2)} + \gamma\right], \forall x \ \blacklozenge\end{aligned}$$

Computation of Equation (2.18) Replacing the properties $f_{t_1}^{(\alpha)} = f_{t_1}$ and $f_{t_2}^{(\alpha)} = \alpha f_{t_1}$ in Equation (2.17) gives, $\forall x$:

$$\begin{aligned}\frac{1}{u'(w(x,\alpha))} &= \frac{f^{(\alpha)}}{f}\left[\lambda\frac{f_{t_1}^{(\alpha)}}{f^{(\alpha)}} + \mu\frac{f_{t_2}^{(\alpha)}}{f^{(\alpha)}} + \gamma\right] \\ &= \frac{f^{(\alpha)}}{f}\left[\lambda\frac{f_{t_1}}{f^{(\alpha)}} + \mu\frac{\alpha f_{t_2}}{f^{(\alpha)}} + \gamma\right] \\ &= \lambda\frac{f_{t_1}(x|t_1,t_2)}{f(x|t_1,t_2)} + \mu\alpha\frac{f_{t_2}(x|t_1,t_2)}{f(x|t_1,t_2)} + \gamma\frac{f^{(\alpha)}(x|t_1,t_2)}{f(x|t_1,t_2)}, \forall x \ \blacklozenge\end{aligned}$$

B.2 A two-task Principal-Agent model with complete unawareness: the case of an observable second task

In this extension of Section 2.4, we assume that the Agent is completely unaware that her effort for the second task impacts the final performance's distribution (i.e. $\alpha = 0$). Hence, the Agent considers only t_1 as a decision variable. In the meantime, the Principal is looking for a way to incentivize the Agent to choose optimal levels for both efforts t_1 and t_2. As in Section 2.4, we study the case of a risk neutral Principal and a risk averse and possibly prudent Agent. However, we now make the assumption that the Agent's second task is *observable* by the Principal.

B.2.1 The complete unawareness model

The assumptions made in Section 2.4 remain valid for this model. Furthermore, we assume that, being completely unaware ($\alpha = 0$), the Agent chooses to exert no effort t_2. Knowing the Agent's awareness level, the Principal anticipates this, and, hence, does not support t_2's optimal effort choice by an incentive constraint. This would be useless and costly for him. Auster (2013) also argues that there exists no direct *incentive effect* (through performance), and that only the *participation effect* matters. Consequently, according to Auster (2013), the best for the Principal is to leave the Agent unaware. However, in our model, the Principal can create an explicit monetary incentive, since t_2 is observable. As Baron and Kreps (1999, p. 269) explain, "*if a task is not formally recognized in a worker's incentive pay, he or she has less incentive to pay attention to that task*". To do this, he can propose a contract that announces explicitly t_2^*: $w(x, \alpha, t_2^*)$. Making the Agent aware is not important for the Principal. By signaling t_2^*, he actually restricts the Agent's choice set, which is the opposite than enlarging her awareness level. The action of signaling t_2^* is, however, costly for the Principal. We thus make the following assumption:

Assumption 5 When the Agent is completely unaware ($\alpha = 0$) and her second task t_2 is observable, it is in the Principal's interest to signal t_2^* in the contract.

Furthermore, as an incentive for the Agent to exert $t_2 = t_2^*$ despite her complete unawareness, the Principal decides to not pay her if she exerts a lower effort level than t_2^*, such that $w(x, \alpha, t_2) = 0$, $\forall\, t_2 \neq t_2^*$.

Hence, the Principal's maximization program is as follows:

$$\max_{w} \int (x - w(x,\alpha,t_2^*))f(x|t_1,t_2^*)dx \tag{B.7}$$

$$subject\,to$$

$$t_1 \in argmax \int u(w(x,\alpha,t_2^*))g(x|t_1)dx - C(t_1,t_2^*) \tag{B.8}$$

$$\int u(w(x,\alpha,t_2^*))g(x|t_1)dx - C(t_1,t_2^*) \geqslant U_0 \tag{B.9}$$

$$w(x,\alpha,t_2) = 0, \forall\, t_2 \neq t_2^* \tag{B.10}$$

The density function $g(x|t_1)$ considered by the Agent indicates that she is unaware that her second effort has consequences on the distribution of x.

The Lagrangian of the maximization program can be written as:

$$\begin{aligned}\mathcal{L}(w,\lambda,\gamma,\eta) = & \int (x - w(x,\alpha,t_2^*)) \cdot f(x|t_1,t_2^*)dx \\ & + \lambda[\int u(w(x,\alpha,t_2^*))g_{t_1}(x|t_1)dx - t_1] \\ & + \gamma[\int u(w(x,\alpha,t_2^*))g(x|t_1)dx - \frac{1}{2}t_1^2 - \frac{1}{2c}(t_2^*)^2 - U_0] \\ & + \eta[w(x,\alpha,t_2)]\end{aligned} \tag{B.11}$$

where the Lagrange multipliers λ, γ and η are positive (Jewitt, 1988; Jung and Kim, 2015). Similarly to Section 2.3, computing $\frac{\partial \mathcal{L}}{\partial w} = 0$ leads to the following Kuhn-Tucker condition:

$$\frac{1}{u'(w(x,\alpha,t_2^*))} = \frac{g(x|t_1)}{f(x|t_1,t_2^*) - \eta}\left[\lambda \cdot \frac{g_{t_1}(x|t_1)}{g(x|t_1)} + \gamma\right] \tag{B.12}$$

This condition must be satisfied for any level of x, which allows us to characterize the optimal compensation $w^*(x,\alpha,t_2^*)$. The computation of Equation (B.12) is available in Appendix B.2.3. The following Subsection B.2.2 describes the optimal compensation scheme.

B.2.2 Optimal compensation

The positive Lagrange multipliers and the increasing and concave likelihood ratio $\frac{g_{t_1}(x|t_1)}{g(x|t_1)}$ in performance x (cf. Assumption 3) entail that the term into brackets in Equation (B.12) is increasing and concave in x. Hence, the structure of Equation (B.12)'s right-hand-side term depends on the ratio $\frac{g(x|t_1)}{f(x|t_1,t_2^*)-\eta}$. Consequently, when the Agent exerts t_2^*, we recover the results given in Propositions 1 and 4. The shape of the reward does not change, regardless of t_2's observability. Otherwise, her payment is zero.

Contrary to the model with unobservable t_2, this model captures t_2 twice: (a) imperfectly through final performance and (b) perfectly through the direct observation of t_2.

Thus, in the present scenario (α=0), the main difference between both models may concern the *level* of the optimal compensation: on one hand, when the Agent chooses $t_2 = t_2^*$, the Agent's reward w increases directly through t_2^* included in the contract, and indirectly through the impact of t_2^* on the distribution of the performance x (the Principal pays the Agent twice). On the other hand, contrary to the model with an unobservable t_2, when the Agent chooses $t_2 \neq t_2^*$, her payment is zero, regardless of the effort exerted on her first task.
Hence, the Agent's average payment level is lower when t_2 is observable than when unobservable.

B.2.3 Computation related to the complete unawareness model

Computation of Equation (B.12) Differentiating the Lagrangian of the maximization problem (B.7)-(B.9) with respect to the compensation w leads to the following Kuhn-Tucker condition.

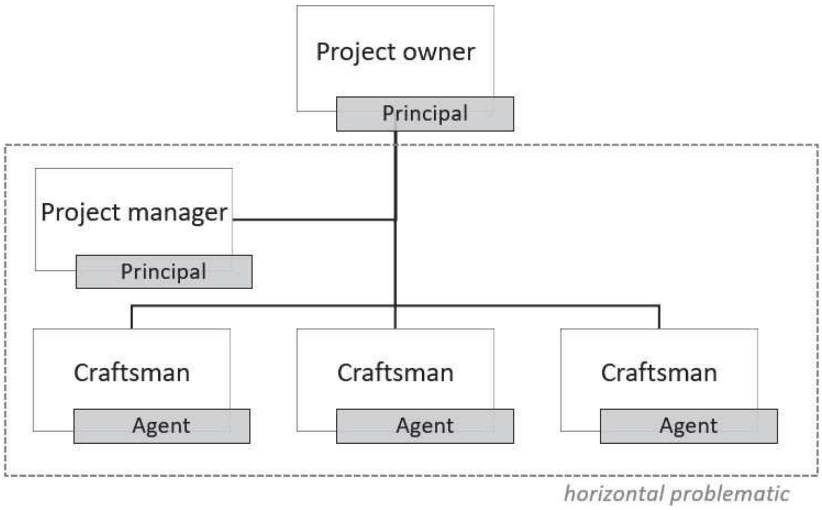
$$
\begin{aligned}
&\frac{\partial \mathcal{L}}{\partial w} = 0\\
\Leftrightarrow & f(x|t_1,t_2^*) = \lambda[u'(w(x,\alpha,t_2^*)) \cdot g_{t_1}(x|t_1)] + \gamma[u'(w(x,\alpha,t_2^*)) \cdot g(x|t_1)] + \eta\\
\Leftrightarrow & \frac{f(x|t_1,t_2^*)}{u'(w(x,\alpha,t_2^*))} = \lambda \cdot g_{t_1}(x|t_1) + \gamma \cdot g(x|t_1) + \frac{\eta}{u'(w(x,\alpha,t_2^*))}\\
\Leftrightarrow & \frac{f(x|t_1,t_2^*)}{u'(w(x,\alpha,t_2^*))} - \frac{\eta}{u'(w(x,\alpha,t_2^*))} = \lambda \cdot g_{t_1}(x|t_1) + \gamma \cdot g(x|t_1)\\
\Leftrightarrow & \frac{f(x|t_1,t_2^*) - \eta}{u'(w(x,\alpha,t_2^*))} = \lambda \cdot g_{t_1}(x|t_1) + \gamma \cdot g(x|t_1)\\
\Leftrightarrow & \frac{1}{u'(w(x,\alpha,t_2^*))} = \lambda \cdot \frac{g_{t_1}(x|t_1)}{f(x|t_1,t_2^*) - \eta} + \gamma \cdot \frac{g(x|t_1)}{f(x|t_1,t_2^*) - \eta}\\
\Leftrightarrow & \frac{1}{u'(w(x,\alpha,t_2^*))} = \frac{g(x|t_1)}{f(x|t_1,t_2^*) - \eta}\left[\lambda \cdot \frac{g_{t_1}(x|t_1)}{g(x|t_1)} + \gamma\right], \forall x. \blacklozenge
\end{aligned}
$$

Chapter 3

Knowledge acquisition or incentive to foster coordination ? A real-effort weak-link experiment with craftsmen

3.1 Introduction

After having studied the *vertical problematic* in Chapter 2, we are interested in Chapter 3 to analyze, in an economic experiment with "real" craftsmen, which contract features a project manager may propose to multiple craftsmen, in order to trigger successful and efficient coordination among them. We may call this the *horizontal problematic* as displayed in Figure 3.1 hereafter.



Note: Both the project owner and the project manager can have the role of the Principal.

Figure 3.1: Horizontal problematic between a project manager and multiple craftsmen

In a lot of situations, coordination is key to success for teams. For example, a sports team can have the best athletes, or a business the most talented employees, if they cannot coordinate their actions towards the goal, they will not succeed. Although necessary, specialization and skills are not always sufficient to achieve the best outcomes.

In this chapter, we present the results of a real-effort lab experiment in which we compare, in a within-group design, individual-based and group-based incentives to coordinate on high effort levels for craftsmen working on renovation projects. The originality of the experiment is that it gathers "real" workers from the construction sector where coordination is essential given the weak-link property of the tasks (i.e. one worker fails to achieve her goal and all the work is spoiled). Furthermore, we do not only compare the effects of different incentives, but also look at the effect of coordination training by comparing subjects having endogenously been trained to coordination and others who have not.

A long literature has shown that in many different situations teams end up coordinating at inefficient outcomes (Van Huyck et al., 1990; Weber et al., 2001; Brandts and Cooper, 2006, ...), and thus, failing to coordinate. Such coordination failure can be due to subject-pool effects (Engelmann and Normann, 2010), the lack of possibility to choose his team members (Riedl et al., 2016), team heterogeneity in terms of productivity (Meidinger et al., 2003), free-riding, even when cooperation is a dominant strategy (Holmstrom, 1982) or strategic uncertainty (Van Huyck et al., 1990).

Importantly, *strategic uncertainty* may make incentive contracts "fragile", particularly in environments presenting a weak-link property (Van Huyck et al., 1990; Cooper et al., 2018). This uncertainty arises (1) when subjects find it too risky to exert a high-effort level (i.e. choosing the payoff-dominant effort) while being not sure about their team members' strategies, and (2) when subjects keep in mind earlier periods of the game. For instance, it has been shown that when earlier outcomes were low, because of one team member choosing a low effort, subjects find it hard to trust the others to coordinate at high effort levels. As exposed by Knez and Simester (2001), a typical example of a weak-link environment is the take-off of an airplane. Before departing, many operations and procedures have to be fulfilled (e.g. cleaning, fueling, loading of the food, security checks, loading of the luggage, passenger boarding, ...). All these tasks are complementary, because if one of these is not well executed, the plane will not take-off on time. Furthermore, some employees' high efforts may be in vain if only one of them does not perform well in her task. Such a linkage corresponds to a "production technology of the weak-link type". It means that a firm's outcome (e.g. on-time departure) depends on the employees' worst performance. In other words, to achieve a high performance, every employee *must* coordinate on exerting high effort levels. As the outcome depends on the worst performance (i.e. the minimum effort) of the members of a team, so does everyone's payoff. Such a contract is thus appropriate to incentivize towards efficient coordination among the employees.

However, using laboratory experiments[1], Van Huyck et al. (1990) have shown that such a mechanism is only efficient for very small groups of workers (i.e. two players). Additional mechanisms are thus required to increase coordination, especially in larger groups. Here again, the experimental literature has pointed out five different tools that are effective to facilitate coordination in weak-link situations.

First, *costless pre-play communication* has been shown to be effective in facilitating

[1]The weak-link technology has been studied in the lab through the so-called weak-link games, also called minimum effort games.

coordination (see, for instance, Cooper et al., 1992; Blume and Ortmann, 2007). When subjects can send messages to their team members, before choosing their action, it reassures players on the team members' intentions to target high effort levels, and helps them overcome strategic uncertainty. Secondly, *endogenous group formation*, where subjects can endogenously choose their group members, has also proved to be very effective. Particularly, Riedl et al. (2016) show how exclusion can be a disciplining device. When high performers can exclude low performers, the latter increase their effort to avoid being excluded. Chen (2017) also points out a social identity effect such that "a person who chooses her own group will more strongly identify with that group, and care more about the outcome of the group's other members". Thirdly, Bornstein et al. (2002) show that *competition between groups* is also effective in increasing coordination. They show that members of a group of seven were coordinating at much higher levels when additionally confronted to an inter-group payment. In such a competition, the group presenting the overall weakest effort level was paid nothing, whereas the other one was paid according to the weakest performance of their group members. The authors show that even when paying the "less efficient" group less (instead of nothing) than the other group, inter-group competition was still significantly more effective (but slightly less) than no competition. Fourthly, Chaudhuri et al. (2009) have proven the effectiveness of *inter-generational advice*. In their game, they simulate non overlapping generations with groups playing non simultaneously. When the first range of groups are done, they can pass on advice (in the form of written messages) to the succeeding groups (i.e. the next generation). Chaudhuri et al. (2009) explain that the second generation must start at an efficient level in order to maintain it in the following periods. Subjects, thus, have to receive the right advice and choose the right action. To achieve this, the authors show that the mechanism is most effective when the advice given from one generation to the next is shared to everybody and made common knowledge. A last efficient mechanism is the *priming of subjects' identity*, tested by Chen et al. (2014). More specifically, when priming a minority identity (e.g. Asian, Caucasian), subjects are less likely to coordinate at high effort levels, whereas priming a school identity significantly increases efficient coordination and high payoffs (Chen et al., 2014). Thus, identity and subjects' prejudices play an important role in coordination.

On the grounds of these evidence, this chapter presents a weak-link game where the *weak-link* is the worst performance exerted by the member of a group of three players. Our subjects are craftsmen working on renovation construction sites. In a within-group design, we introduce successively an *Individual-based Incentive*, and a *Group-based Incentive*. Following Bortolotti et al. (2016), we implement a real-effort task instead of a chosen-effort set-up for two reasons. First, the "selection" of the highest effort with the *Individual Incentive* (and thus the efficiency of this incentive) would be trivial in a chosen-effort set-up. Second, an effort chosen by the subject might not represent his real abilities, and thus the effort he would exert in reality. This can be problematic for the external validation of our results. As mentioned by Bortolotti et al. (2016), chosen-effort set-ups might point to the possible limited external validity of past collected data on weak-link games.

The novelty of our experiment is twofold. First, we do not only compare individual and group incentive for active workers from the construction sector, but we specifically assign subjects' individual performance targets they should achieve. Brandts and Cooper (2007) find that allowing communication between managers (the experimenter) and employees (players) leads to increased efficient coordination and higher payoffs. They recommend that managers request a specific effort level. In addition, contrary to Cooper et al. (2018), we did *not* increase the difficulty of escaping a *performance trap* (i.e. be stuck at low effort levels) by keeping the other team members' past effort levels unobservable. Second, we look at the impact of exogenous training courses on group coordination. More specifically, the pool of subjects is made of construction craftsmen, working, among others, on (low energy) renovations, in the Region Grand Est, in north-eastern France.[2] Some of these subjects have been incentivized to coordinate their efforts (and tasks) through a training course on efficient coordination, they participated in, called *DORéMI*. This training course teaches the craftsmen (1) efficient low energy renovation techniques, (2) how to coordinate their complementary tasks with other craftsmen, and (3) the importance of coordination to achieve high performance. Our control group is composed of craftsmen who did not participate in this training course. We are thus interested in identifying possible behavioral differences between trained and non trained subjects, and seeing if a simple mechanism of exogenous training about coordination is efficient to achieve coordination at high effort levels.

Our paper also contributes to the literature on coordination dynamics by providing evidence of the effect of individual and group weak-link incentives on effort provision and

[2] A renovation site presents the weak-link property. Every craftsman has his own specialty and task to renovate a building. Their tasks are complementary to achieve an efficient final energy performance. Yet, when one of the craftsmen fails to efficiently execute his task, the buildings final performance will be (negatively) impacted. It thus depends on worst performance of all the craftsmen working on the renovation site.

coordination, when subjects have to exert a real effort rather than to choose their action. To our knowledge, Bortolotti et al. (2016) are the first and only one, until today, having implemented *Individual* and *Group Incentives* in a real-effort weak-link game.

Practically, we test subject-pool effects, and more specifically, the coordination capacity between trained and non trained craftsmen. Hence, we implement a "2 x 2" experimental design, where we compare how both subject groups act when facing both treatments (*Individual-based Incentive*, and *Group-based Incentive* with weak-link payment). In other words, we want to determine (1) if it is possible to incentivize towards more coordination through a weakest-link contract (that would make all the craftsmen of one project responsible toward correctly accomplishing a common work), and (2) whether this *Group-based Incentive*[3] has the same incentive effect on both subject groups.

The subjects had to count the number of ones in a table of 50 randomly selected ones and zeros. They had to resolve as many tables as possible in a given time period, by trying to attain individual performance targets (a minimum acceptable target, and a maximum ideal target) in terms of number of tables to resolve. We normalized the cost-of-effort across the subjects by scaling the targets to their actual individual abilities, in a first stage. Every subject thus had his or her own targets, and had to exert a substantial effort to attain the ideal target. In the *Individual treatment*, subjects experienced no strategic uncertainty and were paid according to their individual performance. In the *Group treatment*, subjects were randomly assigned in groups of three, which stayed unchanged for the rest of the experience, except that trained subjects were assigned with other trained subjects, and the same was done for non trained subjects. They were paid according to a weak-link payment function, that is, the worst performance exerted by all the members of their group. Every group member thus received the same payment. As in "standard" weak-link games, subjects experienced strategic uncertainty.

The main results of the experiment suggest that trained subjects coordinate at significantly higher effort levels than non-trained subjects when facing an individual-based incentive. However, when facing a group-based incentive, non-trained subjects seem to "catch up" trained subjects in terms of coordination level, while these latter subjects do not significantly increase their performance level. This result suggests that proposing a group-based incentive to subjects who have previously been trained on coordination, does

[3]The aim of the *Group-based Incentive* is not to teach craftsmen *how* to coordinate their tasks, but rather to seek a common high effort level to achieve low energy performance of the renovated building.

not yield higher coordination levels. Indeed, their exogenous sensitivity to successful and efficient coordination seems to be a sufficient mechanism to incentivize towards common high effort levels. Yet, when enforcing the subjects to play sequentially with a given amount of time for the entire group (i.e. time constraint, trained subjects playing before the last one in the group, seem to adopt a self-restricting strategy, so that they perform significantly worse than when facing an individual-based incentive. It seems that the possibility to not achieve efficient coordination causes them stress. Hence, trained subjects voluntarily target lower performance levels to have the certainty to reach a sufficient high performance, so that the last member in the sequence order has enough time to reach his or her acceptable target. Such a strong effect of time constraint is not visible on the coordination behavior of non trained subjects. Finally, our results suggest that the tested incentives have different impacts on the subject groups' worst performance levels. Indeed, individual-based incentives may be better suited for trained subjects to achieve the highest average worst performance, whereas group-based incentives seem to be more efficient to increase non trained subjects' worst performance.

Let us however mention that relatively few trained subjects could be mobilized to participate in the experiment. It would be interesting to conduct further sessions with trained craftsmen to validate the above mentioned results.

The rest of the chapter is structured as follows. Section 3.2 describes the experimental design. Section 3.3 presents the hypotheses of the paper, and Section 3.4 exposes descriptive statistics and the empirical results. Finally, in Section 3.5 we conclude after a discussion of our results.

3.2 Experimental design

The experiment consists of a real-effort game played repeatedly. Following Abeler et al. (2011) and Marchegiani et al. (2016), in all periods, subjects were confronted with a tedious and focus-demanding task, which consists of counting the number of ones in tables composed by 50 randomly placed ones and zeros. This real-effort task has various advantages: (1) no prior (economic) knowledge is needed from the subjects, (2) nearly no learning is possible from the subjects throughout the game periods, (3) subjects' performance is measurable without difficulty, (4) the boringness ensured a positive cost-of-effort from the subjects, and (5) the pointlessness ensured that no subject could derive any benefit (e.g. personal utility) from it. It ensures that the subjects all have the same utility by participating to this experiment. Furthermore, an important advantage of this simple task is that it is clearly artificial and the output has no value to the experimenter which should reduce tendency for subjects to increase their effort as a way to reciprocate for payments offered by the experimenter.

The experiment is divided in two main phases: an individual productivity elicitation phase and a phase which consists of repeated work. These two phases are detailed below, but Figure 3.2 presents in short the timing of a session. We first elicit individual productivity in Stage I, in order to set individual production targets. Then, Phase II comprises four successive stages, where subjects have to execute a real-effort task, wherein the incentives change from stage to stage.

Throughout the experiment, subjects were randomly assigned to a group of three players having the same exogenous training on coordination. The groups were fixed until the end of the session and it was not possible for a subject to know the identity of the other members of the group. During the experiment, subjects accumulated payoffs in ECU, with the conversion rule $100\,ECU = 1$ euro. The final gains were distributed anonymously in cash after having answered a post-experimental questionnaire in the End Phase.

Subjects were told about the total number of stages from the beginning, however, detailed instructions[4] were read out loud by the experimenter before starting each stage, to ensure that the game's description was common information. Subjects had the possibility to simultaneously read these instructions on paper and ask any question to the experimenter before beginning a stage.

Figure 3.2: Flow of the experiment

[4]The instructions are available in French in Appendix C.1.

