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Towards sufficiency in housing: Agent-based model and transition scenarios

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par

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Als das Kind Kind war,
war es die Zeit der folgenden Fragen:
Warum bin ich ich und warum nicht du?
Warum bin ich hier und warum nicht dort?
Wann begann die Zeit und wo endet der Raum?
Ist das Leben unter der Sonne nicht bloß ein Traum?
Ist was ich sehe und höre und rieche
nicht bloß der Schein einer Welt vor der Welt?
Gibt es tatsächlich das Böse und Leute,
die wirklich die Bösen sind?
Wie kann es sein, daß ich, der ich bin,
bevor ich wurde, nicht war,
und daß einmal ich, der ich bin,
nicht mehr der ich bin, sein werde?
[...]
Als das Kind Kind war,
spielte es mit Begeisterung
und jetzt, so ganz bei der Sache wie damals, nur noch,
wenn diese Sache seine Arbeit ist.
[...]

Lied vom Kindsein von Peter Handke
Der Himmer über Berlin von Wim Wenders, 1986

And while I was writing this review, I discovered that if I were going to review books I should need to do battle with a certain phantom. And the phantom was a woman, and when I came to know her better I called her after the heroine of a famous poem, The Angel in the House. It was she who used to come between me and my paper when I was writing reviews. It was she who bothered me and wasted my time and so tormented me that at last I killed her.

[...]

And when I came to write I encountered her with the very first words. The shadow of her wings fell on my page; I heard the rustling of her skirts in the room. Directly, that is to say, I took my pen in my hand to review that novel by a famous man, she slipped behind me and whispered: "My dear, you are a young woman. You are writing about a book that has been written by a man. Be sympathetic; be tender; flatter; deceive; use all the arts and wiles of our sex. Never let anybody guess that you have a mind of your own. Above all, be pure."

[...]

Thus, whenever I felt the shadow of her wing or the radiance of her halo upon my page, I took up the inkpot and flung it at her. She died hard. Her fictitious nature was of great assistance to her. It is far harder to kill a phantom than a reality. She was always creeping back when I thought I had despatched her. Though I flatter myself that I killed her in the end, the struggle was severe; it took much time that had better have been spent upon learning Greek grammar; or in roaming the world in search of adventures.

[...]

Professions for women, by Virginia Woolf, 1931

Στο παιδὶ …

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Margarita,
Lausanne, Spring 2022

Abstract

Research problem: Housing is responsible for a considerable part of global resource consumption. In Switzerland, it accounts for almost one third of the country's CO_2 emissions and half of the total energy demand. Thus, housing plays an important role in the transition to sustainable development. The prevalent discussion about sustainable housing concentrates on building performance, along with recommendations for enhancing the sustainable behaviour of tenants. Housing has been thoroughly studied from a disciplinary perspective, e.g., economics, social sciences, psychology, engineering. However, little attention has been paid to housing as a system of interrelated actors, e.g., developers, owners, tenants and state, whose actions might be described and explained by different disciplines. Former national housing policies were placing emphasis on affordability, focusing on the construction of affordable dwellings and the promotion of home-ownership. Currently, environmental sustainability has progressively become a clear target of housing policy.

Aim of the research: The aim of this thesis is to investigate how a change in the construction practices of property owners and developers, in combination to a more space-efficient allocation of dwellings to households and a behavioural change of tenants can achieve a substantial reduction in the environmental impact of housing. The focus lies on the interrelations of housing actors, concentrating mainly on the property owners. This dissertation explores which measures and to what extent can lead to a reduction of space consumption of housing and aspires to explore the effects of measures taken by residents, building owners and authorities.