3.2.1 The individual productivity elicitation

After a short (unpaid) training of two minutes (120 seconds), where subjects could become familiar with the task and the manipulation, subjects had five minutes (300 seconds) to count as many tables as possible. In order to elicit individual productivity, subjects were offered a pure piece-rate compensation scheme. For each table correctly processed, they receive 10 ECU. The gain from this first phase is then given by $\pi_i^{elicitation} = 10 \cdot P_{elicitation}$, where $P_{elicitation}$ is the number of tables resolved. Wrong answers were not penalized[5] and the number of tables resolved was displayed on the screen during the task. The screen also displayed a timer to make subjects aware of the time running.

The number of tables they correctly counted was used to design a feasible contractual effort in subsequent parts of the experiment, but subjects were not informed about this. As in Marchegiani et al. (2016) and Cosaert et al. (2019), this phase permitted to normalize the cost-of-effort for the task across players by scaling the *individual performance targets*, assigned in Phase II, to the subjects' actual abilities.

3.2.2 The repeated real-effort game

In Phase II, subjects play three stages repeatedly and the task is again to count ones. Instead of being paid piece-rate as in the previous phase, subjects are offered successively an individual-based and a group-based incentive. For reasons that are exposed below, the three stages are of different time length. In the Stages 1 and 2, subjects had to execute the task during five periods of two minutes (120 seconds) each.[6] The main difference between both is the incentive given to the subjects: either individual or group-based. In Stage 3, the subjects also face a group-based incentive but they do not play simultaneously. They are given six minutes (360 seconds) for the entire group, and the sequence of their intervention is imposed. After a group member reaches his or her acceptable target and passes her turn, or after he or she achieves his or her ideal target, the next subject executes the task with the remaining time.

[5] The subjects had three attempts to solve a table. After three errors, a new table appeared. This was done in order to prevent subjects to guess the number of ones too many times in a row. To prevent guessing, Abeler et al. (2011), for example, deducted a piece-rate of 10 cents when subjects failed in all three attempts.

[6] For the sake of simplification and contrary to Bortolotti et al. (2016), we decided to not sell extra time to subjects to achieve any of the targets.

Acceptable and ideal performance targets

The incentives offered to subjects are based on targets that were assigned to each subject. Indeed, in the beginning of Phase II, subjects were assigned two different individual targets they had to attain in terms of number of rightly counted tables. These targets were set individually following the productivity elicitation in Phase I. During Phase II, they were asked to at least reach the (1) *acceptable performance target*, denoted $P_i^{acceptable\,target}$ (it corresponds to 90% of the productivity exerted in Stage 1), and at best reach the (2) *ideal performance target*, denoted $P_i^{ideal\,target}$ (it corresponds to 110% of the productivity exerted in Stage 1).

In a two minutes period, individual performance targets to pursue were determined as follows[7]:

$$P_i^{acceptable\,target} = 90\% \cdot \frac{P_i^{elicitation}}{5\,min} \cdot 2\,min \tag{3.1}$$

$$P_i^{ideal\,target} = 110\% \cdot \frac{P_i^{elicitation}}{5\,min} \cdot 2\,min \tag{3.2}$$

Subjects were not made aware about how their targets had been determined, nor that every participant had different targets, according to their performance in the elicitation phase. We did not give them this information and announced the targets only in Phase II, in order to prevent from strategic behavior in Phase 1. We justify the 10% discount rate on the acceptable target by the tiredness that can result after repeating the task over and over. As mentioned by Marchegiani et al. (2016), the (acceptable) target should be achieved by exerting a high, but not too high, effort on the task[8]. The ideal target, however, has voluntarily been determined to be more difficult to achieve. Only very motivated subjects would thus try to attain it after having reached the acceptable target.

Why *two* different performance targets? Assigning subjects two different targets is a particularity of this experiment. To our knowledge, we are the first one to propose this. In a socio-economic environment, workers have tasks to execute. They can execute the minimum that has been required by their employer, or they can go further and perform

[7] $P_i^{acceptable\,target}$ was rounded downwards, whereas $P_i^{ideal\,target}$ was rounded upwards to prevent having the same acceptable and ideal targets for some subjects.

[8] Marchegiani et al. (2016) only assigned the subjects the equivalent of our acceptable task in their experiment.

their task even better. For example, a window installer can decide to "correctly" install a window, but he can also decide to install it in a air-tight way to gain energy efficiency of the building. Such tasks are often complementary with tasks of other co-workers. To continue our example, if not every co-worker achieves air-tightness, the energy performance of the building is decreased. We want the subjects to coordinate on the highest possible effort level. Thus, assigning them only one target corresponding to the highest level may not permit to determine whether the subject is willing to achieve the best possible performance, or just the acceptable one. By introducing two performance targets (acceptable and ideal), we can make the following observations. When a subject executes his task until reaching his acceptable performance target $P_i^{acceptable\,target}$, it might indicate that he is willing to coordinate on an acceptable high effort level. However, when he continues to execute it to reach his ideal performance target $P_i^{ideal\,target}$, it might indicate that he is willing to coordinate on an even higher effort level, that is, an ideal very high effort level. In other words, he wants to coordinate on a common goal with the other group members. Concerning the targets' names, we claim that, psychologically, reaching an "acceptable" target already represents an achievement. Wanting to continue until reaching an "ideal" target may indicate the willingness of subjects to accomplish their task in the best possible way, without being satisfied with the minimum acceptable.

Individual-based and group-based incentives

As explained above, Phase II is composed of three stages. In Stage 1, subjects played successively five periods of two minutes. In each period, their payoffs were determined according to an individual-based incentive. Following Bortolotti et al. (2016), the *Individual Incentive* for subject i in Stage 1, denoted π_i^{S1} is defined as follows:

$$\pi_i^{S1} = F + B \cdot \frac{ResolvedTables_i}{P_i^{acceptable\,target}} \tag{3.3}$$

were $ResolvedTables_i$ is the number of correctly counted tables by subject i, that is, the individual performance. We fixed $F = 100$ and $B = 800$. The higher the individual performance, the higher the gain. Contrary to Brandts and Cooper (2006), we did not impute the payment by the individual cost-of-effort, because our real-effort set-up permitted to normalize the cost-of-effort across the subjects.

In Stage 2, subjects also played successively five rounds of two minutes, but in each round, their payoffs were determined according to a group-based incentive. This incentive introduces a weak-link mechanism in order to induce subjects to coordinate on the highest effort level. The weak-link here corresponds to the worst performance of the three members of the group. The payoffs for a subject i in Stage 2 is defined as follows:

$$\pi_i^{S2} = F + B \cdot \min_{i \in 1,2,3} \left[\frac{ResolvedTables_i}{P_i^{acceptable\,target}} \right] \tag{3.4}$$

Incentives (3.3) and (3.4) correspond to a *high performance pay*, that is, low fixed payment F and high incentives B to coordinate at, respectively, execute, high effort levels (Cooper et al., 2018).[9]

In Stage 3, subjects faced the same group-based incentive (3.4). However, they do not play five rounds of 2 minutes each, but instead, execute the task during three periods of six minutes (360 seconds) each. The six minutes where however assigned to the entire group, and subjects had to play sequentially, contrary to before. They played one after another, with an enforced sequence. In each period, subjects had different playing sequence. Individual performance targets were kept unchanged. Indeed, by dividing the six minutes by three (group members), every group member should optimally play two minutes. Subjects had to reach at least $P_i^{acceptable\,target}$. Once attained, a button appeared on the screen to hand over to the next group member at any moment. In case they continued until maximum $P_i^{ideal\,target}$, the handing over occurred automatically.

This stage of the experience has the particularity to indirectly enforce the task chronology (and thus their coordination) among subjects. It was thus very important for the subjects to be attentive to give the last player enough time to reach his or her target. Otherwise, every group member would be impacted by receiving a low payment. Hence, the design of Stage 4 adds a time constraint, which results in a severe "punishment" for the entire group if not considered and respected. This time constraint also adds pressure on the subjects to work quickly to achieve their target.

As explained by Bortolotti et al. (2016), although we measure subjects' real effort, our *Group Incentive* (3.4) shares important characteristics with standard weak-link games[10]. First, the bonus B variates with the firm's (e.g. renovation work) worst performance. Second, subjects (e.g. employees, craftsmen) will receive a positive payment F, even when

[9] A *low performance pay*, on the contrary, has a high fixed payment F and low incentives B to coordinate at, or simply execute, high effort levels.

[10] Recall that they generally consider chosen-effort of subjects.

exerting no effort, or when one of the group members decides not to work. Thus, if realising the task represents a positive cost-of-effort for the subjects, they will only exert a positive effort when they expect every group member to do the same. Furthermore, the subjective cost-of-effort certainly being lower than the bonus amount B (because B has been set to a relatively high amount compared to F), successfully coordinating on reaching at least the acceptable target results in higher payments for all the group members. We thus replicate the trade-off of standard weak-link games, experienced by the subjects, between choosing the risky strategy (i.e. successfully coordinating on exerting high effort by at least achieving the acceptable target) and the safe strategy (i.e. exerting low effort because of the uncertainty that the other group members will exert a positive effort).

3.2.3 Procedures

Subjects were actual craftsmen working, among other, on energy renovations in the Region Grand Est in north-eastern France. They were recruited by the means of the Region Grand Est and coordinators of renovation platforms located in the entire region. They were invited to assist to an information meeting organized by the Region, where they were told that they could also participate in an economic experiment followed by a convivial aperitif organized by the University of Strasbourg. The experiment was conducted with mobile devices (tablets) of the Laboratory of Experimental Economics of Strasbourg (LEES), using the software EconPlay[11].

A total number of 36 subjects participated. The sessions were organized in different locations of the Region. The first session took place in Saint-Dié-des-Vosges in October 2018, with 27 non-trained (to coordination) craftsmen (75%).[12] The subject group with trained craftsmen was tested in a session organized in Sélestat in December 2018, with 9 subjects (25%). Thus, each subject was selected in only one subject group. The entire panel was composed of 9% of women, and 91% of men, who were on average between 41 and 50 years old. Some heterogeneity was to be observed in terms of education level across the panel, so that 34.28% had a higher education, and 5.71% had no education at all. Futhermore, there was no significant difference between trained and non-trained

[11]Software created by Kene Boun My, CNRS engineer at the University of Strasbourg (`www.econplay.fr`).

[12]One of the subjects left during the session because he had difficulties to read the ones and zeros in the tables. To permit the other players of its team to continue the experiment, we replaced the missing subject by one our colleagues of the University of Strasbourg. However, to ensure this member did not bias our results, we decided to eliminate its observation in the final database.

subjects in terms of revenue. The average earnings in the experiment was 32.91 euros (going from 27 to 39 euros). One session lasted one hour and a half, including time for instructions and the post-experience questionnaire.

Our experiment is thus a semi-field experiment, with a controlled environment, but with professionals instead of students. We had two main subject groups: (1) trained on coordination (denoted group T), and (2) non trained on coordination (denoted group NT) on a low energy renovation site. As explained above, craftsmen of subject group T were trained through the *DORéMI* energy renovation training course, which stands for "Operational Device for the Energy Renovation of Individual Houses". Table 3.1 hereafter, summarizes the "2 x 2" design of our experiment.

Table 3.1: Experimental "2x2" design

Subject Group / **Treatment**	*Trained to coordination (T)*	*Not trained to coordination (NT)*
Individual-based incentive (I)	T - I	NT - I
Group-based incentive (G)	T - G	NT - G

Between the periods, subjects had the possibility to briefly rest. During this pause, subjects received statistics on the number of tables they had to solve to attain their acceptable (resp. their ideal) target, the number of tables resolved during the period, the percentage of their acceptable (resp. ideal) target achieved, and their gain for the period. In Stage 3 and 4, where a group incentive was given, they additionally received statistics on the percentage of the acceptable (resp. ideal) target their two group members achieved respectively. Evidence of the efficiency of providing subjects' with information about the members of their own group's previous strategy choices, is mitigated in the literature. Engelmann and Normann (2010) find that it deteriorates efficient group coordination in groups of four, but that it is an efficient instrument in groups of six players. Berninghaus and Ehrhart (2001) find the same latter result with groups of eight, and Brandts and Cooper (2006) with groups of four subjects. Although our experiment analyses groups of only three players, we decided to implement this feature for two reasons. First, it is a more realistic real life situation, and, second, Van Huyck et al. (1990), among others, have shown that smaller groups tend to coordinate more efficiently than larger groups. We, however, choose to not show them information about other group's result, as Chen (2017) shows that it has no significant effect in improving coordination.

3.3 Predictions

We are interested in studying the difference in effort provision when given different types of incentives, namely, an *Individual-based Incentive* (I) and a *Group-based Incentive* (G). Furthermore, as we test these incentives on actual craftsmen, we analyse their coordination behaviour, whether they have been professionally trained for coordination in their work (T), or not (NT).

Participating, for instance, in a training course on the importance of coordination and its application to achieve efficient outcomes, contributes to make individuals more optimistic about coordination.[13] It aims to increase their positive beliefs about the efficiency of coordination. Hence, subjects presenting such a background (i.e. T) certainly are optimistic about the *chance* to achieve coordination at high and efficient levels. As long-term outcomes in coordination games are largely driven by initial beliefs (see Van Huyck et al., 1990), Cooper et al. (2018) state that assigning a *high performance pay*[14] to "optimists" (e.g. trained subjects) *increases the chance* of efficient coordination. Thus, as we assign a high performance pay to both of our subject groups (T and NT), it should intuitively be more efficient on subjects T than on subjects NT. This brings us to the first hypothesis, stated hereafter:

Hypothesis 1 *The average effort in subject groups T is higher than in subject groups NT.*

Considering more specifically the *Group-based Incentive*, it has been designed to induce efficient group coordination. In the weakest-link game, every subject wants to achieve a common goal. Moreover, they are all incentivized to play their "full part" in reaching this common goal, when assured that all the others will also play their "full part" (Barrett, 2016). The game has multiple (pure strategy) Nash equilibria, where subjects of a group have to coordinate and choose the *same* strategy. Indeed, this game does not allow for free-riding. If an individual is the only one to free-ride, he will be "punished" by receiving a low

[13] Note that we have in mind that the fact of being inclined to adopt a cooperative behaviour can also be inherent to a person. We therefore asked a specific question in the final questionnaire to be able to control for this aspect

[14] Recall, as explained in Section 3.2, that the incentive given to the subjects are a *high performance pay*: low fixed payment and high incentives to coordinate at, respectively, to execute high effort levels.

payment, as well as all his team members'[15], according to his achieved performance. He thus has no interest in doing so. Moreover, free-riding is offset by peer pressure (Kandel and Lazear, 1992; Meidinger et al., 2003). The weak-link of the *Group-based Incentive* actually exhibits an inherent peer pressure which encourages coordinated behaviour. Peer pressure has been found to be an efficient solution against coordination failure (Kandel and Lazear, 1992; Carpenter et al., 2009; Corgnet et al., 2015; Falk and Ichino, 2006) among subjects. Kandel and Lazear (1992) stress that the shame felt by the subjects performing worse than the group average, works as an efficient mechanism, and permits to understand the effectiveness of peer pressure. Falk and Ichino (2006) state that when pay is based on group incentives, peer pressure might be decisive in increasing performance, especially if group members can directly exert peer pressure in the form of sanctions. In our game, the peer pressure is exerted through the incentive design in the form of "global" punishment (i.e. low payment). The enhanced performance effect described by Falk and Ichino (2006) may nevertheless also occur in our game, especially because by exerting on low effort and thus achieving a low performance, the strategic uncertainty of the other members will increase. They will thus tend to choose the less risky strategy of a weak.link game, which is, not exerting a high effort. Otherwise, they might work hard without being paid. This situation will lead to a *productivity trap*, also called *performance trap*, mentioned, among others, by Brandts et al. (2007) and Cooper et al. (2018). Contrary to the *Individual-based Incentive*, once uncertainty about the others' future efforts is too high, coordinating on high effort levels is very difficult without the behavior of a controllable instrument as for example communication (through the intervention of an external manager (Brandts and Cooper, 2007), formal punishment (Dai et al., 2015; Vranceanu et al., 2015), or letting the subjects choose their group partners (Riedl et al., 2016; Chen, 2017). To avoid falling in a performance trap, subjects have thus no interest in exerting low effort levels. The peer pressure and the indirect punishment arising from the *Group-based Incentive*, but being absent with the *Individual-based Incentive*, the former incentive should incentivize to exert higher effort levels on average than the latter one, especially if subjects have never been trained to coordinate. This brings us to Hypothesis 2 stated hereafter:

Hypothesis 2 *In the NT group of subjects, the average effort with the Group-based Incentive is higher than with the Individual-based Incentive.*

[15]Recall that subjects are assigned to the same group with the same members during the entire experiment.

However, as explained for Hypothesis 1, assigning a high performance pay (which corresponds to both of our treatments I and G) to subjects T, increases the chance of coordination at high effort levels. Recall that their training may have made their prior beliefs more optimistic about efficient coordination. Thus, the *Group Incentive* is not as incentive on subjects T than on subjects NT, who on average have a less optimistic prior belief on efficient coordination. In other words, the *Group Incentive* might not be more incentive on subjects T than the *Individual Incentive*. This brings us to our last hypothesis, stated as follows:

Hypothesis 3 *In the T group of subjects, the average effort with the Group-based Incentive is not higher than with the Individual-based Incentive.*

3.4 Results

This section presents the main results of our experiment. We first look at some descriptive characteristics of our sample of craftsmen. We then run a series of non-parametric tests in order to validate our hypotheses. An econometric estimation of the drivers of individual performance confirm our predictions and concludes this section.

3.4.1 Descriptive statistics

In our sample of craftsmen, 74% are self-employed and 26% work for a general contractor in the building industry[16]. 89% of the involved firms are "RGE" labeled, which stands in French for "Recognized as environmentally responsible". This label is mandatory in the energy renovation sector in France, in order for the project owners (i.e. clients) to apply for governmental financial aids. This high percentage indicates that, in order to stay competitive and attractive in the energy renovation sector, a firm must apply for this environmental label. Furthermore, 20% of our subjects are specialized in more than one trade, and nearly half of the panel has been working in the building sector for more than 20 years.

In the final questionnaire of the experiment, we ask them a series of general and specific questions about their work as well as coordination at work. Interestingly, it appears that their opinion about coordination depends on the presence or absence of a project manager

[16] General contractors in the building industry include several trades, and can thus propose complementary works to project owners willing to renovate their building.

during the execution phase. The role of a project manager is to help the craftsmen to coordinate their different tasks and interventions on a construction/renovation site. In *presence* of a project manager, T and NT craftsmen evaluate the difficulty to coordinate their tasks during the work, on average around 4.66 on a scale going from 1 to 10, with 10 finding it very difficult to coordinate. This is a rather low estimated difficulty, which tends to show that the intervention of a project manager may reassure workers. Yet, *without* project manager, T subjects find it significantly *more* difficult than NT to coordinate their task with others[17]. A possible explanation may be that T subjects are more sensitive to efficient and successful coordination than NT ones. By answering this question, they may thus have thought in the difficulty of achieving an efficient coordination, resulting in the expected outcome in terms of building performance.

Nevertheless, in *presence* of a project manager, T subjects feel significantly more motivated in trying to coordinate their tasks with others than NT subjects. *Without* manager, however, there is no significant motivation difference between both subject groups. Note that, on average, the subjects of the panel estimates their confidence in their co-workers to be 6.54 on a scale going from 1 to 10. This mitigated confidence level may explain the lessened motivation towards coordination in the absence of a project manager. Yet, in general, T subjects feel significantly more enthusiastic than NT subjects, to coordinate their interventions with their co-workers.

All in all, all subjects believe that it is (very) important to try to coordinate the tasks of all the craftsmen present on a project, and attach great importance to their reputation in the energy renovation sector.

3.4.2 Non-parametric analysis

In this subsection, we analyze the results of the experiment, using the statistical non-parametric Wilcoxon-Mann-Whitney test (with Z, the test's statistic). It permits to test the null hypothesis saying that the medians of two groups are similar.[18] The test does *not* assume a normal distribution, and when the null hypothesis is rejected[19], we can conclude to have a significant difference between both groups.

[17] On average, 6.57 out of 10 for T, compared to 4.88 out of 10 for NT craftsmen.

[18] In other words, the likelihood that a randomly selected variable from the first group is lower or greater than a randomly selected variable from the second group, is equal.

[19] When the p-value of the Wilcoxon rank-sum test is lower than 0.10, the null hypothesis is rejected.

Productivity elicitation

In Phase I, during the individual productivity elicitation, both subject groups (T and NT) had five minutes to resolve as many tables as possible. Figure 3.3 displays, for both groups, the average number of tables they were able to resolve rightly, and those validated with the wrong number of ones counted.

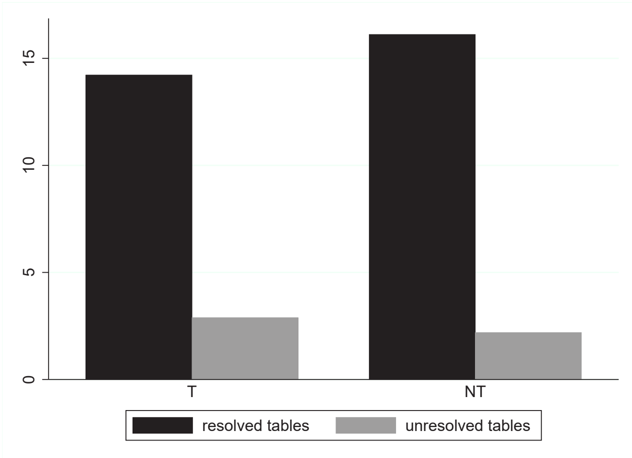


Figure 3.3: Average number of correctly and wrongly resolved tables in the elicitation phase

At first glance, we observe that NT subjects resolved more tables than T, however, the difference between both groups is *not* significant[20]. Whether trained or not, our subjects are not different in terms of individual capacity (i.e. ability) of counting ones in tables. It will thus be possible to compare their performance in the three Stages of the experiment.

Performance indicator

The individual performance targets, given to the subjects in Phase II, are based on the capacity that each subject revealed in Phase I. On the basis of these targets, we determined two *individual performance indicators*. The first one, denoted $PerfIndicator_i^{acceptable}$, is the ratio between the number of revolved tables, and the individual *acceptable* target, as shown hereafter:

$$PerfIndicator_i^{acceptable} = \frac{ResolvedTables_i}{P_i^{acceptable\,target}} \tag{3.5}$$

[20] $Z = -1.079$, p-value $= 0.281$

The second indicator, denoted $PerfIndicator_i^{ideal}$, is the ratio between the number of revolved tables, and the individual *ideal* target, as presented hereafter[21]:

$$PerfIndicator_i^{ideal} = \frac{ResolvedTables_i}{P_i^{ideal\,target}} \tag{3.6}$$

In other words, the performance indicators give us the percentage of a target (acceptable or ideal) that has been achieved by the subjects. Recall that in our experiment, the period ended automatically once a subject achieved his ideal target. Hence, $PerfIndicator_i^{ideal}$ cannot be superior to 100%, contrary to $PerfIndicator_i^{acceptable}$.

Table 3.2 summarizes the average performance indicators of both groups of subjects, throughout the stages, where different incentives are given. It also indicates the average worst group performances throughout the stages[22]. As a reminder, Stage 1 tested an individual-based incentive (**I**), Stage 2 tested a group-based incentive *without* time constraint (**G**), and Stage 3 tested a group-based incentive *with* time constraint (**G + t.c.**), where the entire group had a given time to accomplish the individual tasks *sequentially*.

Table 3.2: Summary of average acceptable, ideal and worst group performances of T and NT when facing different incentives

Performance indicator	**I**	**G**	**G + t.c.**
Trained to coordination (T)			
$\overline{PerfIndicator}_{acceptable}$	142.4 %	142.8 %	138.9 %
$\overline{\min_{i\in 1,2,3}\left[PerfIndicator_i^{acceptable}\right]}$	117 %	112.2 %	112.6 %
$\overline{PerfIndicator}_{ideal}$	90.9 %	90.9 %	88.3 %
$\overline{\min_{i\in 1,2,3}\left[PerfIndicator_i^{ideal}\right]}$	79.9 %	77.5 %	74.3 %
Not trained to coordination (NT)			
$\overline{PerfIndicator}_{acceptable}$	121.9 %	131.8 %	130.5 %
$\overline{\min_{i\in 1,2,3}\left[PerfIndicator_i^{acceptable}\right]}$	100 %	113.7 %	110.6 %
$\overline{PerfIndicator}_{ideal}$	84.2 %	90.2 %	90.1 %
$\overline{\min_{i\in 1,2,3}\left[PerfIndicator_i^{ideal}\right]}$	68.7 %	79.5 %	76.3 %

I: *Individual-based incentive*, G: *Group-based incentive*, t.c.: *time constraint*.

Observing the average performances throughout the experiment, both subject groups always perform better than their acceptable target, but never achieve their ideal target. In

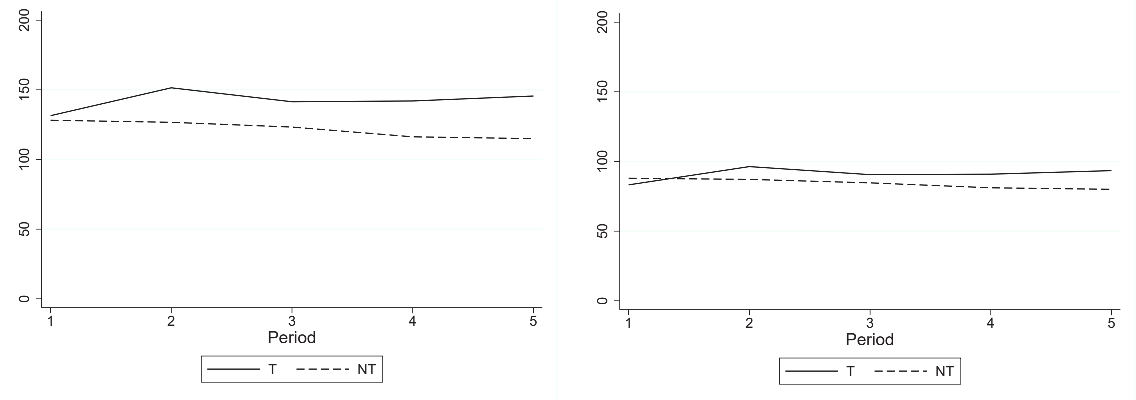
[21]Recall that $P_i^{acceptable\,target}$ is the individual's acceptable target, $P_i^{ideal\,target}$ is the individual's ideal target, and $ResolvedTables_i$ is the number of tables resolved by the individual.

[22]Recall that the worst group performance is actually the minimum $PerfIndicator_i^{acceptable}$ of a group

the remaining of the subsection, we analyze and interpret the different achieved performances summarized in Table 3.2.

Individual-based incentive

The performances presented in Table 3.2 show that on average, T subjects, who have been trained and sensitized on efficient coordination, performed better than NT subjects when facing an individual-based incentive. Figure 3.4 displays the averages throughout the five periods of Stage 1, and we observe that T subjects achieve higher percentages of their targets than NT subjects in all five periods. This is true for both types of performance and the difference is statistically significant[23].



(a) $PerfIndicator_i^{acceptable}$ (b) $PerfIndicator_i^{ideal}$

Figure 3.4: Evolution of subjects' average performance throughout the five periods of facing an individual-based incentive (Stage 1)

Hypothesis 1 of the paper is thus confirmed with the following result:

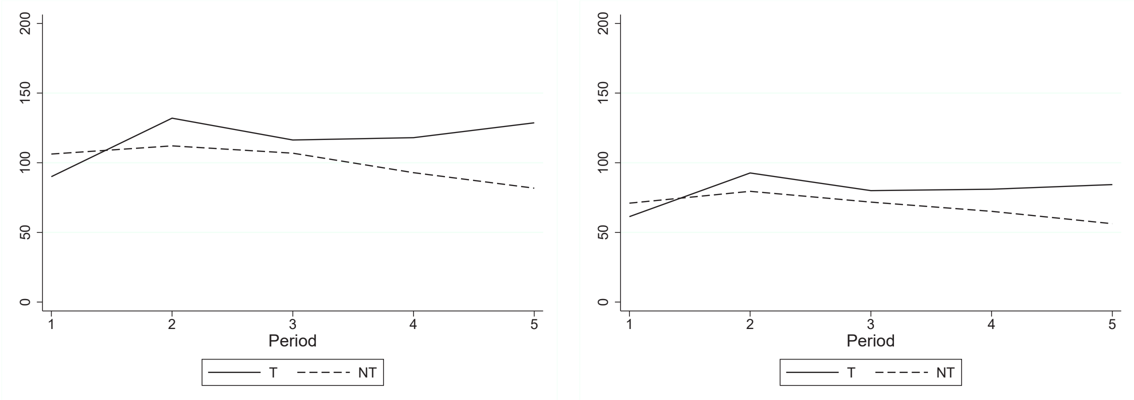
Result 1 *When facing an individual-based incentive, ex-ante trained subjects (T) are more efficient than the non-trained ones (NT) towards coordinating at their target levels.*

This first result seems to indicate that training about coordination may have an effect on how subjects are willing to coordinate on higher effort levels. The subjects who have been trained are significantly more efficient than the others.

This finding is also visible when observing the average worst performances of each group, on Figure 3.5. Apart from the first period, T subjects' worst performances are higher than those of NT subjects'. The Wilcoxon rank-sum test indeed shows us that, on average, T group subjects' worst performance are significantly higher than NT group

[23] $PerfIndicator_i^{acc.}$: $Z = 4.548$, p-value $= 0.000$; $PerfIndicator_i^{ideal}$: $Z = 2.011$, p-value $= 0.044$

subjects', when facing an individual-based incentive.[24] We can also see that, contrary to T, NT group subjects' worst performance has the tendency to decrease over the periods of the Stage, indicating a tiredness or a decrease in the motivation to coordinate efficiently.



(a) $\min_{i\in 1,2,3}\left[PerfIndicator_i^{acceptable}\right]$ (b) $\min_{i\in 1,2,3}\left[PerfIndicator_i^{ideal}\right]$

Figure 3.5: Evolution of the groups' average worst performance throughout the five periods of facing an individual-based incentive (Stage 1)

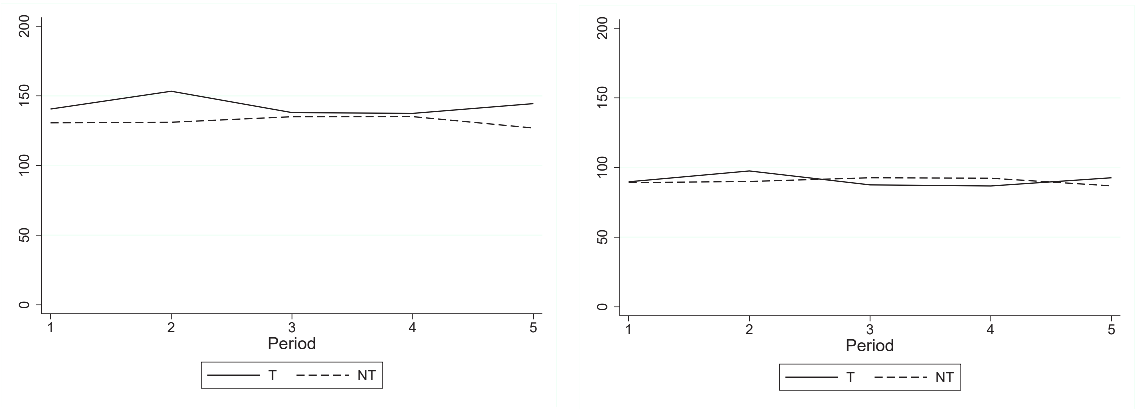
Let us now analyze subjects' performances when facing a group-based incentive.

Group-based incentive *without* time constraint

In Stage 2 of the experiment, subjects were confronted with group-based incentives, so that their payoff depended on the worst performance of all the members of a team. They still play simultaneously (i.e. *without* time constraint). This means that they were not enforced to "manage" the time given to their other team members to execute their task.

In Table 3.2, we do not see much difference between T and NT subjects. When observing the evolution of T subjects' coordination levels on Figure 3.6, we see that their average performance stays similar throughout the five periods of Stage 2. However, when comparing stages 1 and 2, we can clearly see that NT subjects' average performance increased a lot compared to when under individual-based incentive as displayed in Figure 3.4. This important effect on NT subjects' performance is such that both groups' coordination levels seem to end up being more or less confounded, especially with regard to the ideal target.

[24] $WorstPerfInd._{group}^{acc.}$: $Z = 3.454$, p-value $= 0.001$; $WorstPerfInd._{group}^{ideal}$: $Z = 3.189$, p-value $= 0.001$



(a) $PerfIndicator_i^{acceptable}$ (b) $PerfIndicator_i^{ideal}$

Figure 3.6: Evolution of subjects' average performance throughout the five periods of facing a group-based incentive *without* time constraint (Stage 2)

Wilcoxon rank-sum test shows that NT subjects perform better when knowing that their payoff also depends on the performance of their team members. Indeed, compared to when facing an individual-based incentive, they coordinate at significantly higher effort levels (with respect to their targets) when given a group-based incentive[25]. On the contrary, we observe that T subjects do not significantly perform better with a group-based, than with an individual-based incentive[26]. Interestingly, it seems that having been trained leads to an already high level of performance, such that the group-based incentive does not impact coordination behaviour. This leads us to the Result 2, that validates hypotheses 2 and 3:

Result 2 *When facing a group-based incentive (without time constraint), contrary to T subjects, NT subjects coordinate at more efficient performance levels than when facing an individual-based incentive.*

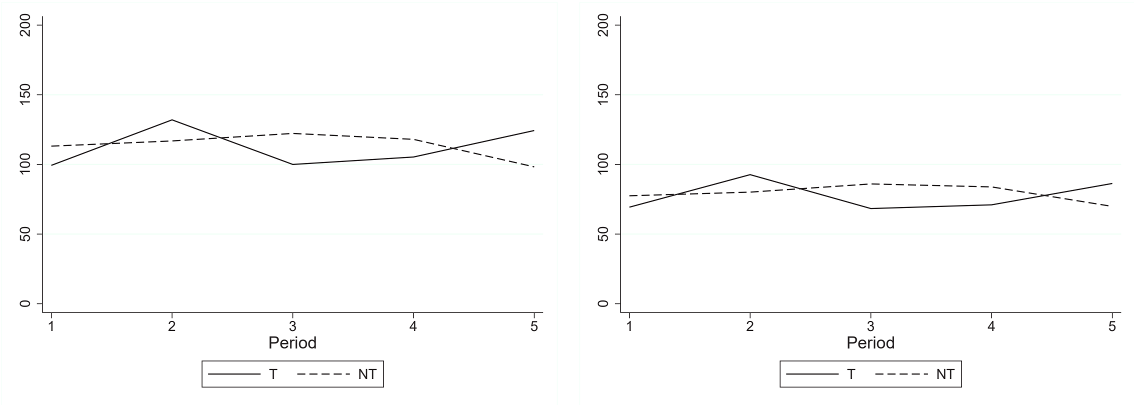
This result may partly be due to the increase in performance of NT subject groups' average worst performance when facing a group-based incentive, compared to when facing an individual-based incentive. We indeed find that NT subject groups' worst performance is significantly higher with the group-based incentive than with the individual-based incentive.[27] Although we observe more variation of the worst performance for T subject groups throughout the periods with the group-based incentive, than with the individual-based

[25] $PerfIndicator_i^{acc.}$: $Z = -2.575$, p-val $= 0.010$; $PerfIndicator_i^{ideal}$: $Z = -2.726$, p-value $= 0.006$

[26] $PerfIndicator_i^{acc.}$: $Z = 0.070$, p-value $= 0.945$; $PerfIndicator_i^{ideal}$: $Z = -0.263$, p-value $= 0.793$

[27] $WorstPerfInd._{group}^{acc.}$: $Z = -4.147$, p-value $= 0.000$; $WorstPerfInd._{group}^{ideal}$: $Z = -3.967$, p-value $= 0.000$

incentive, we find that the difference is not significant (as for the average performance of every T subject).[28] Figure 3.7, hereafter, displays both subject groups' average worst performance when facing a group-based incentive *without* time constraint.



(a) $\min_{i \in 1,2,3}\left[PerfIndicator_i^{acceptable}\right]$ (b) $\min_{i \in 1,2,3}\left[PerfIndicator_i^{ideal}\right]$

Figure 3.7: Evolution of the groups' average worst performance throughout the five periods of facing a group-based incentive *without* time constraint (Stage 2)

Yet, regarding total performances, we observe that when facing such a group-based incentive, T subjects still significantly perform better than NT subjects, towards coordinating at their acceptable target[29], contrary to coordinating towards their ideal target[30].

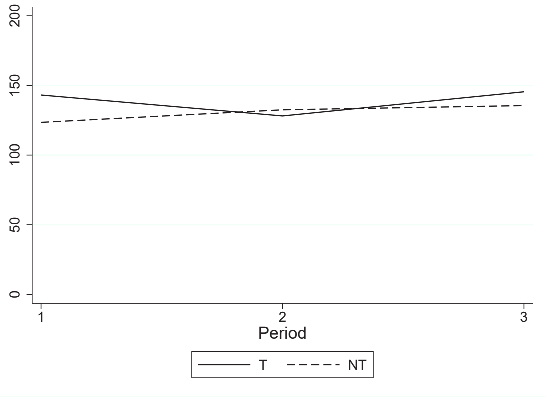
Group-based incentive *with* time constraint

In the last stage of the game (Stage 3), subjects were confronted with a group-based incentive with time constraint. They had a given time for their entire team, and had to play sequentially. The sequence of their respective intervention was enforced, since every of the three team members experienced all the positions (1^{st}, 2^{nd}, or 3^{rd} member to intervene) throughout the three periods of the stage. This set-up enforced the subjects playing in the first and second position to "manage" the time they allow for the next team members. Indeed, leaving the last player not enough time to coordinate at a high enough performance level, would impact the payoff of all the members.

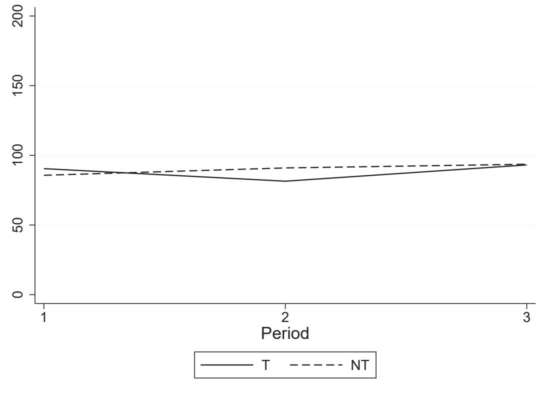
Regarding subjects' average coordination performance levels, we notice that there is no clear "domination" from one group of subjects to the other (see Table 3.2). As for Stage 2, we do not observe differences throughout the three periods of Stage 3 in Figure 3.8. The

[28] $WorstPerfInd._{group}^{acc.}$: $Z = 1.435$, p-value $= 0.151$; $WorstPerfInd._{group}^{ideal}$: $Z = 1.175$, p-value $= 0.240$
[29] $Z = 2.531$, p-value $= 0.011$
[30] $Z = 0.328$, p-value $= 0.743$

Wilcoxon rank-sum test, indeed, shows that, there is, on average, no significant difference between T and NT subjects' coordination performance, when playing sequentially, while facing a group-based incentive[31].



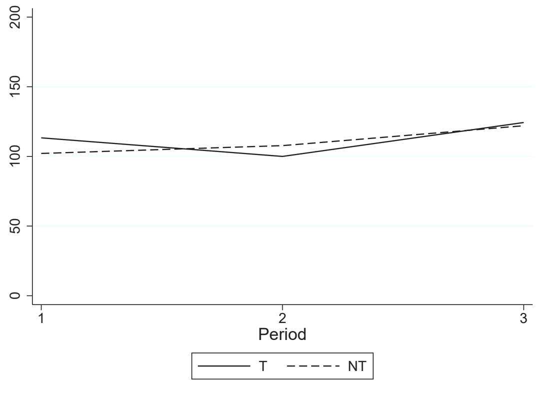
(a) $PerfIndicator_i^{acceptable}$



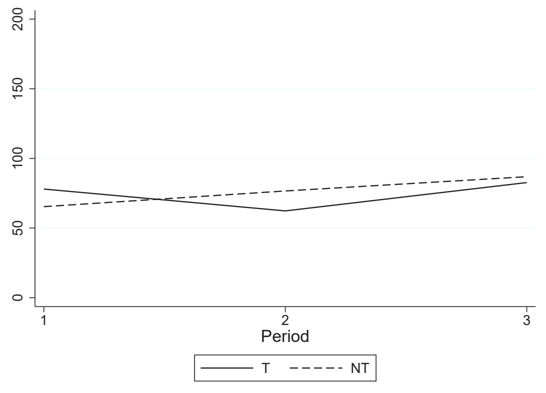
(b) $PerfIndicator_i^{ideal}$

Figure 3.8: Evolution of subjects' average performance throughout the three periods of facing a group-based incentive *with* time constraint (Stage 3)

The distribution of both groups' average worst performance is very similar to the total performance, as can be seen on Figure 3.9, hereafter. We find that there is no significant difference between T and NT group subject's average worst performance, when facing a group-based incentive *without* time constraint.[32]



(a) $PerfIndicator_i^{acceptable}$



(b) $PerfIndicator_i^{ideal}$

Figure 3.9: Evolution of the groups' average worst performance throughout the three periods of facing a group-based incentive *with* time constraint (Stage 3)

Although it is important to notice that these results do not take into account the sequence order in which the subjects intervened. The sequential set-up being a notable

[31] $PerfIndicator_i^{acc.}$: $Z = 1.368$, p-value $= 0.171$; $PerfIndicator_i^{ideal}$: $Z = -0.659$, p-value $= 0.510$
[32] $WorstPerfInd._{group}^{acc.}$: $Z = 0.232$, p-value $= 0.816$; $WorstPerfInd._{group}^{ideal}$: $Z = -0.821$, p-value $= 0.412$

difference with the previously one in Stage 2 (i.e. group-based incentive *without* time constraint), the order of play may affect the performance. The average performances, given the sequence order, and with respect to subjects' acceptable and ideal targets, are summarized in Figure 3.10.

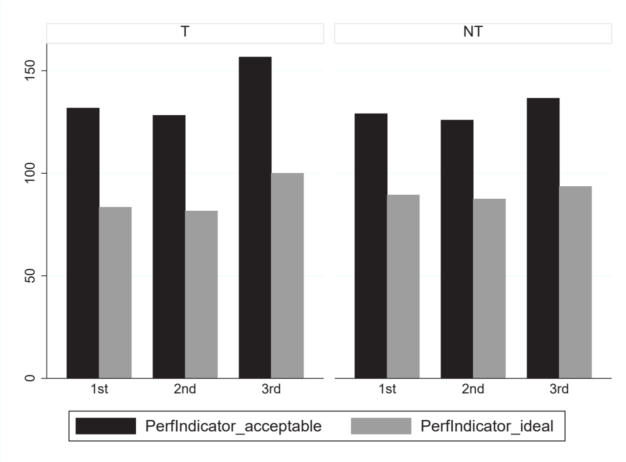


Figure 3.10: Subjects' average performance according to their sequence order

A first observation is that, when playing in the 3^{rd} position, T subjects achieve 100% of their ideal target. This was, on average, not the case when playing simultaneously. We indeed find that there is a significant difference of T subjects' coordination performance, towards reaching their *ideal* target[33]. This is not the case towards reaching their *acceptable* target[34], and for NT subjects, who perform significantly equally than without time constraint (i.e. Stage 2)[35].

Regarding the effect of time constraint on T subjects, we observe that, while there is no significant difference between those intervening at the first and second position[36], the last player to intervene performs significantly better than the first two players[37].

These results indicate that time constraint may affect T subjects' coordination performances. A possible mechanism may be the stress felt by T subjects intervening before the last one. As they seem to be more sensitive than NT subjects towards high and successful coordination (cf. Result 1), the possibility to *not* achieve efficient coordination causes them stress. As a response strategy, we notice that they censor themselves by voluntar-

[33] $PerfIndicator_i^{ideal}$: $Z = -2.157$, p-val $= 0.031$
[34] $PerfIndicator_i^{acc.}$: $Z = -1.219$, p-val $= 0.223$
[35] $PerfIndicator_i^{acc.}$: $Z = -0.810$, p-val $= 0.418$; $PerfIndicator_i^{ideal}$: $Z = -1.386$, p-val $= 0.166$
[36] $PerfIndicator_i^{acc.}$: $Z = 0.139$, p-value $= 0.889$; $PerfIndicator_i^{ideal}$: $Z = 0.226$, p-value $= 0.821$
[37] 1^{st} vs. 3^{rd}: $PerfInd_i^{acc.}$: $Z = -1.74$, p-val $= 0.082$; $PerfInd_i^{ideal}$: $Z = -2.840$, p-val $= 0.005$
2^{nd} vs. 3^{rd}: $PerfInd_i^{acc.}$: $Z = -2.011$, p-value $= 0.044$; $PerfInd_i^{ideal}$: $Z = -2.842$, p-val $= 0.005$

ily targeting a lower performance level and have the *certainty* to reach a sufficient high performance (even if lower than what they could have reached with more time), so that the last member has enough time to reach his or her acceptable target. This observation is supported by the fact that T subjects perform significantly worse (when not the last player) when facing a group-based incentive with time constraint, than when facing an individual-based incentive[38].

This brings us to a third result:

Result 3 *When playing sequentially and facing a group-based incentive, T subjects intervening before the last member are less efficient at coordinating on high effort levels than the last member. Moreover, time constraint makes them perform worse than when facing an individual-based incentive without time constraint.*

Regarding NT subjects, we find that they do not perform significantly better when being the last member to intervene, than when not.[39] Yet, when playing as the first or second member, we observe that NT subjects do *not* perform significantly better, than when facing an individual-based incentive.[40] *Without* time constraint, this was however the case (cf. Result 2). Nevertheless, they also do *not* significantly perform worse *with* than *without* time constraint.[41] Hence, in a first place, time constraint seemed to put a certain pressure on players intervening before the last one. Yet, in a second place, it becomes clear that it does not significantly alter the efficiency of giving NT subjects a group-based, instead of an individual-based incentive. Note that when considering the average performance of all the group members, we find that NT subjects perform significantly better with the group-based (*with* time constraint), than with the individual-based incentive.[42]

This brings us to a fourth result, presented hereafter:

Result 4 *Time constraint has a limited impact on NT subjects playing before the last member, so that we observe that it is more efficient (in terms of coordination) to give NT subjects a group-based incentive (when playing simultaneously or sequentially), than an individual-based incentive.*

[38] $PerfIndicator_i^{acc.}$: $Z = 1.977$, p-value $= 0.048$; $PerfIndicator_i^{ideal}$: $Z = 2.220$, p-value $= 0.026$

[39] 1^{st} vs. 3^{rd}: $PerfInd_i^{acc.}$: $Z = -1.091$, p-val $= 0.275$; $PerfInd_i^{ideal}$: $Z = -1.132$, p-val $= 0.258$
2^{nd} vs. 3^{rd}: $PerfInd_i^{acc.}$: $Z = -1.315$, p-value $= 0.189$; $PerfInd_i^{ideal}$: $Z = -1.518$, p-val $= 0.129$

[40] $PerfIndicator_i^{acc.}$: $Z = -1.042$, p-val $= 0.297$; $PerfIndicator_i^{ideal}$: $Z = -1.348$, p-val $= 0.178$

[41] $PerfIndicator_i^{acc.}$: $Z = 1.065$, p-value $= 0.287$; $PerfIndicator_i^{ideal}$: $Z = 0.604$, p-val $= 0.546$

[42] $PerfIndicator_i^{acc.}$: $Z = -1.987$, p-val $= 0.047$; $PerfIndicator_i^{ideal}$: $Z = -2.400$, p-val $= 0.016$

To understand why the difference between the first two and the last member to play, is significant for T, let us take a look at the time subjects spent to execute their task. As the entire team was given six minutes (360 seconds) to play, every member should optimally have played two minutes (120 seconds) each. Figure 3.11, hereafter, displays the time spent by T and NT to execute their task, with respect to their order of intervention.