Methods: Housing is characterised by a high level of complexity, therefore a transdisciplinary approach is adopted that allows to use methods from various disciplines. The Swiss housing market and its unique attributes, e.g., dwelling and household characteristics, residential mobility, land reserves and housing policy, are studied in order to demystify the Swiss housing sector. In this thesis, we study a subset of the Swiss rental housing market; it comprises two housing cooperatives: ABZ in Zurich and SCHL in Lausanne as well as the insurer and asset manager Swiss Mobiliar. Their housing stocks, of approximately 10,000 dwellings, are examined in depth and are used as a case study. Extensive data gathering from digital and non digital sources allowed to create an exhaustive inventory of the building stock of the three large-

scale property owners. The data on tenants was limited, thus, we conducted a tenant survey. Furthermore, a series of workshops with both tenants and property owners were organised to better understand their decision-making processes. This dissertation explores the challenges, constraints and possibilities for integrating goals of long-term sustainable development into housing. For that purpose, a bottom-up agent-based model (ABM) is built, which portrays the case study housing system. The model describes both housing supply and demand. The main actors of the rental housing market (property owners and households) are represented in the model by agents; the owner agents make decisions about their building stock and tenants, while the household agents choose a dwelling based on their needs and housing preferences. The dynamic evolution of both owners and households and the interaction between them is simulated in the model and allows the study of emergent phenomena. This research underlined the importance of a transdisciplinary approach of housing. The present thesis attempts the assessment of the environmental impact of housing through the lens of housing sufficiency. Space consumption, in terms of dwelling surface and floor area per capita, is considered as the largest determinant of resource consumption, because it escalates energy and material demand.
Results: This dissertation introduces a context-specific agent-based model that simulates the housing decisions of property owners and tenants. The simulation results show that measures taken to decrease the environmental impact of housing and space consumption are inadequate if owners do not change their construction practices and households do not actively change their housing behaviour. Most measures explored in this thesis, if implemented individually, succeed in reducing the rate of increase in space consumption but fail to reverse the upward trend. A more space-efficient allocation of dwellings to households proves to have a certain effect. However, only when combined with other measures, such as the densification of the existing building stock and a change in construction practices, a significant decrease of environmental impact is observed. Lastly, the environmental objectives cannot be achieved without the active participation of both owners and tenants.

KEYWORDS: Housing, Housing construction, Sustainable development, Environmental impact, Agent-based modelling (ABM)

Résumé

Problématique : Le secteur du logement est responsable pour une partie considérable de la consommation mondiale de ressources. En Suisse, il représente presque un tiers des émissions de CO_2 du pays et la moitié de la demande énergétique totale. Le logement joue donc un rôle important pour la transition vers le développement durable. Le débat actuel sur le logement durable se concentre sur la performance énergétique des bâtiments, ainsi que sur les mesures à prendre pour améliorer le comportement durable des locataires. Le logement a fait l'objet d'études approfondies en fonction des différentes disciplines par ex. économie, sciences sociales, psychologie, ingénierie. Cependant, peu d'attention a été portée au logement en tant que système d'acteurs interdépendants, par exemple les développeurs, les propriétaires, les locataires et l'État, dont les actions pourraient être décrites et expliquées par différentes disciplines. Les anciennes politiques nationales du logement mettaient l'accent sur l'accessibilité financière, en se concentrant sur la construction de logements abordables et la promotion de l'accession à la propriété. Actuellement, la durabilité environnementale est progressivement devenue un objectif clair de la politique du logement.

Objectif : L'objectif de cette thèse est d'étudier comment un changement dans les pratiques de construction des propriétaires et des développeurs, combiné à une allocation plus efficace de l'espace des logements aux ménages et à un changement de comportement des locataires, peut permettre une réduction substantielle de l'impact environnemental du logement. L'accent est mis sur les interrelations entre les acteurs du logement, en se concentrant principalement sur les propriétaires. Cette thèse explore quelles mesures dans quelle ampleur peuvent conduire à une réduction de la consommation d'espace des logements et aspire à explorer les effets des mesures prises par les occupants, les propriétaires d'immeubles et les autorités.

Méthodes : Le logement est caractérisé par un haut niveau de complexité, c'est pourquoi une approche transdisciplinaire est adoptée qui permet d'utiliser des méthodes de différentes disciplines. Le marché suisse du logement et ses attributs uniques, par exemple les caractéristiques des logements et des ménages, la mobilité résidentielle, les réserves foncières et la politique du logement, sont étudiés afin de démystifier le secteur du logement en Suisse. Dans cette thèse, nous étudions un sous-ensemble du marché suisse du logement locatif ; il comprend