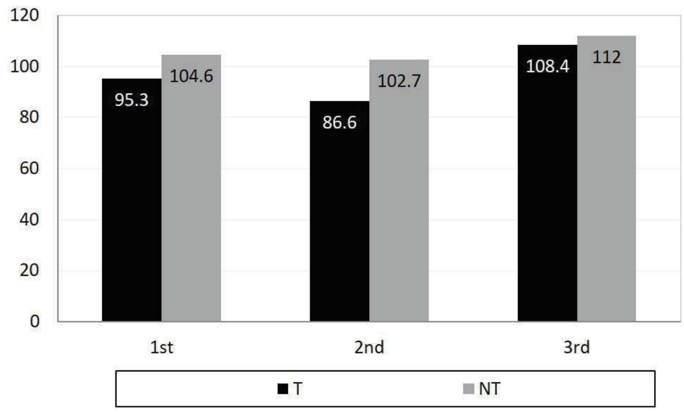


Figure 3.11: Average time spent for the task, given the subjects' sequence order (in seconds)

A first obvious observation, is that on average, teams did not use the entire time at their disposal. Yet, we note only a significant difference in time spent, between N and NT, when being the 2^{nd} member to play.[43] More interestingly, for T and NT respectively, there are significant differences in time spent, between all the incentive types.[44] On average, subjects needed (or used) significantly *more* time to achieve their targets with the individual-based incentive than with the group-based incentive, and this difference is even larger with the group-based incentive *with* time constraint.[45] When facing a group-based incentive, both groups also spent significantly more time *without* than *with* time constraint.[46]

By contemplating the average performances of the entire group (the last member to intervene, included), when playing sequentially and facing a group-based incentive, we find that T subjects do not perform significantly worse anymore than when facing an individual-based incentive[47] or a group-based incentive *without* time constraint[48]. As

[43] 1^{st}: $Z = -0.849$, p-val $= 0.396$; 2^{nd}: $Z = -1.851$, p-val $= 0.064$; 3^{rd}: $Z = -0.472$, p-val $= 0.637$

[44] Except for T, who do not spend significantly *more* time with the individual-based, than with the group-based incentive *without* time constraint ($Z = 0.572$, p-value $= 0.567$)

[45] For T, individual vs. group *with* time constraint: $Z = 2.111$, p-value $= 0.035$
For NT, individual vs. group *without* time c.: $Z = 2.244$, p-value $= 0.025$; individual vs. group *with* time c.: $Z = 3.257$, p-value $= 0.001$

[46] *Without* vs. *with* time c., for T: $Z = 1.836$, p-val $= 0.066$; for NT: $Z = 1.817$, p-val $= 0.069$

[47] $PerfIndicator_i^{acc.}$: $Z = 0.837$, p-val $= 0.4024$; $PerfIndicator_i^{ideal}$: $Z = 0.596$, p-val $= 0.552$

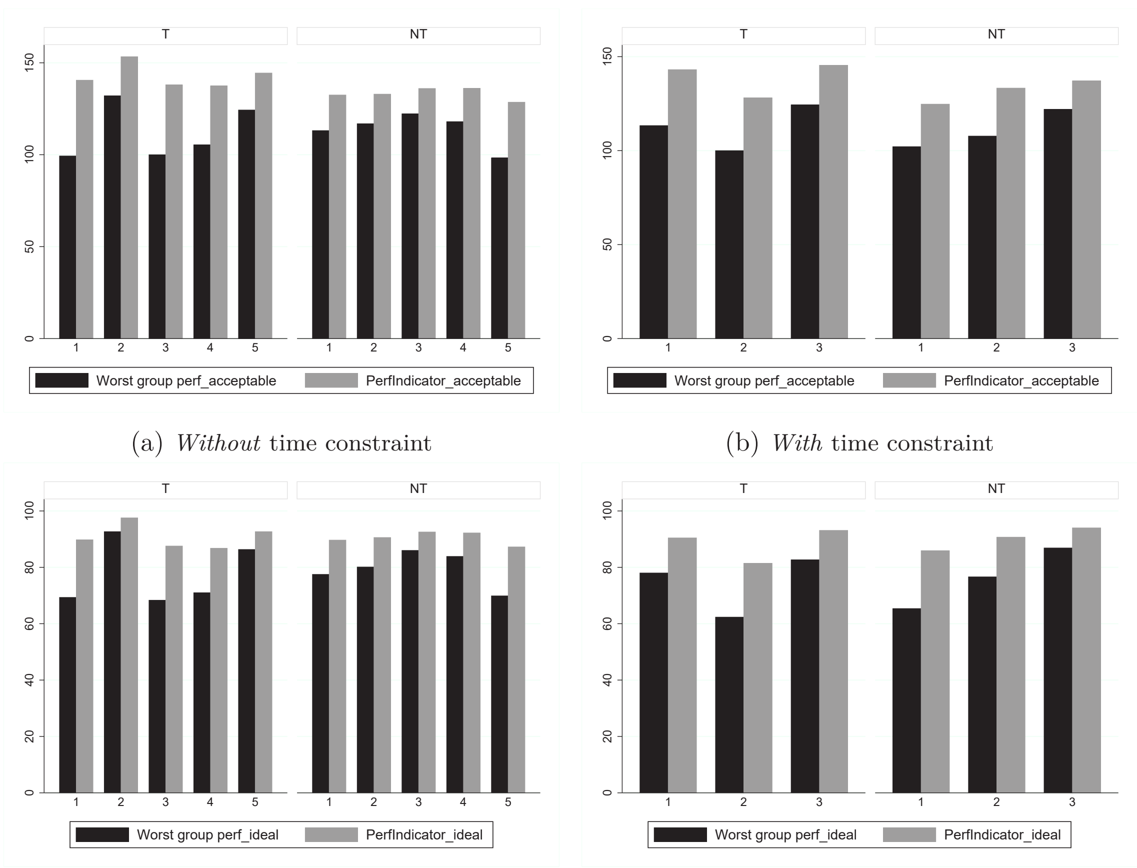
[48] $PerfIndicator_i^{acc.}$: $Z = 0.705$, p-val $= 0.481$; $PerfIndicator_i^{ideal}$: $Z = 0.748$, p-val $= 0.455$

mentioned earlier, the inclusion of the last member's coordination performance level significantly increases the global performance of the group. However, the previous analysis on subjects' performance level when they are not the last in the sequence, shows us a decreased performance of the first and second subjects compared to *without* time constraint. Hence, when facing a group-based incentive, all the members of the group will be "punished" by receiving a lower payment. This indicates that time constraint has a twofold negative impact regarding T subjects: (1) it lowers their coordination performance level, and (2) it lowers their final payoffs.
These findings allow us to state a last result:

Result 5 *We observe that it is not efficient to impose time constraint on T subjects, because it "inhibits" their coordination performance, and punishes them by lowering their payments.*

Interestingly when subjects face a group-based incentive, not all the team members seem to be responsible for lowering the coordination level (and thus the payoff) of the group throughout the periods. Indeed, the worst group performance in the first period does not seem to negatively influence the other group members' in the following periods. This result is in accordance with the observations made by Bortolotti et al. (2016), but it is different to standard chosen effort experiments results where a bad performance in the beginning of a stage has been shown to spoil the performance of the whole team for the remaining periods. This phenomenon is visible in Figure 3.12 that shows the average performances for each period of Stages 2 and 3. Note also that there is no significant difference in the average worst group performance level, between T and NT subjects[49].

[49] $WorstPerfInd^{acc.}_{group}$: *Without* time constraint: $Z = -1.259$, p-val $= 0.208$; *with* time constraint: $Z = 0.232$, p-val $= 0.816$
$WorstPerfInd^{ideal}_{group}$: *Without* time constraint: $Z = -1.464$, p-val $= 0.143$; *with* time constraint: $Z = -0.821$, p-val $= 0.412$



(a) *Without* time constraint

(b) *With* time constraint

(c) *Without* time constraint

(d) *With* time constraint

Figure 3.12: Evolution of the average worst group performances and their $PerfIndicator$ throughout the periods of facing a group-based incentive

Nevertheless, we see that on average, the worst group performance reaches at least subject's acceptable target level (see Figure 3.12 (a) and (b)), which indicates that they at least try to achieve their "first" target (i.e. a "good quality" work). On the contrary, the ideal target is never attained by T, nor by NT subjects (see Figure 3.12 (c) and (d)).

3.4.3 Econometric analysis

In order to verify the validity of our results, we perform an econometric analysis where we control for a series of factors, namely, heterogeneity of the subjects. To do so, we apply a multiple linear regression analysis by running different model specifications. The econometric model for a subject i can be written as follows:

$$PerfIndicator_i^p = \alpha + \gamma Z_i + \beta_K X'_{iK} + \varepsilon_i$$

where $PerfIndicator_i^p$ with $p = (acceptable, ideal)$ are the dependent variables, α represents the intercept, γ is the estimated coefficient of the independent variable Z, β_K captures the estimated coefficient for the vector X_K which includes K exogenous control variables[50] and ε_i the error term. The tables 3.3, 3.4 and 3.5, hereafter, display different regressions. In Table 3.3, the first two specifications are concerned with Stage 1 (individual-based incentives), specifications 3 and 4 with Stage 2 (group-based incentives *without* time constraint). We compare T and NT subjects' average performances when facing those incentives. The last two columns (5 and 6) compare the individual-based and the group-based incentive *without* time constraint, for T and NT respectively.

As stated in Result 1 when facing an individual-based incentive, T subjects perform significantly better towards coordinating at their acceptable target[51], than NT subjects (column 1). Result 1 needs however to be moderated, as this difference is not significant towards reaching their ideal target[52] (column 2), contrary to the results of the non-parametric analysis. When controlling for other factors these latter results are not significant anymore.

Regarding the performance difference between T and NT, when facing a group-based incentive (*without* time constraint), we find that T subjects do *not* perform significantly better than NT subjects, regardless of the performance targeted ($PerfIndicator_i^{acc.}$[53] in column 3, and $PerfIndicator_i^{ideal}$[54] in column 4). Recall that with the non-parametric analysis, we found a significant difference between both groups, towards reaching their ideal target. This interesting new finding implies the following result:

Result 6 *When facing a group-based incentive, NT subjects "catch up" the performance levels T subjects acquired with their exogenous training, so that there is no significant difference in coordination performance between both groups.*

Now comparing both incentive types with regard to T and NT subjects respectively, we find that, as stated in Result 2, NT subjects perform significantly better when given a group-based, than an individual-based incentive ($PerfIndicator_i^{acc.}$[55] in column 5, and

[50] The control variables included in the model specifications are the dummy variables *Age>40* (Age>40 = 1 if the subject is more than 40 years old, and 0 otherwise), *Men* (Men = 1 if the subject is a man, and 0 otherwise), and *High education* (High education = 1 if the subject has a diploma higher than high-school, and 0 otherwise).

[51] t-statistic = 2.34, p-value = 0.025

[52] t-statistic = 1.33, p-value = 0.192

[53] t-statistic = 1.28, p-value = 0.209

[54] t-statistic = 0.31, p-value = 0.757

[55] t-statistic = 3.03, p-value = 0.005

$PerfIndicator_i^{ideal}$[56] in column 6). Moreover, we see that, as before, T subjects do not perform significantly differently when facing a group-based (*without* time constraint), than when facing an individual-based incentive ($PerfIndicator_i^{acc.}$[57] in column 5, and $PerfIndicator_i^{ideal}$[58] in column 6). This confirms the fact that the exogenous training followed by NT subjects may play a role in T subjects' coordination behaviour, and that adding a group-based incentive does not lead them towards even higher coordination levels.

Table 3.3: Determinants of performance in I and G

	(1) $PerfInd^{acc.}$	(2) $PerfInd^{ideal}$	(3) $PerfInd^{acc.}$	(4) $PerfInd^{ideal}$	(5) $PerfInd^{acc.}$	(6) $PerfInd^{ideal}$
T	20.62*	6.250	12.86	1.254		
	(2.34)	(1.33)	(1.28)	(0.31)		
NT					baseline	baseline
T					21.50*	6.771
					(2.45)	(1.47)
NT - I					baseline	baseline
NT - G					9.892**	6.015**
					(3.03)	(3.16)
T - I					baseline	baseline
T - G					-9.515	-6.038
					(-1.34)	(-1.45)
Age>40	2.307	-0.501	4.006	0.331	3.157	-0.0850
	(0.35)	(-0.12)	(0.47)	(0.10)	(0.47)	(-0.03)
Men	4.193	0.813	11.07	4.856	7.631	2.835
	(0.60)	(0.12)	(0.96)	(0.98)	(1.23)	(0.67)
High education	-4.075	-2.992	0.588	-0.0873	-1.743	-1.540
	(-0.50)	(-0.69)	(0.06)	(-0.03)	(-0.21)	(-0.45)
Constant	122.2***	85.41***	128.9***	89.56***	120.6***	84.48***
	(18.60)	(18.94)	(19.28)	(23.21)	(18.84)	(19.78)
N	175	175	175	175	350	350
R^2	0.090	0.031	0.040	0.009	0.076	0.036

t statistics in parentheses ; std. errors corrected at an individual level
$^{\#}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
(1) and (2) compare T and NT when facing an individual-based incentive (I).
(3) and (4) compare T and NT when facing a group-based incentive *without* time constraint (G).
(5) and (6) compare I and G, for T and NT respectively.

In Table 3.4, all the specifications are concerned with Stage 3 (G + t.c.), and more specifically, the comparison of T and NT subjects' performances, respectively, when being third to play, or not. Note that when studying T subjects' performances (cf. columns 1

[56] t-statistic $= 3.16$, p-value $= 0.003$
[57] t-statistic $= -1.34$, p-value $= 0.190$
[58] t-statistic $= -1.45$, p-value $= 0.157$

and 2), we do not include control variables, because of small number of observations (27). While there exist no exact rule about the number of covariates to be included in a model, we apply the thumb rule according to Koebel et al. (2016) by using 10 observations per covariate, to prevent the problem of overfitting.

The results of the econometric analysis confirms those of the non-parametric analysis (cf. Results 3 and 4). Namely, contrary to NT subjects ($PerfIndicator_i^{acc.}$[59] in column 3, and $PerfIndicator_i^{ideal}$[60] in column 4), the last T subjects to intervene, perform significantly better than the first two ($PerfIndicator_i^{acc.}$[61] in column 1, and $PerfIndicator_i^{ideal}$[62] in column 2).

Table 3.4: Determinants of performance in G+t.c.

	(1) $PerfInd^{acc.}$	(2) $PerfInd^{ideal}$	(3) $PerfInd^{acc.}$	(4) $PerfInd^{ideal}$
3^{rd} seq. order	baseline	baseline	baseline	baseline
1^{st} seq. order	-24.89*	-16.56*	-7.538	-4.154
	(-2.96)	(-3.07)	(-1.12)	(-0.98)
2^{nd} seq. order	-28.44*	-18.44*	-10.65	-6.077
	(-3.09)	(-3.25)	(-1.48)	(-1.41)
Age>40			-8.044	-8.705*
			(-1.32)	(-2.13)
High education			-2.586	-4.872
			(-0.38)	(-1.57)
Men			14.32#	7.606***
			(1.87)	(3.75)
Constant	164.0***	100.5***	138.7***	97.51***
	(13.67)	(36.39)	(20.74)	(27.48)
N	27	27	78	78
R^2	0.312	0.346	0.093	0.155

t statistics in parentheses ; std. errors corrected at an individual level

# $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

(1) and (2) consider T subjects only, and (3) and (4) consider NT subjects only.

Furthermore, Table 3.5 shows specifications comparing the group-based incentive *with*

[59] 3^{rd} vs. 1^{st}: t-statistic $= -1.12$, p-value $= 0.272$; 3^{rd} vs. 2^{nd}: t-statistic $= -1.48$, p-value $= 0.151$

[60] 3^{rd} vs. 1^{st}: t-statistic $= -0.98$, p-value $= 0.337$; 3^{rd} vs. 2^{nd}: t-statistic $= -1.41$, p-value $= 0.170$

[61] 3^{rd} vs. 1^{st}: t-statistic $= -2.96$, p-value $= 0.018$; 3^{rd} vs. 2^{nd}: t-statistic $= -3.09$, p-value $= 0.015$

[62] 3^{rd} vs. 1^{st}: t-statistic $= -3.07$, p-value $= 0.015$; 3^{rd} vs. 2^{nd}: t-statistic $= -3.24$, p-value $= 0.012$

time constraint, with the individual-based, and the group-based incentive *without* time constraint, for T and NT subjects respectively. Given the previous results, we, however, distinguish between the case where subjects played only the first and the second sequence order (columns 1 and 2), and the case were all the sequence orders are considered (columns 3 and 4) in the group-based incentive *with* time constraint.

On the one hand, when considering all the sequence orders (columns 3 and 4), the econometric analysis confirms our non-parametric results (cf. Results 4 and 5). In this case, T subjects do not perform significantly worse when facing a group-based incentive *with* time constraint, than when given an individual-based[63] or a group-based incentive *without* time constraint[64] (cf. Result 5). On the contrary, NT subjects *do* coordinate at significantly higher levels when given a group-based incentive *with* time constraint, than an individual-based incentive[65] (cf. Result 4).

On the other hand, when considering only the first two sequence orders (columns 1 and 2), we can confirm the fact that NT subjects do not perform significantly better with the group-based incentive *with* time constraint, than with the individual-based incentive[66], an that they also do not perform significantly worse when facing a group-based incentive *with* time constraint, than *without* time constraint[67] (cf. Result 4). Furthermore, we see that, as stated in Result 3, T subjects perform significantly worse when given a group-based incentive *with* time constraint, than when given an individual-based incentive, towards reaching their ideal target[68]. However, Result 3 turns out to be moderated, as they do not perform significantly better towards reaching their acceptable target[69]. This result shows that time constraint especially retains T subjects to work until reaching their ideal target, and prefer to target a lower coordination level. Nevertheless, they do *not* stop before reaching at least their acceptable target. Even though they adopt a self-restricting strategy, as explained in the previous subsection, coordination at a level representing a "good" quality work, seems to remain important to them.

[63] $PerfInd_i^{acc.}$: t-statistic $= 1.42$, p-val $= 0.165$; $PerfInd_i^{ideal}$: t-statistic $= 1.64$, p-val $= 0.110$
[64] $PerfInd_i^{acc.}$: t-statistic $= 0.37$, p-val $= 0.715$; $PerfInd_i^{ideal}$: t-statistic $= 0.56$, p-val $= 0.582$
[65] $PerfInd_i^{acc.}$: t-statistic $= -2.66$, p-val $= 0.012$; $PerfInd_i^{ideal}$: t-statistic $= -2.58$, p-val $= 0.014$
[66] $PerfInd_i^{acc.}$: t-statistic $= -1.26$, p-val $= 0.215$; $PerfInd_i^{ideal}$: t-statistic $= -1.36$, p-val $= 0.181$
[67] $PerfInd_i^{acc.}$: t-statistic $= 0.77$, p-val $= 0.449$; $PerfInd_i^{ideal}$: t-statistic $= 0.52$, p-val $= 0.605$
[68] t-statistic $= 1.94$, p-val $= 0.061$
[69] t-statistic $= 1.68$, p-val $= 0.103$

Table 3.5: Determinants of performance in I, G and G+t.c. with respect to individual performances

	(1) $PerfInd^{acc.}$	(2) $PerfInd^{ideal}$	(3) $PerfInd^{acc.}$	(4) $PerfInd^{ideal}$
T	3.086	-6.116	9.096	-1.887
	(0.29)	(-1.25)	(0.98)	(-0.53)
NT - G+t.c	baseline	baseline	baseline	baseline
NT - I	-5.612	-4.200	-8.644*	-5.905*
	(-1.26)	(-1.36)	(-2.66)	(-2.58)
NT - G	4.281	1.815	1.249	0.110
	(0.77)	(0.52)	(0.33)	(0.05)
T - G+t.c.	baseline	baseline	baseline	baseline
T - I	17.99	12.59#	12.13	8.461
	(1.68)	(1.94)	(1.42)	(1.64)
T - G	8.475	6.551	2.618	2.423
	(0.89)	(1.12)	(0.37)	(0.56)
Age>40	-0.319	-2.406	0.318	-2.015
	(-0.05)	(-0.79)	(0.05)	(-0.68)
Man	8.793	3.518	9.331	3.834
	(1.51)	(1.00)	(1.56)	(1.15)
High education	-2.512	-2.091	-2.441	-1.987
	(-0.32)	(-0.67)	(-0.31)	(-0.66)
Constant	127.5***	89.62***	130.3***	91.11***
	(32.25)	(34.20)	(29.62)	(34.36)
N	420	420	455	455
R^2	0.069	0.043	0.068	0.038

t statistics in parentheses ; std. errors corrected at an individual level

# $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

(1) and (2) exclude 3^{rd} order sequence in G+t.c.; (3) and (4) include it.

Finally, in Table 3.6, all the specifications compare both groups' worst performances, when facing different incentives. More specifically, regressions (1) and (2) compare both group-based incentives with the individual-based incentive, for T and NT subjects, and (3) and (4) compare the group-based incentive *with* time constraint, with the individual-based and the group-based incentive *without* time constraint, for T and NT subjects.

The econometric analysis confirms the results given in the non-parametric analysis. We indeed see that NT subject groups' worst performance levels are significantly higher when facing group-based incentives (*without* and *with* time constraint), than when facing an individual-based incentive (columns 1 and 2). For T subject groups, we find the opposite result. Their worst performance levels are significantly lower then facing a group-based incentive, than when facing an individual-based incentive (columns 1 and 2). Finally, we also see in Table 3.6 that neither T nor NT subject groups' worst performances significantly vary between both group-based incentives (columns 3 and 4).[70] These findings indicate that they may be due to the fact that the worst performances of the groups (and not only the best group performances) vary a lot given what type of incentive subjects are facing. This brings us to a last result:

Result 7 *Incentive types impact the worst group performance levels, so that this latter one is lower with group-based than with individual-based incentives, for T subjects, and higher with group-based than with individual-based incentives, for NT subjects.*

This result is interesting and important when being confronted to a weak-link production type. Indeed, when the final outcome (and not only the payoff) of a teamwork depends on the lowest performance of the team, the most important output is precisely this worst performance level. Result 7 may thus be important to consider when proposing an appropriate contract in the context of a weak-link environment, as for example a low energy renovation or construction work.

[70] This was not the case for T subject groups, according to the non-parametric analysis.

Table 3.6: Determinants of performance in I, G and G+t.c. with respect to worst group performances

	(1) $WorstPerf^{acc.}_{group}$	(2) $WorstPerf^{ideal}_{group}$	(3) $WorstPerf^{acc.}_{group}$	(4) $WorstPerf^{ideal}_{group}$
NT	baseline	baseline	baseline	baseline
T	18.21*	11.58*	3.117	-1.516
	(2.69)	(2.72)	(0.58)	(-0.38)
NT - I	baseline	baseline	-10.65***	-7.567**
			(-3.65)	(-3.51)
NT - G	13.73***	10.75***	3.075	3.183
	(4.02)	(3.77)	(0.84)	(1.07)
NT - G+t.c.	10.65***	7.567**	baseline	baseline
	(3.65)	(3.51)		
T - I	baseline	baseline	15.09*	13.10*
			(2.67)	(2.71)
T - G	-18.53**	-13.08**	-3.431	0.017
	(-3.33)	(-2.85)	(-0.78)	(0.00)
T - G+t.c.	-15.09*	-13.10*	base line	base line
	(-2.67)	(-2.71)		
Age>40	8.024*	-0.160	8.024*	-0.160
	(2.04)	(-0.04)	(2.04)	(-0.04)
Men	10.40#	8.182#	10.40#	8.182#
	(1.83)	(1.85)	(1.83)	(1.85)
High education	-9.044	-5.065	-9.044	-5.065
	(-1.44)	(-1.17)	(-1.44)	(-1.17)
Constant	99.02***	69.44***	109.7***	77.01***
	(19.89)	(17.40)	(31.41)	(23.48)
N	429	429	429	429
R^2	0.097	0.069	0.097	0.069

t statistics in parentheses ; std. errors corrected at an individual level

$^{\#}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

(1) and (2) compare group-based incentives with the individual-based incentive, for T and NT subjects.

(3) and (4) compare the group-based incentive *with* time constraint, with the individual-based and the group-based incentive *without* time constraint, for T and NT subjects.

3.5 Discussion and concluding remarks

In this paper, we presented an experiment where subjects played a real-effort weak-link game. The aim of the study was to analyze the coordination capacity of *ex-ante* trained and non trained (to coordination) craftsmen, when facing individual-based and group-based incentives *without* and *with* time constraint (with weak-link payment). A particularity of the experiment is the behavior of individual performance targets (a minimum acceptable, and a maximum ideal target) subjects had to achieve.

Our results suggest that trained subjects coordinate at significantly higher effort levels than non-trained subjects when facing an individual-based incentive. However, when facing a group-based incentive, non-trained subjects appear to "catch up" trained subjects in terms of coordination level, while these latter subjects do not significantly increase their performance level compared to when given an individual-based incentive. This suggests that proposing a group-based incentive to subjects who have previously been trained on coordination does not yield higher overall coordination levels. Indeed, their enhanced sensitivity to successful and efficient coordination (that is, their optimist beliefs about coordination) seems to be a sufficiently strong mechanism to incentivize towards coordinating at high effort levels. This corroborates the findings of Cooper et al. (2018), who suggest that assigning a high performance pay to "optimists", increases the probability of high and successful coordination. The fact that, in our experiment, trained subjects were aware about their team members' same training reinforced their trust in the coordination capacity of the other members, and may explain the realization of this result. Yet, an unexpected result when enforcing the subjects a sequential game (with a group-based incentive) with a given amount of time for the entire group (i.e. time constraint) is that, contrary to non trained subjects, trained subjects playing before the last one in the group perform significantly worse than the last player. By adopting a self-restricting strategy, they perform significantly worse than when facing an individual-based incentive. As the possibility to *not* achieve efficient coordination causes them stress, trained subjects voluntarily target lower performance levels (than their real ability), so that the last member in the sequence order has enough time to reach his or her acceptable target. Such a strong (and negative) effect of time constraint is not visible on the coordination behavior of non trained subjects. Indeed, they perform significantly better with a group-based than with an individual-based incentive, whether they have to play simultaneously or sequentially.

In hand of the results presented in this section, imposing a time constraint when subjects have to intervene sequentially (i.e. attributing delay penalties to the entire team when coordination on high performance levels has failed in a given time), does not seem to be an efficient solution to incentivize towards successful coordination. This is particularly the case for subjects having participated in a training on coordination. However, training courses on coordination, although time demanding and expensive, is a very efficient alternative measure to group-based incentives. Though this latter incentive is very efficient to increase performance of subjects who have never participated in a training course on coordination. Group contracts may thus be a good solution, cheaper (with regard to time and money) than a training, to incentivize towards efficient coordination. However, when working in an environment presenting the weak-link property, our results indicate that it may be more efficient to assign group-based incentives (*with* or *without* time constraint) to non trained subjects, and individual-based incentives to trained subjects. This result is in contradiction with the one presented by Bortolotti et al. (2016), who find that group-based incentives are as effective as individual-based incentives. Considering non trained subjects (as it is the case in other studies), we observe that worst performance is significantly lower with individual-based than with group-based incentives.

The small number of trained subjects having participated to the experiment (9) compared to the number of non trained subjects (27), constitutes the main limitation of the present study. The reason for this small number, is the difficulty to mobilize them simultaneously in a given location, as only around 200 craftsmen were trained through this particular training course (Dorémi), in the entire Grand Est Region, in northeastern of France. It would however be interesting to conduct a further session with trained subjects, to increase the possibility of external validation of the results.

In a further version of this experiment it would also be interesting to add a stage, where subjects would *not* be paid beyond their acceptable target. This would allow us to determine if subjects actually took into account the fact that they were assigned two distinct targets, and not only an ideal one, in their coordination behavior.

Appendix C

C.1 Instructions of the experiment in French

C.1.1 Informations générales

Nous vous remercions de participer à cette expérience sur la prise de décision. Dans cette expérience, vos gains dépendent de vos décisions et de celles d'autres participants. Nous vous demandons donc de lire attentivement ces instructions, elles doivent vous permettre de bien comprendre l'expérience. Toutes vos décisions sont anonymes. Vous n'entrerez jamais votre nom sur l'ordinateur. Vous indiquerez vos choix à la tablette devant laquelle vous êtes assis(e).

À partir de maintenant nous vous demandons de ne plus parler. Si vous avez une question levez la main et un expérimentateur viendra vous répondre en privé. Il est formellement interdit de communiquer avec un autre participant pendant l'expérience. Si vous ne respectez pas cette règle vous serez exclu de l'expérience et de tout paiement éventuel.

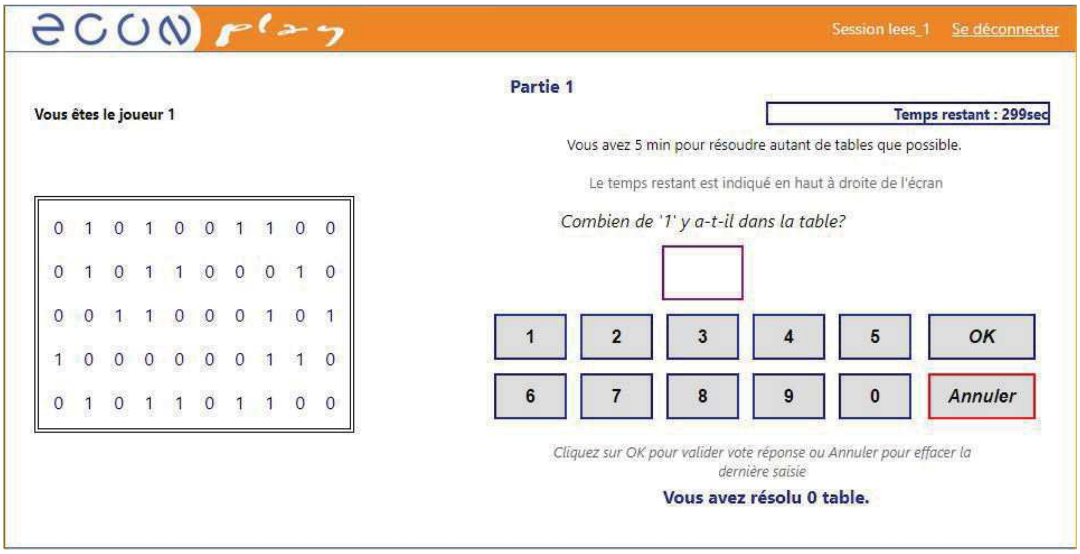
Tout au long de l'expérience, vous ferez partie d'un groupe composé de 3 joueurs choisis aléatoirement par l'ordinateur : vous et 2 autres joueurs participant à l'expérience. Vous ne pouvez pas connaitre l'identité des autres membres de votre groupe, de même qu'aucun membre de votre groupe ne peut connaitre votre identité. Vous ne connaissez pas non plus la constitution des autres groupes. Votre groupe restera identique tout au long de l'expérience.

L'expérience sera subdivisée en 4 parties. Les instructions spécifiques à chaque partie vous seront transmises avant celle-ci. Dans chaque partie, vous pourrez accumuler des gains exprimés en ECU (devise propre au jeu). à la fin de l'expérience vos gains totaux en ECU accumulés au cours des 4 parties seront convertis en euros au taux suivant : $100ECU = 1$ euro.

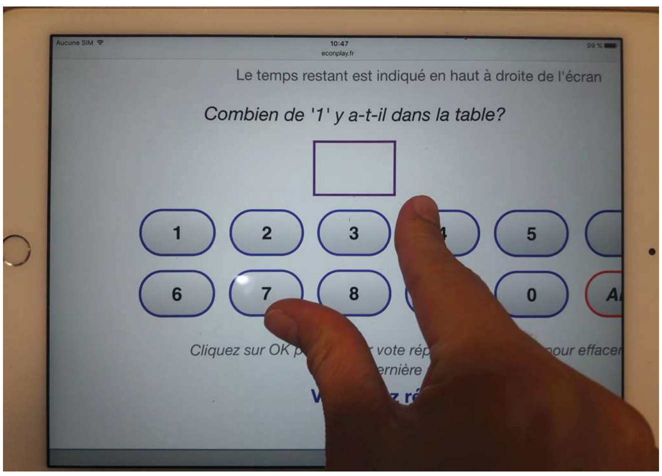
Les gains en euros que vous aurez réalisés vous seront alors versés en liquide.

C.1.2 Instructions de la Partie 1

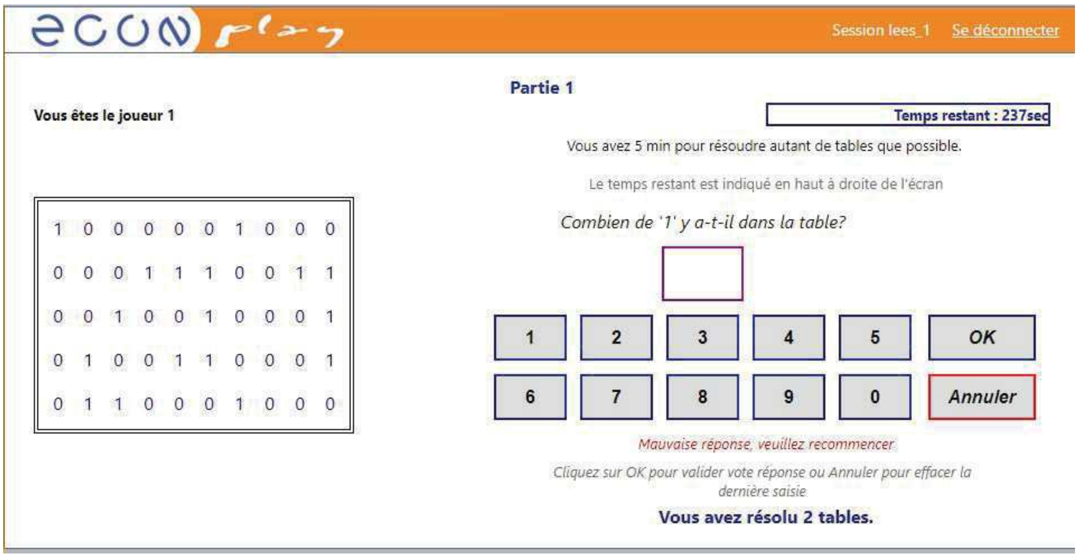
Lors de la Partie 1, votre tâche consiste à compter le nombre de '1' présents dans une table composée de '0' et '1'. Vous avez 5 minutes, soit 300 secondes, pour résoudre le plus de tables possibles. Le jeu se présente de la manière suivante :



Sur l'écran est présent une table composée de '0' et '1' et vous devez entrer, à l'aide des touches numériques, le nombre de '1' dans la fenêtre de réponse située à droite. Vous n'avez pas besoin d'appuyer sur la case vide avant de taper les chiffres : la saisie se fera directement à l'aide des touches numériques. Pour valider votre réponse, il faut appuyer sur "OK". Si vous voulez modifier votre réponse, il faut appuyer sur "Annuler", puis retaper votre réponse à l'aide des touches numériques. Le temps restant est affiché sous forme de compte à rebours en secondes en haut à droite de l'écran. Si vous voyez qu'en cliquant 2 fois de suite sur l'écran, vous avez zoomé, vous pouvez à tout moment dé-zoomer en faisant glisser 2 doigts dans un mouvement de pincement sur l'écran, comme indiqué sur la photo suivante :



Si vous validez un résultat incorrect, un message d'erreur apparaîtra comme indiqué sur la capture d'écran suivante :



Vous aurez alors 2 nouvelles chances pour donner la bonne réponse. Si vous vous trompez 3 fois, un nouveau tableau sera généré. En bas à droite, le nombre de tables résolues est affiché. Notez que vous ne serez pas pénalisé si vous vous trompez. Seul le nombre de tables résolues sera pris en compte.

Gardez en tête que le compte à rebours des 5 minutes démarre dès que la première table est affichée.

À la fin de la période de 5 minutes, un écran affichera le nombre de tables que vous avez correctement résolues, ainsi que votre gain pour cette période.

Vous toucherez 10 ECU par table résolue. Si vous avez par exemple compté correctement 5 tables, votre gain sera de 50 ECU :

$$Gain\,P1 = 5 \cdot 10 = 50\,ECU$$

Les gains de cette Partie vous seront payés à la fin de l'expérience.

Avant de commencer la Partie 1, vous aurez une phase d'entraînement de 2 minutes, pour vous familiariser avec le jeu et le fonctionnement de la tablette. Cette phase ne sera pas rémunérée.

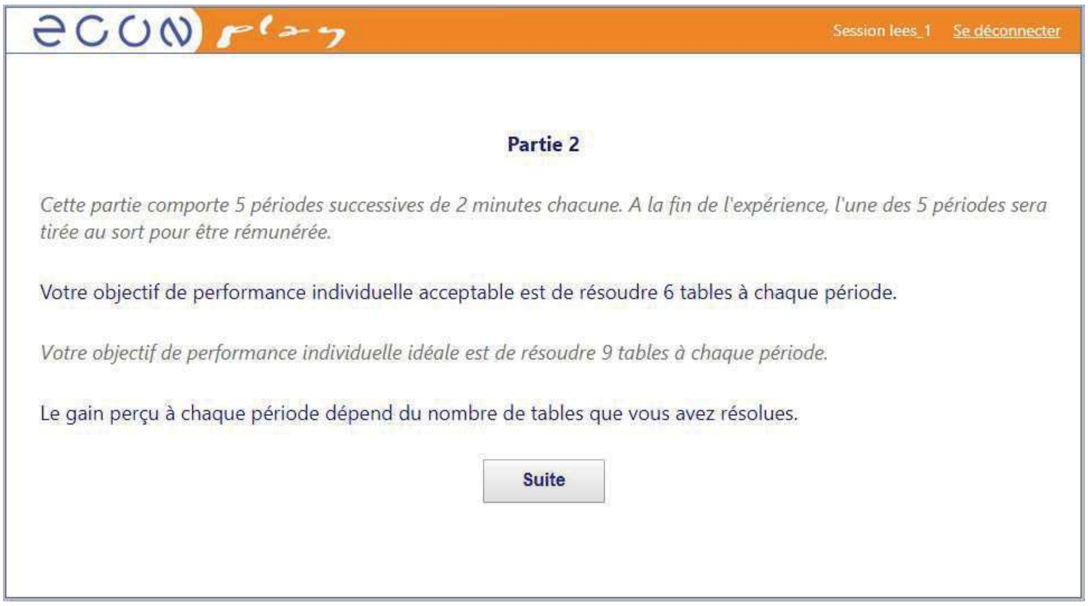
C.1.3 Instructions de la Partie 2

Dans la Partie 2, votre tâche consiste à nouveau à compter le nombre de '1' présents dans des tables composées de '0' et '1'. Vous faites toujours partie du même groupe de 3 personnes. La Partie 2 est divisée en 5 périodes de 2 minutes, soit 120 secondes, chacune. Contrairement à la Partie 1, vos gains dépendent de la réalisation des objectifs qui vous sont assignés. En effet, deux objectifs vous seront donnés:

1. Un objectif de performance individuelle ACCEPTABLE

2. Un objectif de performance individuelle IDEALE

Pour comprendre la différence entre ces deux objectifs, voyons un exemple concret. Imaginez un menuisier sur un chantier de rénovation. L'objectif acceptable représente le fait que le menuisier ait correctement posé la nouvelle fenêtre. L'objectif idéal représente le fait que le menuisier ait posé sa fenêtre de telle sorte à ce qu'elle puisse permettre d'atteindre le niveau d'étanchéité à l'air minimum requis pour atteindre un niveau BBC (Bâtiment Basse Consommation). En pratique, il faut au minimum atteindre votre objectif acceptable, mais atteindre votre objectif idéal vous permet de contribuer à l'atteinte du niveau BBC. L'objectif acceptable sera donc toujours inférieur à l'objectif idéal. Vos objectifs à atteindre vous seront communiqués au début de la Partie 2, comme affiché ci-dessous. Vos objectifs peuvent être différents que sur cette capture d'écran.



Vos gains lors de chaque période de 2 minutes sont déterminés par votre performance individuelle et sont calculés de la manière suivante :

$$Gain\,P2 = 100 + 800 \cdot \frac{tables\,résolues}{objectif\,de\,performance\,ind.\,ACCEPTABLE}$$

Prenons un exemple dans lequel on vous demande de résoudre 4 tables pour atteindre votre objectif acceptable, et de résoudre 6 tables pour atteindre votre objectif idéal. Si vous résolvez 3 tables pendant la période de jeu, vous avez atteint $\frac{3}{4}$ (soit 75%) de votre objectif acceptable et votre gain pour cette période est

$$Gain\,P2 = 100 + 800 \cdot \left(\frac{3}{4}\right) = 700\,ECU$$

Si au contraire, vous résolvez 4 tables, vous avez rempli 100% votre objectif acceptable et votre gain est

$$Gain\,P2 = 100 + 800 \cdot \left(\frac{4}{4}\right) = 900\,ECU$$

De même, si vous résolvez 5 tables (soit 125% de votre objectif acceptable) votre gain est

$$Gain\,P2 = 100 + 800 \cdot \left(\frac{5}{4}\right) = 1100\,ECU$$

La réalisation de votre objectif idéal n'intervient pas dans vos gains. Cependant, si vous aviez, toujours dans le même exemple, réussi à résoudre 6 tables (soit 150% de votre objectif acceptable), vous avez rempli vos deux objectifs, acceptable et idéal, et votre gain pour cette période est

$$Gain\,P2 = 100 + 800 \cdot \left(\frac{6}{4}\right) = 1300\,ECU$$

Dans le jeu, vous ne pouvez pas aller au-delà de votre objectif idéal. Lorsque vous atteignez le nombre de tables résolues qui correspond à cet objectif, la période de jeu s'achève, et les résultats sont affichés. Une page vous affichera les informations suivantes :

1. Le nombre de tables à résoudre pour atteindre votre objectif acceptable ;
2. Le nombre de tables à résoudre pour atteindre votre objectif idéal ;
3. Le nombre de tables que vous avez résolues lors de la période de jeu ;
4. Le pourcentage de tables résolues par rapport à votre objectif acceptable ;
5. Le pourcentage de tables résolues par rapport à votre objectif idéal ;
6. Votre gain pour cette période (en ECU).

Le gain que vous remporterez pour la Partie 2 sera tiré au sort parmi les 5 périodes de jeu que vous allez jouer. Vous ne remportez donc le gain que d'une seule période sur 5 jouées.

C.1.4 Instructions de la Partie 3

La Partie 3 est similaire à la Partie 2 que vous venez de jouer. Vous jouerez toujours 5 périodes de 2 minutes chacune. Cependant, vos gains pour chaque période seront calculés différemment qu'à la Partie 2.

Lors de la Partie 2, vos gains dépendaient uniquement de votre performance individuelle lors de chaque période de jeu. Dans la Partie 3, vos gains dépendent aussi de la performance individuelle des autres membres de votre groupe. Plus précisément, ils dépendent de la performance individuelle du membre du groupe qui a fait la plus faible performance par rapport à son objectif de performance individuelle acceptable. Les gains des trois membres du groupe sont identiques et sont calculés comme ceci :

$$Gain\,P3 = 100 + 800 \cdot (\text{plus faible atteinte de l'obj. accecptable au sein du groupe})$$

Prenons un exemple. Vous avez atteint votre objectif acceptable, soit 100%, le 2nd membre du groupe a atteint 125% de son objectif acceptable, et le 3ème membre du groupe a atteint 75% de son objectif acceptable. Le gain de chacun des membres de votre groupe sera le même:

$$Gain\,P3 = 100 + 800 \cdot 75\% = 700\,ECU$$

Si au contraire, vous avez atteint 50% de votre objectif acceptable, le 2nd membre du groupe a atteint 140% de son objectif acceptable, et le 3ème membre du groupe a atteint 90% de son objectif acceptable, le gain de chacun des membres de votre groupe sera le suivant:

$$Gain\,P3 = 100 + 800 \cdot 50\% = 500\,ECU$$

Le gain que vous remporterez pour la Partie 3 sera tiré au sort parmi les 5 périodes de jeu que vous allez jouer. Vous ne remportez donc le gain que d'une seule période sur 5 jouées.

C.1.5 Instructions de la Partie 4

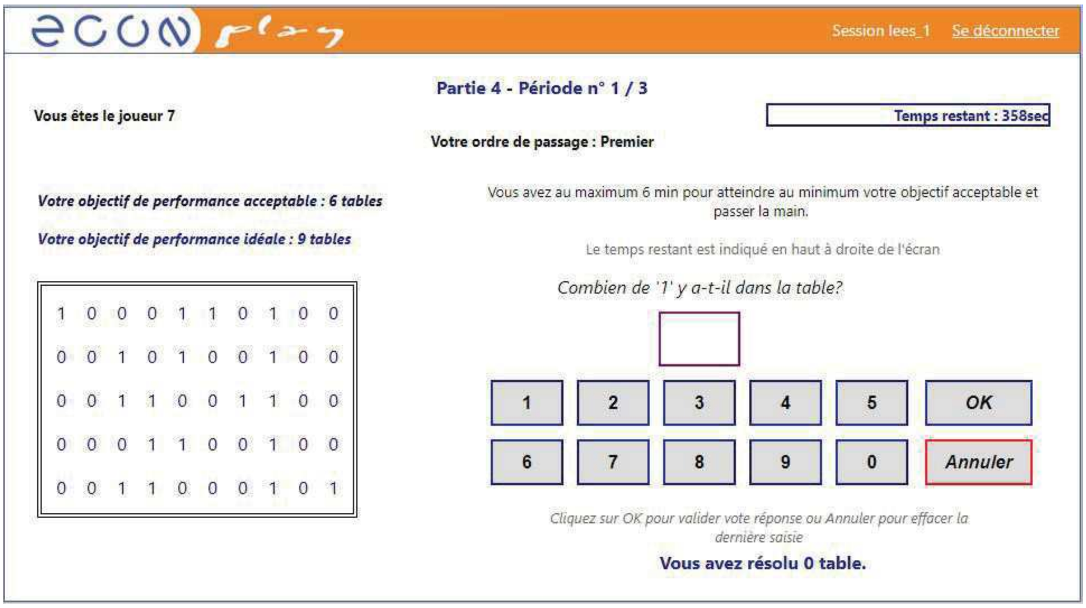
Vos gains à la Partie 4 seront calculés de la même manière qu'à la Partie 3. Le jeu sera le même que dans toutes les parties précédentes.

Le changement à la Partie 4 est que vous allez effectuer votre tâche chacun à votre tour au sein du groupe dont vous faites partie. Plus précisément, le jeu consistera en 3 périodes de 6 minutes, soit 360 secondes, chacune.