deux coopératives de logement : ABZ à Zurich et SCHL à Lausanne ainsi que la société d'assurance et de gestion de fonds Swiss Mobiliar. Leur parc immobilier, qui compte environ 10,000 logements, est examiné en profondeur et sert d'étude de cas. Une vaste collecte de données tirées de sources numériques et non numériques a permis de créer un inventaire exhaustif du parc immobilier des trois grands propriétaires. Les données sur les locataires étaient limitées, et on a mené une enquête auprès des locataires. En outre, une série de workshops avec les locataires et les propriétaires ont été organisés afin de mieux comprendre leurs mécanismes de prise de décision. Cette thèse explore les défis, les contraintes et les possibilités d'intégrer les objectifs du développement durable à long terme dans le logement. À cette fin, un modèle multi-agent bottom-up (ABM) est développé, qui représente le système de logement de l'étude de cas. Le modèle décrit à la fois l'offre et la demande de logements. Les principaux acteurs du marché du logement locatif (propriétaires et ménages) sont représentés dans le modèle par des agents ; les agents propriétaires prennent des décisions concernant leur parc immobilier et leurs locataires, tandis que les agents ménages choisissent un logement en fonction de leurs besoins et de leurs préférences. L'évolution dynamique des propriétaires et des ménages et l'interaction entre eux sont simulées dans le modèle et permettent l'étude des phénomènes émergents. Cette recherche a souligné l'importance d'une approche transdisciplinaire du logement. La présente thèse tente d'évaluer l'impact environnemental du logement à travers le prisme de la notion de suffisance du logement. La consommation d'espace, en termes de surface de logement et de surface de plancher par habitant, est considérée comme le plus grand déterminant de la consommation de ressources, car elle intensifie la demande d'énergie et de matériaux.
Résultats : Cette thèse introduit un modèle multi-agent contextuel qui simule les décisions de logement des propriétaires et des locataires. Les résultats de la simulation montrent que les mesures prises pour diminuer l'impact environnemental du logement et de la consommation d'espace sont inadéquates si les propriétaires ne changent pas leurs pratiques de construction et si les ménages ne modifient pas activement leur comportement en matière de logement. La plupart des mesures explorées dans cette thèse, si elles sont mises en œuvre individuellement, parviennent à réduire le taux d'augmentation de la consommation d'espace mais ne parviennent pas à inverser la tendance à l'augmentation de la consommation d'espace. Une allocation plus efficace de l'espace des logements aux ménages a un certain effet. Cependant, ce n'est que lorsqu'elle est combinée à d'autres mesures, telles que la densification du parc immobilier existant et un changement des pratiques de construction, qu'une diminution significative de l'impact environnemental est observée. Enfin, les objectifs environnementaux ne peuvent être atteints sans la participation active des propriétaires et des locataires.

MOTS CLÉS : Logement, Construction de logements, Développement durable, Impact environnemental, Modèle multi-agent (ABM)

Zusammenfassung

Forschungsfrage: Der Wohnungsbau ist für einen erheblichen Teil des weltweiten Ressourcenverbrauchs verantwortlich. In der Schweiz ist er für fast ein Drittel der CO_2-Emissionen und die Hälfte des gesamten Energiebedarfs verantwortlich. Daher spielt der Wohnungsbau eine wichtige Rolle beim Übergang zu einer nachhaltigen Entwicklung. Die derzeitige Diskussion über nachhaltigen Wohnungsbau konzentriert sich auf Gebäude und auf Empfehlungen zur Verbesserung des nachhaltigen Verhaltens der Mieter. Der Wohnungsbau wurde von verschiedenen Disziplinen, z.B. Wirtschaft, Sozialwissenschaften, Psychologie und Ingenieurwesen, einzeln eingehend untersucht. Dem Wohnungswesen als einem System miteinander in Wechselbeziehung stehender Akteure, z.B. Bauträger, Eigentümer, Mieter und Staat, deren Handlungen von verschiedenen Disziplinen fachübergreifend beschrieben und erklärt werden könnten, wurde jedoch wenig Aufmerksamkeit geschenkt. Frühere nationale Wohnungspolitik legte den Schwerpunkt auf die Bezahlbarkeit und konzentrierte sich auf den Bau von erschwinglichen Wohnungen und die Förderung von Wohneigentum. Gegenwärtig ist die ökologische Nachhaltigkeit zunehmend zu einem ausdrücklichen Ziel der Wohnungspolitik geworden.