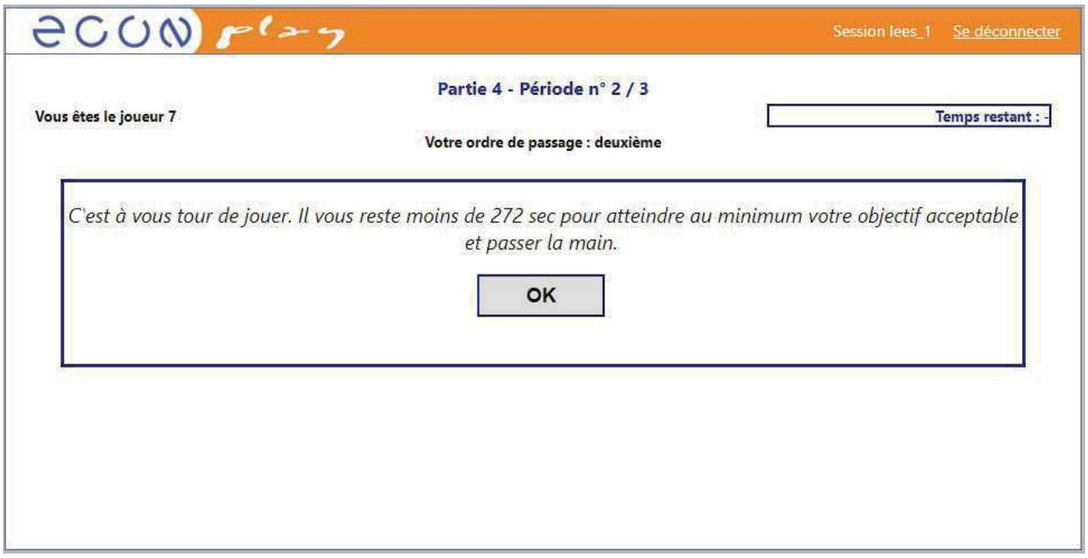
Au cours de chaque période, un des membres du groupe commencera en premier et aura comme auparavant l'objectif d'atteindre au moins son objectif acceptable. Il pourra alors continuer pour essayer d'atteindre son objectif idéal.

Dès qu'il atteint son objectif acceptable, il peut passer la main au joueur suivant. Par contre, s'il le souhaite, il peut continuer jusqu'à atteindre son objectif idéal puis passer la main automatiquement au joueur suivant.

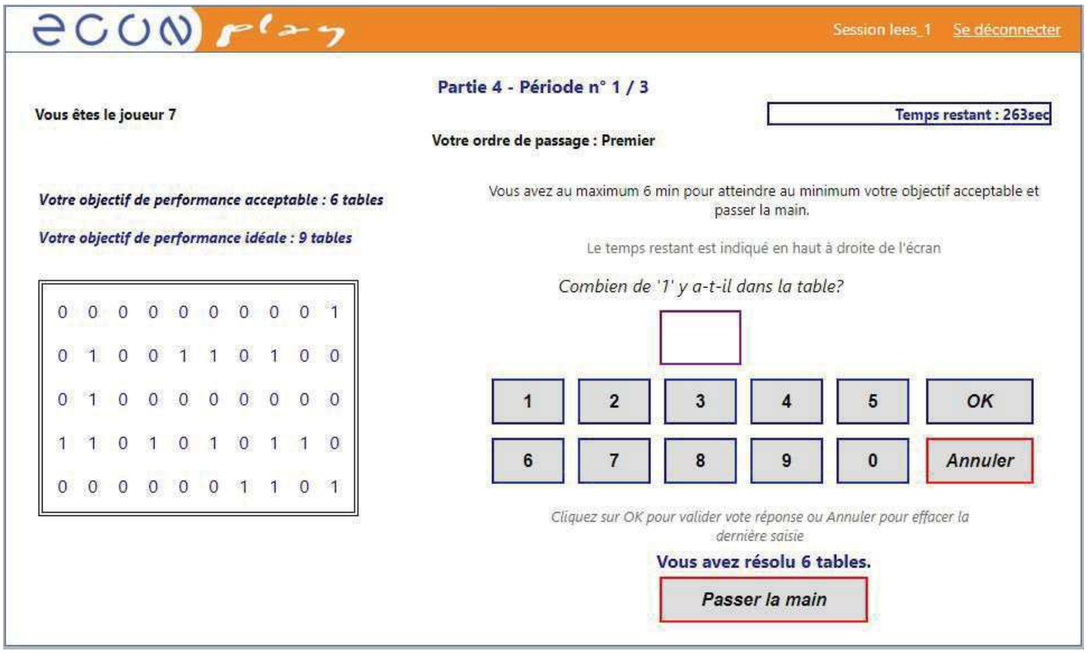
Les 360 secondes disponibles dans cette période sont pour l'ensemble du groupe. Le nombre de secondes utilisées par un joueur ne sont plus disponibles pour les suivants. Le temps restant sur le total des 360 secondes est affiché en haut à droite. Au moment de jouer, votre ordre de passage pour la période vous est indiqué sur l'écran. Votre ordre de passage est déterminé aléatoirement. Si vous êtes le 1er joueur à jouer, le jeu démarrera immédiatement comme indiqué sur la capture d'écran suivante :



Si vous êtes le $2^{ème}$ ou le $3^{ème}$ à jouer, le temps restant à jouer vous sera précisé sur un écran à part avant de commencer à jouer. Sur la capture d'écran suivante par exemple, l'ordre de passage du joueur 7 est $2^{ème}$ à la période 2 sur 3. Il lui reste 272 secondes à jouer à partir du moment où il appuie sur "OK". Cela signifie que le 1^{er} membre du groupe a déjà joué pendant $(360 - 272 =)$ 88 secondes avant lui.



Si vous êtes le 1^{er} ou le $2^{ème}$ joueur dans l'ordre de passage, dès que vous atteignez votre objectif acceptable, un bouton "Passer la main" apparait en bas à droite de l'écran comme indiqué sur la capture d'écran suivante :



Vous avez alors le choix soit de passer la main au prochain joueur pour qu'il puisse commencer à jouer, soit de continuer à jouer jusqu'à au plus votre objectif idéal. Si vous décidez de continuer, vous pourrez quand même passer la main à tout moment.

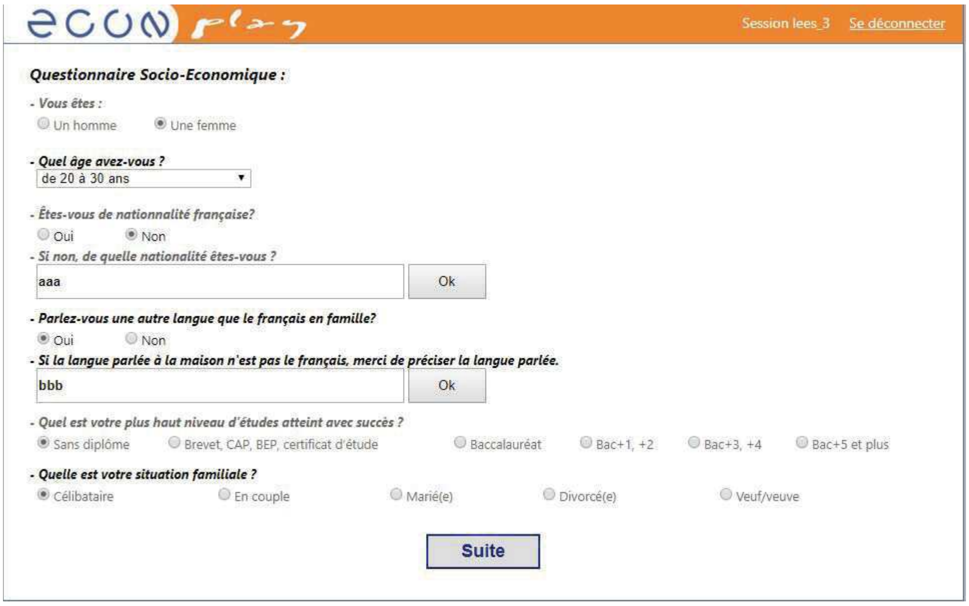
Gardez en tête que vos gains sont calculés comme à la Partie 3 et dépendent de la plus faible performance individuelle du groupe. Il est donc important de laisser suffisamment de temps aux joueurs qui vont jouer après vous.

Prenons un exemple. Vous atteignez 100% de votre objectif acceptable en 125 secondes et vous décidez de passer la main au prochain joueur. Puis, le second joueur atteint son objectif acceptable mais décide de continuer à jouer. Il décide de passer la main lorsqu'il a atteint 110% de son objectif acceptable, après 200 secondes de jeu. Il reste alors $(360 - 125 - 200 =)$ 35 secondes au dernier joueur pour jouer. Il atteint alors 40% de son objectif acceptable avec les 35 secondes restantes. La plus faible performance individuelle du groupe est donc de 40%. Le gain de chaque joueur est alors de

$$Gain\,P4 = 100 + 800 \cdot 40\% = 420\,ECU$$

Le gain que vous remporterez pour la Partie 4 sera tiré au sort parmi les 3 périodes de jeu que vous allez jouer. Vous ne remportez donc le gain que d'une seule période sur 3 jouées.

C.2 Post-experimental questionnaire in French



Session lees_3 Se déconnecter

Questionnaire Socio-Economique :

- Vous êtes :
Un homme / Une femme

- Quel âge avez-vous ?
de 20 à 30 ans

- Êtes-vous de nationalité française?
Oui / Non

- Si non, de quelle nationalité êtes-vous ?
aaa
Ok

- Parlez-vous une autre langue que le français en famille?
Oui / Non

- Si la langue parlée à la maison n'est pas le français, merci de préciser la langue parlée.
bbb
Ok

- Quel est votre plus haut niveau d'études atteint avec succès ?
Sans diplôme / Brevet, CAP, BEP, certificat d'étude / Baccalauréat / Bac+1, +2 / Bac+3, +4 / Bac+5 et plus

- Quelle est votre situation familiale ?
Célibataire / En couple / Marié(e) / Divorcé(e) / Veuf/veuve

Suite

Session lees_3 Se déconnecter

- Quelle est votre position religieuse?
athé/agnostique / catholique / protestant / orthodoxe / musulman / juif / hindouiste / bouddhiste / Autre

- Quelles sont les ressources mensuelles de l'ensemble de votre ménage (en brut) ?
jusqu'à 1000€
entre 1001€ et 2000€
entre 3001€ et 4000€
entre 4001€ et 5000€
entre 5001€ et 6000€
entre 6001€ et 7000€
entre 7001€ et 8000€
entre 8001€ et 10000€
plus de 10000€
Ne veux pas répondre

Suite

Session lees_3 Se déconnecter

- Comment vous voyez-vous? Êtes-vous généralement une personne qui prend des risques ou essayez-vous de les éviter? Veuillez cocher une case sur l'échelle ci-dessous, où 0 signifie « peur du risque » et 10 signifie « prêt à prendre des risques »:

Peur du risque — Prêt à prendre des risques

○ 0 ◉ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ 10

- En règle générale, quelle est la confiance que vous accordez à vos collègues au travail?

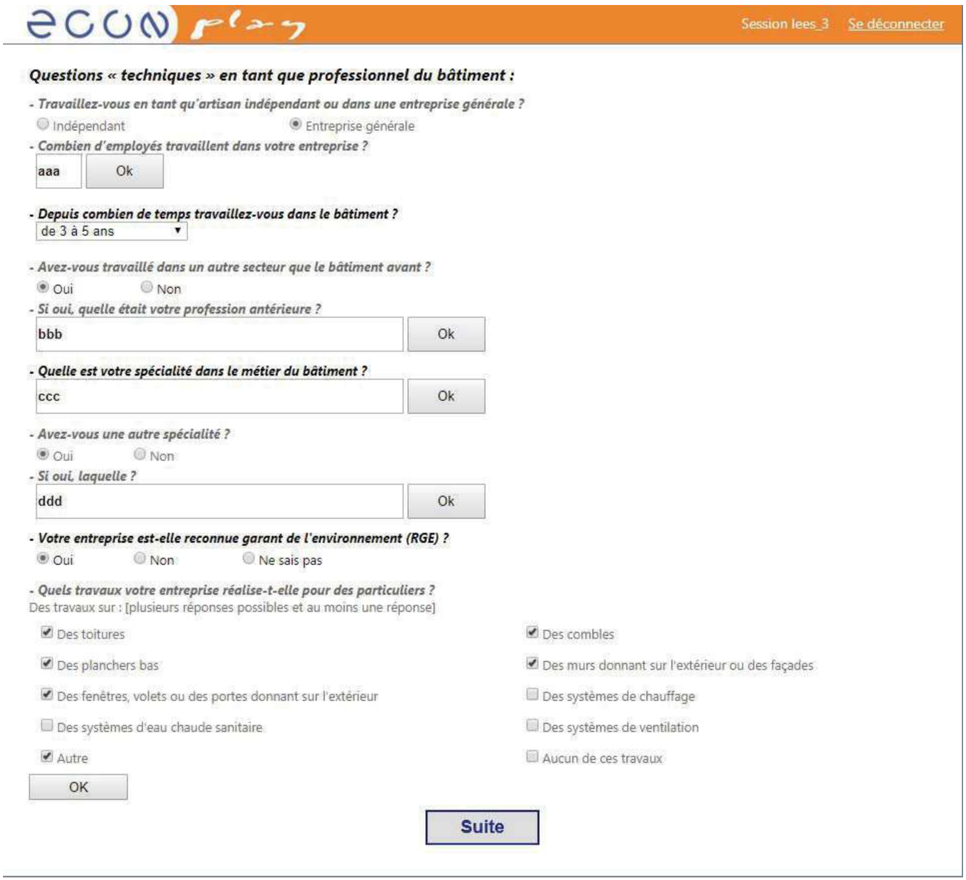
Confiance nulle — Confiance très élevée

○ 0 ◉ 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ 6 ○ 7 ○ 8 ○ 9 ○ 10

16. De manière générale, faites-vous confiance facilement ou pensez-vous que la personne en face de vous cherche à tirer 'profit' de vous?

○ Je fais confiance facilement ◉ Je pense que l'autre cherche à tirer profit de moi

Suite



Session lees_3 Se déconnecter

Questions « techniques » en tant que professionnel du bâtiment :

- Travaillez-vous en tant qu'artisan indépendant ou dans une entreprise générale ?

○ Indépendant ◉ Entreprise générale

- Combien d'employés travaillent dans votre entreprise ?

aaa Ok

- Depuis combien de temps travaillez-vous dans le bâtiment ?

de 3 à 5 ans

- Avez-vous travaillé dans un autre secteur que le bâtiment avant ?

◉ Oui ○ Non

- Si oui, quelle était votre profession antérieure ?

bbb Ok

- Quelle est votre spécialité dans le métier du bâtiment ?

ccc Ok

- Avez-vous une autre spécialité ?

◉ Oui ○ Non

- Si oui, laquelle ?

ddd Ok

- Votre entreprise est-elle reconnue garant de l'environnement (RGE) ?

◉ Oui ○ Non ○ Ne sais pas

- Quels travaux votre entreprise réalise-t-elle pour des particuliers ?

Des travaux sur : [plusieurs réponses possibles et au moins une réponse]

- [x] Des toitures
- [x] Des combles
- [x] Des planchers bas
- [x] Des murs donnant sur l'extérieur ou des façades
- [x] Des fenêtres, volets ou des portes donnant sur l'extérieur
- [ ] Des systèmes de chauffage
- [ ] Des systèmes d'eau chaude sanitaire
- [ ] Des systèmes de ventilation
- [x] Autre
- [ ] Aucun de ces travaux

OK

Suite

econ play — Session lees_3 — Se déconnecter

- Avez-vous déjà suivi une ou plusieurs formations BBC ? (Par formation BBC, nous entendons toute formation grâce à laquelle vous avez appris comment construire ou rénover de manière plus performante dans le but de réaliser des économies d'énergies.)

(•) Oui ( ) Non

- Quelle(s) formation(s) avez-vous suivi(es) ?

aaa [Ok]

- Quand avez-vous participé à votre(vos) formation(s) ?

bbb [Ok]

- Avez-vous eu accès à des subventions pour vous former ?

(•) Oui ( ) Non

- Parmi ces chantiers, à combien de chantiers avez-vous participé depuis votre(vos) formation(s) ? (Précisez un nombre approximatif si vous ne connaissez pas le nombre exact de chantiers.)

ccc [Ok]

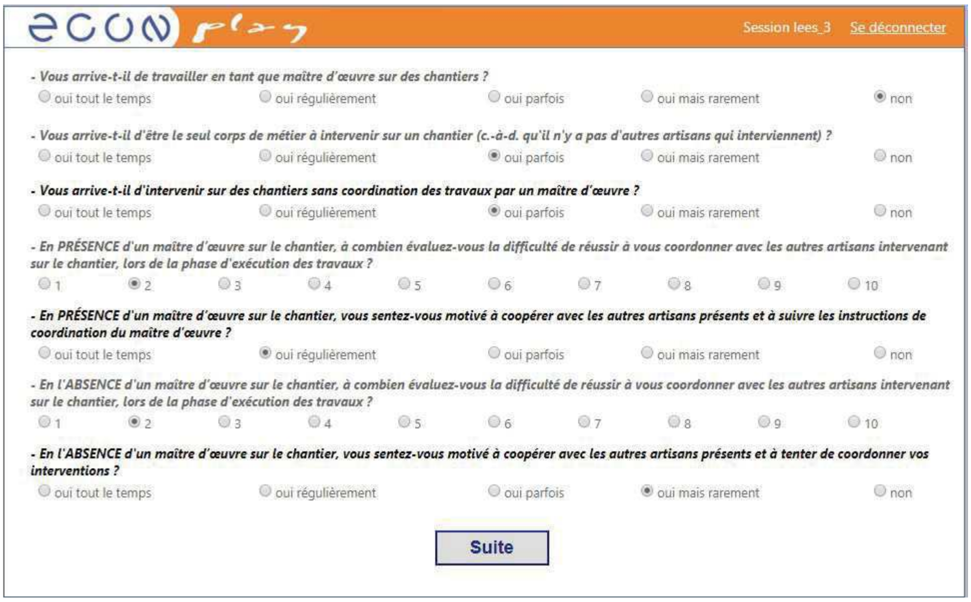
- À combien de chantiers de rénovation avez-vous participé depuis votre(vos) formation(s) ? (Précisez un nombre approximatif si vous ne connaissez pas les nombre exact de chantiers.)

ddd [Ok]

- Parmi ces chantiers de rénovation, combien étaient des chantiers de rénovation énergétique, où vous avez pu appliquer de nouvelles connaissances apprises lors de votre(vos) formation(s) ? (Précisez un nombre approximatif si vous ne connaissez pas les nombre exact de chantiers.)

eee [Ok]

[Suite]



econ play — Session lees_3 — Se déconnecter

- Vous arrive-t-il de travailler en tant que maître d'œuvre sur des chantiers ?

( ) oui tout le temps ( ) oui régulièrement ( ) oui parfois ( ) oui mais rarement (•) non

- Vous arrive-t-il d'être le seul corps de métier à intervenir sur un chantier (c.-à-d. qu'il n'y a pas d'autres artisans qui interviennent) ?

( ) oui tout le temps ( ) oui régulièrement (•) oui parfois ( ) oui mais rarement ( ) non

- Vous arrive-t-il d'intervenir sur des chantiers sans coordination des travaux par un maître d'œuvre ?

( ) oui tout le temps ( ) oui régulièrement (•) oui parfois ( ) oui mais rarement ( ) non

- En PRÉSENCE d'un maître d'œuvre sur le chantier, à combien évaluez-vous la difficulté de réussir à vous coordonner avec les autres artisans intervenant sur le chantier, lors de la phase d'exécution des travaux ?

( ) 1 (•) 2 ( ) 3 ( ) 4 ( ) 5 ( ) 6 ( ) 7 ( ) 8 ( ) 9 ( ) 10

- En PRÉSENCE d'un maître d'œuvre sur le chantier, vous sentez-vous motivé à coopérer avec les autres artisans présents et à suivre les instructions de coordination du maître d'œuvre ?

( ) oui tout le temps (•) oui régulièrement ( ) oui parfois ( ) oui mais rarement ( ) non

- En l'ABSENCE d'un maître d'œuvre sur le chantier, à combien évaluez-vous la difficulté de réussir à vous coordonner avec les autres artisans intervenant sur le chantier, lors de la phase d'exécution des travaux ?

( ) 1 (•) 2 ( ) 3 ( ) 4 ( ) 5 ( ) 6 ( ) 7 ( ) 8 ( ) 9 ( ) 10

- En l'ABSENCE d'un maître d'œuvre sur le chantier, vous sentez-vous motivé à coopérer avec les autres artisans présents et à tenter de coordonner vos interventions ?

( ) oui tout le temps ( ) oui régulièrement ( ) oui parfois (•) oui mais rarement ( ) non

[Suite]

Session lees_3 Se déconnecter

- Faut-il d'après vous que les différents corps de métiers travaillant sur un même chantier coordonnent leurs interventions lors de la phase d'exécution des travaux ?

oui c'est très important ○ oui c'est important ○ oui mais je ne sais pas si cela est vraiment nécessaire ○ non je pense que c'est une perte de temps

- Sur une échelle de 1 à 10, à combien évaluez-vous l'importance que vous attribuez à votre réputation sur le marché de la rénovation énergétique ?

1 2 3 4 5 6 7 8 9 10

Suite

Session lees_3 Se déconnecter

- Sur une échelle de 1 à 10, à quel point correspondes les affirmations suivantes pour vous :

- Ouvert d'esprit et curieux.

1 2 3 4 5 6 7 8 9 10

- Honnête.

1 2 3 4 5 6 7 8 9 10

- Habilité à discuter de manière libre avec quelqu'un, même s'il ne s'agit pas d'un aspect positif.

1 2 3 4 5 6 7 8 9 10

- Digne de confiance.

1 2 3 4 5 6 7 8 9 10

- Encourageant avec les autres.

1 2 3 4 5 6 7 8 9 10

- Respectueux des autres membres d'un groupe.

1 2 3 4 5 6 7 8 9 10

- Prendre en compte les remarques et suggestions de quelqu'un.

1 2 3 4 5 6 7 8 9 10

- Être enthousiaste à l'idée de coopérer et de coordonner votre travail sur un chantier avec les autres.

1 2 3 4 5 6 7 8 9 10

Suite

General Conclusion

The main objective of the thesis is to increase the number of energy retrofitting measures in the long-term through making the energy renovation market more reliable, sustainable and capable of existing without financial intervention of the State. Large consumption savings can thus be made, leading to reducing emissions of greenhouse gases and slowing global warming down. The declared objective is addressed from an empirical, theoretical and experimental perspective.

Chapter 1 is motivated by determining potential psychological risk factors with respect to energy related behaviors that could explain a systematic overestimation of the predicted *ex-post* energy consumption. Identifying such factors does not only permit to design more accurate prediction models (used by thermal energy auditors), but it also allows insurance companies and banks to more adequately measure the risk for households to not carry out sufficient savings. They will thus be able to better estimate insurance premiums and interest rates for energy renovation related products and credit loans.

However, households' behaviors *ex-post* to an energy renovation are far from being the only factors influencing the non-achievement of the energy performance related to an individual building. Factors intervening at the renovation stage do not have to be underestimated, as, for instance, the quality of the craftsmen's work. This assertion is the starting point of **Chapters 2 and 3**. Rather than assessing the magnitude of this risk, in these chapters we focus on determining adequate contracts allowing in the end to improve the flow and quality of work on a renovation site.

Additionally to reducing the risk of not achieving energy efficient buildings, it may reassure households in the reliability of renovation projects, thus contributing to the long-term existence of the energy renovation market.

The present thesis thus refers to the literature in economics (e.g. behavior, construction, contract theory, energy, experiment) and uses concepts of the psychology literature, that permitted to bring up several interesting findings summarized below.

More precisely, **Chapter** 1 identifies four cognitive biases leading to a distortion of occupants' energy behaviors (i.e. *Status Quo Bias* with respect to manual ventilation and *Optimism Bias* with respect to daily attention paid to energy consumption), their environmental attitudes (i.e. *Attitude-Behavior Gap*) and their environmental motivations (i.e. *Intention-Behavior Gap*). Analyzing separately the Net Losing Energy Savings (i.e. the EPG of those having consumed *more* than predicted) and the Net Gaining Energy Savings (i.e. the EPG of those having consume *less* than, or as predicted), with respect to the renovation program *Je rénove BBC* conducted by EDF and the Alsace region, permitted to point out the fact that the four studied cognitive biases played a significant role in the EPG of households exhibiting higher consumption patterns than predicted. The percentage of these households represents about 38% of the entire database of 129 households, obtained through a self-administrated questionnaire. These findings could be highlighted through analyzing our imputed database. We indeed applied a multiple imputation method to impute the 7% of missing observations, allowing us to obtain more robust results with respect to households consuming more than predicted.

The estimation results show that households presenting Net Losing Energy Savings and not adapting their manual ventilation habits in the renovated house (i.e. *Status Quo Bias*) ended up having on average a nearly 27% larger EPG than those adapting these habits. Regarding the *Optimism Bias*, it has a large impact on the EPG: households presenting Net Losing Energy Savings and declaring to pay less attention to their daily energy consumption than before renovation ended up exhibiting a 343% larger EPG than those continuing to pay attention to their consumption. This shows the importance for households to not solely rely on the energy performance of the building, but also to rely on an adapted energy related behavior to achieve the targeted consumption. However, our analysis points out that this negative effect can be lowered by heating under 19°C during the night: the EPG between the concerned households turned out to decrease on average by 35% per degree less heated. Finally, we observed an *Attitude-Behavior Gap* and an *Intention-Behavior Gap* with respect to households consuming more and less than predicted. More particularly, occupants reporting to be more concerned about ecological and environmental issues than before do, on average, not consume less than the others (i.e. *Attitude-Behavior Gap*). Moreover, those declaring to having renovated because they were (very) motivated to live in an environmental friendly house, do not consume less than the less motivated households (i.e. *Intention-Behavior Gap*).

Beyond these results describing how these cognitive biases impact the EPG, a contribution of Chapter 1 may lie in the different steps of the methodology we applied. Dealing with a relatively small sample (129 respondents), the problem of overparametrization has to be avoided by including a limited number of parameters in our regressions. We thus applied learning models to select as control variables, the covariates that best explain our dependent variable (i.e. the EPG). Furthermore, as a self-reported behavior (as a measurement for a cognitive bias) might potentially suffer from an 'omitted variable bias' (i.e. endogeneity problem) when this behavior is caused by another factor than the cognitive bias, we apply a method estimating causal effects (i.e. the 'inverse probability of treatment weighting' method). This permits us to obtain a modified database. Running our model regressions again with this latter database allows us to assess that the households' self-declared energy related behaviors and environmental related attitudes do not seem to suffer from an endogeneity problem, with respect to the observed variables. This interesting finding indicates that using occupants' declarations as a measurement for cognitive biases may to some extent be a valid method. We however observed a potential endogeneity problem related to the measurement variable of the *Intention-Behavior Gap*: the motivation households' experienced to renovate in order to live in an environmental friendly house may be caused by non observed factors.

All in all, our results point to the fact that cognitive biases may indeed play a role in the occurrence of an EPG, and that studying their impact through occupants' declarations may be a valid solution. Until now, the energy literature seems to have been reluctant to study psychological factors with respect to households' energy consumption. This may be due to two main reasons: (1) measuring such factors can be problematic (e.g. what behavior should be tested) and (2) there is a lack of databases comprising such household declarations.

Nevertheless, Chapter 1's findings can be useful to deduce key (policy) implications in two ways.

First, the results point to the importance to design effective tools to inform occupants about the risk (e.g. consuming more than predicted) related to not adapting their energy related behaviors in low energy buildings. Raising awareness about the occurrence of cognitive biases is key to reduce the EPG in such buildings.

As such, it would be necessary to explain households to limit manual ventilation to a few minutes per day, to continue to pay attention to their energy consumption once the renovation works are undertaken, and to heat under 19°C at night. This message can be transmitted through (1) the advice of the prime contractor[1] or/and (2) the introduction of energy conservation nudges. The use of descriptive, injunctive messages (i.e. emoticons) or instructive energy-saving tips represent helpful tools to sustain and encourage pro-conservation behavior (see, for instance, Rasul and Hollywood, 2012). It would be interesting to test the efficiency of such information instruments with respect to households' energy consumption and their EPG.

Second, our findings provide valuable insights to improve the predicted energy consumption by integrating underlying occupant habits that influence the EPG. For instance, at an individual project level, thermal energy auditors could meet the households before estimating a savings prediction, to ask them about their habits (e.g. heating, airing, attention to energy consumption). However, as we detected an *Attitude-Behavior Gap* and an *Intention-Behavior Gap*, information about the tendency to be concerned about environmental issues, or willing to live in an environmental friendly house, may not be an indicator about a less energy consuming household. All these information would permit to establish a general behavior profile that could be integrated in the prediction model, allowing to make energy consumption predictions more reliable. Further efforts would be needed to determine to what extent these behaviors may impact the energy consumption. Nevertheless, by doing so, the risk of not achieving the predicted energy consumption is reduced, which may incentivize banks and insurance companies to more and more rely on these predictions. This way, it allows them to avoid ethical issues that could arise by using household information to estimate the risk per individual behavior profile, which may be considered as "discriminating". Better rely on predictions and taking into account the average likelihood to consume more than predicted (based on our database, the likelihood of attaining Net Losing Energy Savings is 38%) will permit them to improve and develop insurance contracts and leverage bank loans.

Yet, a number of limits may emerge from the above recommendations. First, individually collecting information about households' habits to estimate savings predictions is costly (in time and money). However, the underlying benefits for the thermal energy auditors might appear in the mid and long term: more reliable predictions will lead to more

[1]The participants of the *Je rénove BBC* program have told us about their trust in the advice of the project's prime contractor.

reassured households and banks, which will lead to an increase in the number of renovation projects and a more sustainable renovation market, thus resulting in more clients for the auditors. A second limit lies in the difficulty to directly consider the declarations we used to measure the cognitive biases to improve prediction models. Most of the self-reported behaviors we used arise from questions asking how a given behavior evolved compared to before renovation[2], which cannot be answered before renovation. As such, only general habits existing before renovation can be integrated in the prediction models. Finally, although our empirical results are valid and robust, our sample size is relatively small. To validate the formulated policy implications, our findings should be replicated and extended by using a national representative and large sample.

Another approach to reduce the risk of non-achievement of energy performance is to incentivize craftsmen to better execute the renovation works. Although unpredictable events (e.g. harsh weather conditions, receiving defective materials) can happen, we have the possibility to improve craftsmen's workmanship through designing more adequate contracts. The analysis of such contracts is addressed in the remaining chapters of the thesis. We focus on contract designs from two different perspectives: the first type of contract is designed for one two-task Agent (cf. **Chapter 2**) and the second type of contract is designed to trigger teamwork and coordination among multiple Agents (cf. **Chapter 3**).

The research in **Chapter 2** develops a two-task theoretical model between a Principal (e.g. a project manager) and an Agent (e.g. a craftsman), where the Agent may underestimate the actual impact one of her tasks (e.g. participating in a training course about efficient renovation techniques) has on the distribution of the outcome (e.g. the building's final energy performance). Knowing the Agent's unawareness degree, the Principal proposes an adequate contract incentivizing her to exert high effort levels when she has two tasks to execute. This chapter determines the optimal reward structures to offer the Agent.

We show that when both parties have symmetric awareness levels (i.e. the Agent does not underestimate the above mentioned impact), the optimal compensation is affected by (1) the assumption of the Monotone Concave Likelihood Ratio Property and (2) the degree of downside risk aversion (i.e. prudence) of both parties. The Agent refuses a

[2]E.g. 'Do you open less/equally/more your windows than before renovation?', 'Are you paying less/equally/more attention to your energy consumption than before?', 'You have the tendency to be less/equally/more concerned about ecological and environmental issues than before.'

strictly concave reward in performance when being too prudent, because such a contract is too risky (i.e. variable) on the downside. The shape of the optimal reward in this case depends on the Principal's risk preferences, who has to make a trade-off between *incentive effect* and *downside risk effect*.

Now when asymmetric awareness emerges (i.e. the Agent underestimates the above mentioned impact), we show that the previous trade-off still prevails in same cases. An interesting additional finding is that the Principal strategically takes the Agent's awareness level into account: the more the Agent underestimates the impact of her task on the performance distribution, (1) the more the Principal pays her for low performance levels, and (2) the less he pays her for high performance levels. Indeed, in high performance levels he finds it useless to pay her much, since her unawareness will lead her to neglect the corresponding task.

As far as possible, no general policy conclusion can be recommended without having empirical information about the parties' risk preferences in real life. However, we can conclude that, when the craftsman underestimates how much recent renovation techniques can increase the buildings' energy efficiency, it may be appropriate to propose him a higher salary for "low" performance levels, and a lower salary for energy efficient performance levels.

More possible recommendations may be drawn from our results arising from experimentally testing individual-based and group-based incentives on trained and non trained (to coordination) "real" craftsmen. By doing so, **Chapter 3** suggests that trained craftsmen coordinate at significantly higher effort levels than non-trained craftsmen when facing an individual-based incentive. However, when facing a group-based incentive, non-trained craftsmen seem to "catch up" trained craftsmen in terms of coordination level, while these latter craftsmen do not significantly increase their performance level. This finding indicates that proposing a group-based incentive to subjects who have previously been trained on coordination, does not yield higher coordination levels. Indeed, their exogenous sensitivity to successful and efficient coordination seems to be a sufficient mechanism to incentivize towards common high effort levels. Yet, when enforcing the craftsmen to play sequentially with a given amount of time for the entire group (i.e. time constraint), trained craftsmen playing before the last one in the group, seem to adopt a self-restricting strategy, so that they perform significantly worse than when facing an individual-based incentive. It seems that the possibility to not achieve efficient coordination causes them stress. Hence, trained craftsmen voluntarily target lower performance levels to have the certainty to reach a sufficient high performance, so that the last member in the sequence order has enough time to reach his acceptable target. Such a strong effect of time constraint is not visible on the coordination behavior of non trained craftsmen. Finally, our results show that the tested incentives have different impacts on the craftsmen groups' worst performance levels. Indeed, individual-based incentives may be better suited for trained craftsmen to achieve the highest average worst performance, whereas group-based incentives seem to be more efficient to increase non trained craftsmen' worst performance.

Results of **Chapter 3** suggest that imposing a time constraint when craftsmen have to intervene sequentially (i.e. attributing delay penalties to the entire team when coordination on high performance levels has failed for a given amount of time), does not seem to be an efficient solution to incentivize towards successful coordination. This is particularly the case for craftsmen having participated in a training on coordination. However, training courses on coordination, although time demanding and expensive, are a very efficient alternative measure to group-based incentives. Hence, this latter incentive is very efficient to increase the performance of craftsmen who have never participated in a training course on coordination. Group contracts may thus be a good solution, cheaper (with regard to time and money) than a training, to incentivize towards efficient coordination. However, when working in an environment presenting the weak-link property, our results indicate that it may be more efficient to assign group-based incentives (*with* or *without* time constraint) to non trained subjects, and individual-based incentives to trained subjects. This result is in contradiction with the one presented by Bortolotti et al. (2016), who find that group-based incentives are as effective as individual-based incentives. Considering non trained craftsmen (as it is the case in other studies), we observe that worst performance is significantly lower with individual-based than with group-based incentives.

The external validity of the experiment's results may be increased due to the implementation of a real effort task instead of a chosen effort set up, and the intervention of subjects from the "real" world. However, the results of **Chapter 3** have to be considered prudently, since we encountered difficulties to mobilize trained craftsmen to participate in our experiment (9 trained subjects, compared to 27 non trained subjects). This experiment should thus be replicated by conducting further sessions with trained craftsmen.

Another limit of our experiment is the ability to determine if the participants actually took into account the fact that they were assigned two distinct targets (i.e. an acceptable and an ideal target). This makes it harder to conclude about whether craftsmen just targeted the highest goal, or whether they were actually prone to achieve "an energy efficient result". Indeed, during the sessions, craftsmen were informed about what both targets could represent in the "real" world: reaching an acceptable accomplished task, or reaching an ideal executed task permitting the building to be energy efficient. In a further version of this experiment, it may thus be interesting to eliminate the monetary incentive for the craftsmen after having reached their acceptable target.

We may conclude with saying that further efforts and research are needed since there are still uncertainties about which factors, including their magnitude, play a role in the risk of having an Energy Performance Gap. Yet, this thesis contributed to detect (from the literature neglected) psychological risk factors (i.e. cognitive biases) impacting this gap, which may allow, if taken into account, to make energy consumption prediction models more accurate. Finally, we also proposed more appropriate contract designs for craftsmen allowing to achieve energy efficient buildings more systematically, since they contribute to trigger better executed renovation works.

Bibliography

Abeler, J., A. Falk, L. Goette, and D. Huffman (2011). Reference Points and Effort Provision. *The American Economic Review VO - 101* (2), 470.

ADEME (2016). Rénovation énergétique de l'habitat : 15 initiatives de territoires (Réf. 8890). Technical report, I Care & Consult, ADEME.

Aktouf, O. (1987). *Méthodologie des sciences sociales et approche qualitative des organisations: une introduction à la démarche classique et une critique*. Presses de l'Université du Québec.

Anker-Nilssen, P. (2003). Household energy use and the environmentâa conflicting issue. *Applied Energy 76*(1), 189–196.

Arrow, K. J. (1971). *Essays in the theory of risk bearing*. Chicago: Markham Publishing Co.

Auster, S. (2013). Asymmetric awareness and moral hazard. *Games and Economic Behavior 82*, 503–521.

Austin, P. C. (2011). An introduction to propensity score methods for reducing the effectsof confounding in observational studies. *Multivariate behavioral research 46*(3), 399–424.

Aydin, E., N. Kok, and D. Brounen (2017). Energy efficiency and household behavior: the rebound effect in the residential sector. *RAND Journal of Economics (Wiley-Blackwell) 48*(3), 749–782.

Azur, M. J., E. A. Stuart, C. Frangakis, and P. J. Leaf (2011). Multiple imputation by chained cquations: What is it and how does it work? *International Journal of Mthods in Psychiatric Research 20*(1), 40–49.

Barnes, S. A., S. R. Lindborg, and J. W. Seaman (2006). Multiple imputation techniques in small sample clinical trials. *Statistics in Medicine 25*(2), 233–245.

Baron, J. (2011). *Thinking and Deciding* (4th ed.). Cambridge University Press.

Baron, J. and D. Kreps (1999). *Strategic Human Resources: Frameworks for General Managers*. New York: Wiley.

Baron, J. and I. Ritov (2004). Omission bias, individual differences, and normality. *Organizational Behavior and Human Decision Processes 94*(2), 74–85.

Barrett, S. (2016). Coordination vs. voluntarism and enforcement in sustaining international environmental cooperation. *Proceedings of the National Academy of Sciences 113*(51), 14515 LP – 14522.

Becker, L. J., C. Seligman, R. H. Fazio, and J. M. Darley (1981, sep). Relating Attitudes to Residential Energy Use. *Environment and Behavior 13*(5), 590–609.

Belaid, F. and T. Garcia (2016). Understanding the spectrum of residential energy-saving behaviours: French evidence using disaggregated data. *Energy Economics 57*, 204–214.

Bell, M. and R. Lowe (2000). Energy efficient modernisation of housing: a UK case study. *Energy and Buildings 32*(3), 267–280.

Benavot, A., M. Antoninis, M. Barry, N. Bella, N. Köseleci Blanchy, M. Delprato, G. Hertelendy, C. Jere, P. Joshi, K. Kubacka, L. Loupis, K. Lythrangomitis, A. McWilliam, A. Mechtar, B. Millar, C. Mukizwa, Y. Murakami, T. L. Owens, J. Randrianatoavina, K. Redman, M. Rajnov, A. E. Ruszkiewicz, W. Smith, E. Subden, R. Vidarte, and A. Zubairi (2016). Education for people and planet: creating sustainable futurs for all. Technical report, UNESCO.

Berninghaus, S. K. and K.-M. Ehrhart (2001). Coordination and information: recent experimental evidence. *Economics Letters 73*(3), 345–351.

Blasch, J. and C. Daminato (2018). Behavioral anomalies and energy-related individual choices: the role of status-quo bias.

Blaug, M. (1972). The Correlation between Education and Earnings: What Does It Signify? *Higher Education 1*(1), 53.

Blume, A. and A. Ortmann (2007). The Effects of Costless Pre-Play Communication: Experimental Evidence from Games with Pareto-ranked Equilibria. *Journal of Economic Theory 132*, 274–290.

Board, O. and K.-S. Chung (2009). Object-based unawareness: Theory and applications. *University of Minnesota*.

Bolton, P. and M. Dewatripont (2005). *Contract theory*. The MIT Press.

Bornstein, G., U. Gneezy, and R. Nagel (2002). The effect of intergroup competition on group coordination: an experimental study. *Games and Economic Behavior 41*(1), 1–25.

Bortolotti, S., G. Devetag, and A. Ortmann (2016). Group incentives or individual incentives? A real-effort weak-link experiment. *Journal of Economic Psychology 56*(C), 60–73.

Branco, G., B. Lachal, P. Gallinelli, and W. Weber (2004). Predicted versus observed heat consumption of a low energy multifamily complex in Switzerland based on long-term experimental data. *Energy and Buildings 36*(6), 543–555.

Brandts, J. and D. J. Cooper (2006). A Change Would Do You Good .... An Experimental Study on How to Overcome Coordination Failure in Organizations. *The American Economic Review 96*(3), 669–693.

Brandts, J. and D. J. Cooper (2007). It's What You Say, Not What You Pay: An Experimental Study of Manager-Employee Relationships in Overcoming Coordination Failure. *Journal of the European Economic Association 5*(6), 1223–1268.

Brandts, J., D. J. Cooper, and E. Fatas (2007). Leadership and overcoming coordination failure with asymmetric costs. *Experimental Economics 10*(3), 269–284.

Breiman, L. (2001). Random forests. *Machine learning 45*(1), 5–32.

Carpenter, J., S. Bowles, H. Gintis, and S.-H. Hwang (2009). Strong reciprocity and team production: Theory and evidence. *Journal of Economic Behavior and Organization 71*, 221–232.

Centre scientifique et technique du bâtiment (CSTB) (2008). TH-C-E ex calculation method.

Chaigneau, P., N. Sahuguet, and B. Sinclair-Desgagne (2017). Prudence and the convexity of compensation contracts. *Economic Letters 157*, 14–16.

Chaudhuri, A., A. Schotter, and B. Sopher (2009). Talking Ourselves to Efficiency: Coordination in Inter-Generational Minimum Effort Games with Private, Almost Common and Common Knowledge of Advice. *The Economic Journal 119*(534), 91–122.

Chen, R. (2017). Coordination with endogenous groups. *Journal of Economic Behavior & Organization 141*, 177–187.

Chen, T., T. He, M. Benesty, and Others (2015). Xgboost: extreme gradient boosting. *R package version 0.4-2*, 1–4.

Chen, Y., S. X. Li, T. X. Liu, and M. Shih (2014). Which hat to wear? Impact of natural identities on coordination and cooperation. *Games and Economic Behavior 84*, 58–86.

Cooper, D. J., C. A. Ioannou, and S. Qi (2018). Endogenous incentive contracts and efficient coordination. *Games and Economic Behavior 112*, 78–97.

Cooper, R., D. DeJong, R. Forsythe, and T. Ross (1992). Communication in Coordination Games. *The Quarterly Journal of Economics 107*(2), 739–771.

Corgnet, B., R. Hernan-Gonzalez, and S. Rassenti (2015). Peer Pressure and Moral Hazard in Teams: Experimental Evidence. *Review of Behavioral Economics 2*(4), 379–403.

Cosaert, S., M. Lefebvre, and L. Martin (2019). Earnings and work time targets in effort provision tasks: a revealed preference analysis. *Mimeo*.

Cranmer, S. J. and B. A. Desmarais (2017). What Can We Learn from Predictive Modeling? *Political Analysis 25*(2), 145–166.

Dai, Z., R. M. Hogarth, and M. C. Villeval (2015). Ambiguity on audits and cooperation in a public goods game. *European Economic Review 74*, 146–162.

de Wilde, P. (2014, may). The gap between predicted and measured energy performance of buildings: A framework for investigation. *Automation in Construction 41*, 40–49.

De Young, R. (2000). Expanding and evaluating motives for environmentally responsible behavior. *Journal of Social Issues 56*(3), 509–526.

Deci, Edwards, L. and R. M. Ryan (1985). *Intrinsic Motivation and Self-Determination in Human Behavior*.

Dekel, E., B. L. Lipman, and A. Rustichini (1998). Standard State-Space Models Preclude Unawareness. *Econometrica 66*(1), 159–173.

Delzendeh, E., S. Wu, A. Lee, and Y. Zhou (2017, dec). The impact of occupants' behaviours on building energy analysis: A research review. *Renewable and Sustainable Energy Reviews 80*, 1061–1071.

Diekmann, A. and P. Preisendörfer (1992). Persönliches Umweltverhalten. *Kölner Zeitschrift für Soziologie und Sozialpsychologie 44*(2), 226–251.

Efron, B. (1994). Missing Data, Imputation, and the Bootstrap. *Journal of the American Statistical Association 89*(426), 463–475.

Engelmann, D. and H.-T. Normann (2010). Maximum effort in the minimum-effort game. *Experimental Economics 13*(3), 249–259.

Etner, J. and M. Jeleva (2014). Underestimation of probabilities modifications: characterization and economic implications. *Economic Theory VO - 56* (2), 291.

European Commission (2014). Energy Efficiency and its contribution to energy security and the 2030 Framework for climate and energy policy (COM(2014) 520 final). Technical report, European Commission, Brussels.

Fagart, M.-C. and B. Sinclair-Desgagné (2007). Ranking Contingent Monitoring Systems. *Management Science 53*(9), 1501–1509.

Falk, A. and A. Ichino (2006). Clean Evidence on Peer Effects. *Journal of Labor Economics 24*(1), 39–57.

Frederiks, E. R., K. Stenner, and E. V. Hobman (2015a). Household energy use: Applying behavioural economics to understand consumer decision-making and behaviour. *Renewable and Sustainable Energy Reviews 41*, 1385–1394.

Frederiks, E. R., K. Stenner, and E. V. Hobman (2015b). The socio-demographic and psychological predictors of residential energy consumption: A comprehensive review.

Gabaix, X. and D. Laibson (2006). Shrouded attributes, consumer myopia, and information suppression in competitive markets. *Quarterly Journal of Economics 121*(2), 505–540.

Gadenne, D., B. Sharma, D. Kerr, and T. Smith (2011). The influence of consumers environmental beliefs and attitudes on energy saving behaviours. *Clean Cooking Fuels and Technologies in Developing Economies 39*(12), 7684–7694.

Galanis, S. (2013). Unawareness of theorems. *Economic Theory 52*(1), 41–73.

Galanis, S. (2015). The value of information under unawareness. *Journal of Economic Theory 157*, 384–396.

Galvin, R. (2014, feb). Making the ârebound effect' more useful for performance evaluation of thermal retrofits of existing homes: Defining the âenergy savings deficit' and the âenergy performance gap'. *Energy & Buildings 69*, 515–524.

Ganassali, S. and J. Moscarola (2004). Protocoles d'enquête et efficacité des sondages par internet. *Décisions Marketing* (33), 63–75.

Ganjisaffar, Y., R. Caruana, and C. V. Lopes (2011). Bagging gradient-boosted trees for high precision, low variance ranking models. In *Proceedings of the 34th international ACM SIGIR conference on Research and development in Information Retrieval*, pp. 85–94. ACM.

Geanakoplos, J. (1989). Game theory without partitions, and applications to speculation and consensus.

Gerarden, T. D., R. G. Newell, and R. N. Stavins (2017). Assessing the Energy-Efficiency Gap. *Journal of Economic Literature 55*(4), 1486–1525.

Gillingham, K. and K. Palmer (2014, jan). Bridging the Energy Efficiency Gap: Policy Insights from Economic Theory and Empirical Evidence. *Review of Environmental Economics and Policy 8*(1), 18–38.

Gollier, C., B. Jullien, and N. Treich (2000). Scientific progress and irreversibility: an economic interpretation of the 'Precautionary Principle'. *Journal of Public Economics 75*(2), 229–253.

Graham, J., A. Olchowski, and T. Gilreath (2007). How many imputations are really needed? Some Practical clarifications of multiple imputation theory. *Prevention Science 8*, 206–2.

Gram-Hanssen, K. (2011). Households' energy use - which is the more important: efficient technologies or user practices? Denmark, Europe. Linköping University Electronic Press.

Gram-Hanssen, K. and S. J. Darby (2018). âHome is where the smart isâ? Evaluating smart home research and approaches against the concept of home. *Energy Research & Social Science 37*, 94–101.

Grossman, S. J. and O. D. Hart (1983). An Analysis of the Principal-Agent Problem. *Econometrica* (1), 7—-.

Grund, S., O. Lüdtke, and A. Robitzsch (2016). Multiple imputation of multilevel missing data: An introduction to the R Package pan. *SAGE Open 6*(4), 1–17.

Guerra Santin, O. (2010). *Actual energy consumption in dwellings; the effect of energy performance regulations and occupant behaviour*. Sustainable Urban Areas. Delft University Press.

Guerra Santin, O. (2013). Occupant behaviour in energy efficient dwellings: evidence of a rebound effect. *Journal of Housing and the Built Environment 28*(2), 311–327.

Haas, R., H. Auer, and P. Biermayr (1998). The impact of consumer behavior on residential energy demand for space heating. *Energy and Buildings 27*(2), 195–205.

Häckel, B., S. Pfosser, and T. Tränkler (2017). Explaining the Energy Efficiency Gap-Expected Utility Theory versus Cumulative Prospect Theory. *Energy Policy 111*, 414–426.

Halpern, J. and L. Rêgo (2014). Extensive games with possibly unaware players. *Mathematical Social Sciences 70*, 42–58.

Hau, A. (2011). Optimal Brokerage Commissions for Fair Insurance: A First Order Approach. *The Geneva Risk and Insurance Review 36*(2), 189–201.

Hayek, F. A. (1967). Rules. Perception and intelligibility. *Studies in philosophy, politics and economics*, 43–65.

Heifetz, A., M. Meier, and B. C. Schipper (2006). Interactive unawareness. *Journal of Economic Theory 130*(1), 78–94.

Heifetz, A., M. Meier, and B. C. Schipper (2013). Unawareness, beliefs, and speculative trade. *Games and Economic Behavior 77*(1), 100–121.

Helson, H. (1964). Current trends and issues in adaptation-level theory. *American Psychologist 19*(1), 26–38.

Hens, H., W. Parijs, and M. Deurinck (2010). Energy consumption for heating and rebound effects. *International Conference on Building Energy and Environment (COBEE 2008) 42*(1), 105–110.

Héraud, J.-A. (2011). Reinventing creativity in old Europe: A development scenario for cities within the Upper Rhine Valley cross-border area. *City, Culture and Society 2*(2), 65–73.

Herbig, P., J. Milewicz, and J. E. Golden (1994). Differences in Forecasting Behavior between Industrial Product Firms and Consumer Product Firms. *Journal of Business and Industrial Marketing 9*(1), 60–69.

Hewett, M. J., T. S. Dunsworth, T. A. Miller, and M. J. Koehler (1986). Measured versus predicted savings from single retofits: a sample study. *Energy and Buildings 9*(1), 65–73.

Higgins, J. P., I. R. White, and A. M. Wood (2008). Imputation methods for missing outcome data in meta-analysis of clinical trials. *Clinical Trials 5*(3), 225–239.

Hines, J. M., H. R. Hungerford, and A. N. Tomera (1987, jan). Analysis and Synthesis of Research on Responsible Environmental Behavior: A Meta-Analysis. *The Journal of Environmental Education 18*(2), 1–8.

Holmstrom, B. (1979). Moral hazard and observability. *Bell Journal of Economics 10*(1), 74–91.

Holmstrom, B. (1982). Moral Hazard in Teams. *The Bell Journal of Economics* (2), 324—-.

Holmstrom, B. and P. Milgrom (1991). Multitask Principal-Agent Analyses: Incentive Contracts, Asset Ownership, and Job Design. *Journal of Law, Economics, & Organization*, 24—-.

Hothorn, T., K. Hornik, and A. Zeileis (2006). Unbiased Recursive Partitioning: A Conditional Inference Framework. *Journal of Computational and Graphical Statistics 15*(3), 651–674.

Hyndman, R. J. and A. B. Koehler (2006, oct). Another look at measures of forecast accuracy. *International Journal of Forecasting 22*, 679–688.

Jaffe, A. and R. Stavins (1994, jan). *The energy-efficient gap: What does it mean?*, Volume 22.

Jewitt, I. (1988). Justifying the First-Order Approach to Principal-Agent Problems. *Econometrica 56*(5), 1177–1190.

Jung, J. Y. and S. K. Kim (2015). Information space conditions for the first-order approach in agency problems. *Journal of Economic Theory 160*, 243–279.

Kahneman, D. (2011). *Thinking, fast and slow* (1st ed.). Farrar, Straus and Giroux.

Kahneman, D., J. L. Knetsch, and R. H. Thaler (1991). Anomalies: The Endowment Effect, Loss Aversion, and Status Quo Bias. *The Journal of Economic Perspectives 5*(1), 193–206.

Kahneman, D. and A. Tversky (1984). Choices, values, and frames. *American Psychologist 39*(4), 341–350.

Kandel, E. and E. P. Lazear (1992). Peer Pressure and Partnerships. *Journal of Political Economy 100*(4), 801.

Khoury, J., Z. Alameddine, and P. Hollmuller (2017, sep). Understanding and bridging the energy performance gap in building retrofit. *Energy Procedia 122*(CISBAT 2017 International ConferenceFuture Buildings & Districts - Energy Efficiency from Nano to Urban Scale), 217–222.

Kimball, M. (1990). Precautionary Saving in the Small and in the Large. *Econometrica 58*(1), 53–73.

Kirscht, J. P., D. P. Haefner, S. S. Kegeles, and I. M. Rosenstock (1966). A national study of health beliefs. *Journal of Health an Human Behavior 7*, 248–254.

Knez, M. and D. Simester (2001). Firm Wide Incentives and Mutual Monitoring at Continental Airlines. *Journal of Labor Economics 19*(4), 743–772.

Koebel, B., A. Schmitt, and S. Spaeter (2016). Do Self-Theories on Intelligence Explain Overconfidence and Risk Taking? A Field Experiment. *Revue économique 67*(5), 977–1006.

Kollmuss, A. and J. Agyeman (2002). Mind the Gap: why do people act environmentally and what are the barriers to pro-environmental behavior? *Environmental Education Research 8*(3), 239–260.

Koopmans, C. and D. te Velde (2001a). Bridging the energy efficiency gap: using bottomup information in a top-down energy demand model. *Energy Economics 23*(1), 57–75.

Koopmans, C. C. and D. W. te Velde (2001b). Bridging the energy efficiency gap: using bottom-up information in a top-down energy demand model. *Energy Economics 23*(1), 57–75.

Köszegi, B. (2014). Behavioral Contract Theory. *Journal of Economic Literature 52*(4), 1075–1118.

Kuhn, M. and Others (2008). Caret package. *Journal of statistical software 28*(5), 1–26.

Lampach, N. (2016). *Essays on risk management in the presence of ambiguity*. Ph. D. thesis, University of Strasbourg.

Lampach, N., P. Nguyen-Van, and N. To The (2017). Robustness Analysis of Organic Technology Adoption: Evidence from Northern Vietnamese Tea Production. *available at SSRN: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3037389*.

LaPiere, R. T. (1934). Attitudes vs. Actions. *Social Forces 13*(2), 230–237.

Lee, B. K., J. Lessler, and E. A. Stuart (2010). Improving propensity score weighting usingmachine learning. *Statistics in Medicine 29*(3), 337–346.

Leland, H. E. (1968). Saving and Uncertainty: The Precautionary Demand for Saving. *The Quarterly Journal of Economics 82*(3), 465–473.

Li, J. (2008). Interactive knowledge with unawareness.

Li, J. (2009). Information structures with unawareness. *Journal of Economic Theory 144*(3), 977–993.

Li, S., M. Peitz, and X. Zhao (2016, aug). Information disclosure and consumer awareness. *Journal of Economic Behavior and Organization 128*, 209–230.

Liaw, A. and M. Wiener (2002). Classification and Regression by randomForest. *R News 2*(3), 18–22.

LiCalzi, M. and S. Spaeter (2003). Distributions for the First-Order Approach to Principal-Agent Problems. *Economic Theory* (1), 167—-.

Ligon, J. A. and P. D. Thistle (2013). Background Risk in the Principal-Agent Model. *The Geneva Risk and Insurance Review 38*(2), 115–126.

Lindén A. Carlsson-Kanyama A., B. E. (2006). Efficient and inefficient aspects of residential energy behaviour: What are the policy instruments for change? *Energy Policy 34*(14), 1918–1927.

Little, R. J. A. (1988). A Test of Missing Completely at Random for Multivariate Data with Missing Values. *Journal of the American Statistical Association 83*(404), 1198–1202.

Lund, F. H. (1925). The psychology of belief. *Journal of Abnormal and Social Psychology 20*, 63–81; 174–196.

Ma, W. and B. C. Schipper (2017). Does Exposure to Unawareness Affect Risk Preferences? A preliminary result.

Majcen, D., L. Itard, and H. Visscher (2013, mar). Theoretical vs. actual energy consumption of labelled dwellings in the Netherlands: Discrepancies and policy implications. *Energy Policy 54*, 125–136.

Marchegiani, L., T. Reggiani, and M. Rizzolli (2016). Loss averse agents and lenient supervisors in performance appraisal. *Journal of Economic Behavior & Organization 131*, 183–197.

Maréchal, K. (2009, mar). An Evolutionary Perspective on the Economics of Energy Consumption: The Crucial Role of Habits. *Journal of Economic Issues (Taylor & Francis Ltd) 43*(1), 69–88.

Mayr, E. (1992). The Idea of Teleology. *Journal of the History of Ideas 53*(1), 117–135.

Meidinger, C., J.-L. Rullière, and M.-C. Villeval (2003). Does Team-Based Compensation Give Rise to Problems When Agents Vary in Their Ability? *Experimental Economics 6*(3), 253–272.

Meier, M. and B. C. Schipper (2014). Bayesian games with unawareness and unawareness perfection. *Economic Theory 56*(2), 219–249.

Mengel, F., E. Tsakas, and A. Vostroknutov (2016). Past experience of uncertainty affects risk aversion. *Experimental Economics 19*(1), 151–176.

Milgrom, P. R. (1981). Good News and Bad News: Representation Theorems and Applications. *The Bell Journal of Economics* (2), 380—-.

Mirrlees, J. A. (1999). The Theory of Moral Hazard and Unobservable Behaviour: Part I. *The Review of Economic Studies 66*(1), 3–21.

Mitchell, R. B. (2012, feb). Technology Is Not Enough: Climate Change, Population, Affluence, and Consumption. *The Journal of Environment & Development 21*(1), 24–27.

Modica, S. and A. Rustichini (1994). Awareness and partitional information structures. *Theory and Decision 37*(1), 107–124.

Modica, S. and A. Rustichini (1999). Unawareness and Partitional Information Structures. *Games and Economic Behavior 27*(2), 265–298.

Modica, S. and M. Scarsini (2005). A note on comparative downside risk aversion. *Journal of Economic Theory 122*, 267–271.

Morris, T. P., I. R. White, and P. Royston (2014). Tuning multiple imputation by predictive mean matching and local residual draws. *BMC Medical Research Methodology 14*(1), 75–87.

Moss, S. (2009, feb). Cultivating the Regulatory Focus of Followers to Amplify Their Sensitivity to Transformational Leadership. *Journal of Leadership & Organizational Studies 15*(3), 241–259.

Myung, J. I., Y. Tang, and M. A. Pitt (2009). Evaluation and comparison of computational models. *Methods in enzymology 454*, 287–304.

Nairne, J. and R. Crowder (1982, jul). On the locus of the stimulus suffix effect. *Memory & Cognition 10*(4), 350.

Nermuth, M. (1998). *Information Structures in Economics: Studies in the Theory of Markets with Imperfect Information* (1 ed.). Springer-Verlag Berlin Heidelberg.

Nishant, R., T. S. H. Teo, and M. Goh (2014, aug). Energy Efficiency Benefits: Is Technophilic Optimism Justified?. *IEEE Transactions on Engineering Management 61*(3), 476.

Oktave. Plateforme de rénovation énergétique.

Oliver, R. L. (1977, aug). Effect of Expectation and Discontinuation on Postexposure Product Evaluations: An Alternative Interpretation. *Journal of Applied Psychology 62*(4), 480–486.

Ozaki, R. (2011). Adopting Sustainable Innovation: What Makes Consumers Sign up to Green Electricity? *Business Strategy and the Environment 20*(1), 1–17.

Pal, M. and G. M. Foody (2010). Feature selection for classification of hyperspectral data by SVM. *IEEE Transactions on Geoscience and Remote Sensing 48*(5), 2297–2307.

Páles, Z. (2003). On Approximately Convex Functions. *Proceedings of the American Mathematical Society 131*(1), 243–252.

Payne, S. L. B. (2014). *The Art of Asking Questions: Studies in Public Opinion, 3* (3 ed.). Princeton Legacy Library. Princeton University Press.

Pelletier, L. G., L. Legault, and C. Séguin-Lévesque (2002). Pressure From Above and Pressure From Below as Determinants of Teachers' Motivation and Teaching Behaviors. *Journal od Educational Psychology 94*(1), 186–196.

Pelletier, L. G. and E. Sharp (2008). Persuasive communication and proenvironmental behaviours: How message tailoring and message framing can improve integration of behaviors through self-determined motivation. *Canadian Psychology 49*, 210–217.

Polachek, S. W. and W. S. Siebert (1993). *The Economins of Earnings*. Cambridge University Press.

Poortinga, W., L. Steg, and C. Vlek (2004). Values, environmental concern and environmental behavior: A study into household energy use. *Environment and Behavior 36*(1), 70–93.

Pratt, J. W. (1964). Risk Aversion in the Small and in the Large. *Econometrica Vol. 32*(No. 1/2), pp. 122–136.

R Core Team (2015). R: A language and environment for statistical computing.

Rabin, M. (1998). Psychology and Economics. *Journal of Economic Literature 36*, 11–46.

Rasul, I. and D. Hollywood (2012). Behavior change and energy use: is a ânudge'enough? *Carbon Management 3*(4), 349–351.

Raynaud, M. (2014). *Evaluation ex-post de l'efficacité de solutions de rénovation énergétique en résidentiel*. Ph. D. thesis, Ecole Nationale Supérieure des Mines de Paris.

Riedl, A., I. M. T. Rohde, and M. Strobel (2016). Efficient Coordination in Weakest-Link Games. *The Review of Economic Studies 83*(2), 737–767.

Roderick, A. R. and M. W. Fraser (2008). A Simplified Framework for Using Multiple Imputation in Social Work Research. *Social Work Research 32*(3), 171–178.

Rogerson, W. P. (1985). The First-Order Approach to Principal-Agent Problems. *Econometrica* (6), 1357—-.

Rosenhan, D. and S. Messick (1966). Affect and Expectation. *Journal of Personality and Social Psychology 3*(1), 38–44.

Rosenow, J. and R. Galvin (2013). Evaluating the evaluations: Evidence from energy efficiency programmes in Germany and the UK. *Energy and Buildings 62*, 450–458.

Samuelson, C. D. and M. Biek (1991). Attitudes Toward Energy Conservation: A Confirmatory Factor Analysis. *Journal of Applied Social Psychology 21*(7), 549–568.

Samuelson, W. and R. Zeckhauser (1988). Status Quo Bias in Decision Making. *Journal of Risk and Uncertainty 1*, 7–59.

Sanders, C. and M. Phillipson (2006). Review of differences between measured and theoretical energy savings for insulation measures. *EST Report December*.

Sandmo, A. (1968). Portfolio Choice in a Theory of Saving. *The Swedish Journal of Economics 70*(2), 106–122.

Sapci, O. and T. Considine (2014). The link between environmental attitudes and energy consumption behavior. *Journal of Behavioral and Experimental Economics 52*, 29–34.

Seligman, C., J. M. Darley, and L. J. Becker (1978). Behavioral approaches to residential energy conservation. *Energy and Buildings 1*(3), 325–337.

Sharot, T. (2011a). The optimism bias. *Current Biology 21*(23), R941–R945.

Sharot, T. (2011b). *The Optimism Bias: A Tour of the Irrationally Positive Brain.* New York: Pantheon Books.

Sinclair-Desgagne, B. (1999). How to Restore Higher-Powered Incentives in Multitask Agencies. *Journal of Law, Economics, & Organization* (2), 418—-.

Sinclair-Desgagné, B. and H. Gabel (1997). Environmental Auditing in Management Systems and Public Policy. *Journal of Environmental Economics and Management 33*(3), 331–346.

Sinclair-Desgagne, B. and S. Spaeter (2018). Incentive Contracts and Downside Risk Sharing. *The Journal of Law, Economics, and Organization 34*(1), 79–107.

Stadelmann, M. (2017). Mind the gap? Critically reviewing the energy efficiency gap with empirical evidence. *Energy Research & Social Science 27*, 117–128.

Stuart, E. A., H. A. Huskamp, K. Duckworth, J. Simmons, Z. Song, M. E. Chernew, and C. L. Barry (2014). Using propensity scores in difference-in-differences models to esti-mate the effects of a policy change. *Health Services and Outcomes Research Methodology 14*(4), 166–182.

Sunikka-blank, M. and R. Galvin (2012). Introducing the prebound effect : the gap between performance and actual energy consumption. *Building Research & Information 3218*, 37–41.

Tatiana De Meester Anne-Françoise Marique, A. D. H. S. R. (2013). Impacts of occupant behaviours on residential heating consumption for detached houses in a temperate climate of the northern part of Europe. *Energy and Buildings 57*, 313–323.

Tetlow, R. M., C. van Dronkelaar, C. P. Beaman, A. A. Elmualim, and K. Couling (2015). Identifying behavioural predictors of small power electricity consumption in office buildings.

Thaler, R. (1980). Toward a positive theory of consumer choice. *Journal of Economic Behavior & Organization 1*(1), 39–60.

Valkila, N. and A. Saari (2013). Attitude-behaviour gap in energy issues: Case study of three different Finnish residential areas. *Energy for Sustainable Development 17*(1), 24–34.

Van den Brom, P., A. Meijer, and H. Visscher (2019, jan). Actual energy saving effects of thermal renovations in dwellingsâlongitudinal data analysis including building and occupant characteristics. *Energy & Buildings 182*, 251–263.

Van den Brom, P. I., A. Meijer, and H. J. Visscher (2017). Performance gaps in energy consumption: household groups and building characteristics. *Building Research & Information.*

Van Huyck, J. B., R. C. Battalio, and R. O. Beil (1990). Tacit Coordination Games, Strategic Uncertainty, and Coordination Failure. *The American Economic Review 80*(1), 234–248.

Van Raaij, W. F. and T. M. M. Verhallen (1983a). A behavioral model of residential energy use. *Journal of Economic Psychology 3*(1), 39–63.

Van Raaij, W. F. and T. M. M. Verhallen (1983b). Patterns of residential energy behavior. *Journal of Economic Psychology 4*(1), 85–106.

Vanberg, V. (2002). Rational choice vs. program-based behavior: Alternative theoretical approaches and their relevance for the study of institution. *Rationality and Society 14*, 7–53.

Varian, H. R. (2014). Big data: New tricks for econometrics. *Journal of Economic Perspectives 28*(2), 3–28.

Vink, G., L. Frank, J. Pannekoek, and S. Van Buuren (2014). Predictive mean matching imputation of semicontinuous variables. *Statistica Neerlandica 68*(1), 61–90.

Visscher, H., F. Meijer, D. Majcen, and L. Itard (2016, aug). Improved governance for energy efficiency in housing. *Building Research & Information 44*(5-6), 552–561.

Von Thadden, E.-L. and X. Zhao (2012). Incentives for Unaware Agents. *The Review of Economic Studies* (3), 1151—-.

Von Thadden, E.-L. and X. Zhao (2014). Multi-task agency with unawareness. *Theory & Decision 77*(2), 197—-.

Vranceanu, R., F. El Ouardighi, and D. Dubart (2015). Team Production with Punishment Option: Insights from a Real-Effort Experiment. *Managerial and Decision Economics 36*, 408–420.

Watson, D. (1992, aug). Correcting for Acquiescent Response Bias in the Absence of a Balanced Scale. *Sociological Methods & Research 21*(1), 52.

Weber, R., C. Camerer, Y. Rottenstreich, and M. Knez (2001). The Illusion of Leadership: Misattribution of Cause in Coordination Games. *Organization Science 12*(5), 582.

Weinstein, N. D. (1980). Unrealistic Optimism About Future Life Events. *Journal of Personality and Social Psychology 39*(5), 806–820.

Westreich, D., J. Lessler, and M. J. Funk (2010). Propensity score estimation: neural networks,support vector machines, decision trees (cart), and meta-classifiers as alternatives tologistic regression. *Journal of Clinical Epidemiology 63*(8), 826–833.

Williamson, B. (2012). The Gap between Design and Build: Construction Compliance towards 2020 in Scotland. Technical report, Edinburgh Napier University, Edinburgh.

Ye, J., J.-H. Chow, J. Chen, and Z. Zheng (2009). Stochastic gradient boosted distributed decision trees. In *Proceedings of the 18th ACM conference on Information and knowledge management*, pp. 2061–2064. ACM.

Zeileis, A., T. Hothorn, and K. Hornik (2008). Model-Based Recursive Partitioning. *Journal of Computational and Graphical Statistics 17*(2), 492–514.

Zhao, X. (2008). Moral hazard with unawareness. *Rationality and Society 20*(4), 471–496.

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Résumé

Cette thèse vise à contribuer à rendre le marché de la rénovation énergétique durable et autonome. Pour y parvenir, notre objectif est de contribuer à quantifier le risque de non atteinte de la performance énergétique après rénovation. Dans un premier chapitre, nous analysons les facteurs psychologiques à prendre en compte pour améliorer les futurs modèles de prédictions de consommation d'énergie. En nous appuyant sur le programme de rénovation *Je rénove BBC*, nous mettons en évidence quatre biais cognitifs des ménages impactant négativement la différence entre la consommation d'énergie réelle et prédite. Par la suite, nous étudions les structures de contrats les plus appropriés pour améliorer le déroulement des chantiers de rénovation, incitant les artisans à mieux travailler. Ainsi, nous déterminons d'une part des contrats destinés à un Agent devant effectuer deux tâches et qui sous-estime l'impact de l'une d'entre elles sur la performance du bâtiment. D'autre part, nous testons des incitations individuelles et de groupe sur la capacité de plusieurs Agents réels (artisans) à se coordonner, selon leur formation initiale (formation *DORéMI* ou autre).

Mots-clés: biais cognitifs, économétrie appliquée, théorie des contrats, économie expérimentale, rénovation énergétique

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Abstract

This thesis aims at contributing to make the energy renovation market long-lasting and self-sustaining. To achieve this, our objective is to quantify the risk of not achieving energy performance after renovation. In a first chapter, we analyze the psychological factors that should be taken into account to improve future energy consumption prediction models. Drawing on the *Je rénove BBC* renovation program, we highlight four cognitive biases of households that negatively impact the difference between actual and predicted energy consumption. Then, we study the most appropriate contract structures to improve the flow and quality of renovation projects, encouraging craftsmen to work better. Thus, on one hand, we determine optimal contracts for an Agent who has to perform two tasks and underestimates the impact of one of them on the building's performance. On the other hand, we test individual-based and group-based incentives on the ability of several real Agents (craftsmen) to coordinate, according to their initial training (*DORéMI* training or other).

Keywords: cognitive biases, applied econometrics, contract theory, experimental economics, energy renovation