Ziel: In dieser Arbeit soll untersucht werden, wie durch eine Änderung der Baupraktiken von Immobilieneigentümern und Bauträgern in Verbindung mit einer flächeneffizienteren Zuteilung von Wohnungen an Haushalte und einer Verhaltensänderung der Mieter eine erhebliche Verringerung der Umweltauswirkungen von Wohnraum erreicht werden kann. Der Fokus liegt dabei auf den in Wechselbeziehung stehenden Akteuren im Wohnungswesen, wobei der Schwerpunkt auf den Immobilieneigentümern liegt. Diese Dissertation geht der Frage nach, welche Massnahmen in welchem Umfang zu einer Reduktion des Flächenverbrauchs von Wohnungen führen können und untersucht die Auswirkungen von Massnahmen der Bewohner, der Gebäudeeigentümer und der Behörden.

Methoden: Der Wohnungsbau ist durch eine hohe Komplexität gekennzeichnet, weshalb ein transdisziplinärer Ansatz gewählt wird, der es erlaubt, Methoden aus verschiedenen Disziplinen zu verwenden. Der Schweizer Wohnungsmarkt und seine besonderen Merkmale, z.B. Wohnungs- und Haushaltsmerkmale, Wohnmobilität, Bodenreserven und Wohnungspolitik, werden untersucht, um den Schweizer Wohnungssektor zu verstehen. In dieser Arbeit wird eine Teilmenge des schweizerischen Mietwohnungsmarktes untersucht; sie umfasst zwei Wohnbaugenossenschaften: ABZ in Zürich und SCHL in Lausanne, sowie den Versicherer und Vermögensverwalter Swiss Mobiliar. Deren Wohnungsbestände von rund 10'000 Wohnungen werden eingehend untersucht und dienen als Fallstudie. Eine umfangreiche Datenerhebung aus digitalen und nicht-digitalen Quellen ermöglichte es, ein umfassendes Inventar des Gebäudebestands der drei grossen Immobilienbesitzer zu erstellen. Die verfügbaren Daten über Mieter waren unzureichend, sodass eine Mieterbefragung durchgeführt wurde. Darüber hinaus wurde eine Reihe von Workshops mit Mietern und Immobilieneigentümern organisiert, um deren Entscheidungsprozesse besser zu verstehen. In dieser Dissertation werden die Herausforderungen, Beschränkungen und Möglichkeiten der Integration von Zielen der langfristigen nachhaltigen Entwicklung im Wohnungsbau untersucht. Zu diesem Zweck wird ein Bottom-up agentenbasiertes Modell (ABM) entwickelt, das das Wohnungssystem der Fallstudie abbildet. Das Modell beschreibt sowohl das Wohnungsangebot als auch die Nachfrage. Die Hauptakteure des Mietwohnungsmarktes (Immobilieneigentümer und Haushalte) werden in dem Modell durch Agenten dargestellt; die Eigentümer-Agenten treffen Entscheidungen über ihren Gebäudebestand und ihre Mieter, während die Haushalts-Agenten eine Wohnung auf der Grundlage ihrer Bedürfnisse und Wohnpräferenzen auswählen. Die dynamische Entwicklung sowohl der Eigentümer als auch der Haushalte und die Interaktion zwischen ihnen wird im Modell simuliert und ermöglicht die Untersuchung von emergenten Phänomenen. Diese Untersuchung unterstreicht die Bedeutung eines disziplinübergreifenden Ansatzes für das Wohnungswesen. In der vorliegenden Arbeit wird der Versuch unternommen, die Umweltauswirkungen des Wohnens unter dem Aspekt der "Wohnungssuffizienzßu bewerten. Der Flächenverbrauch, gemessen an der Wohnfläche und der Bodenfläche pro Kopf, wird als die wichtigste Determinante des Ressourcenverbrauchs angesehen, da er den Energie- und Materialbedarf erhöht.

Ergebnisse: Die Simulationsergebnisse zeigen, dass Massnahmen zur Verringerung der Umweltauswirkungen des Wohnens und des Flächenverbrauchs unzureichend sind, wenn die Eigentümer ihre Baupraktiken und die Haushalte ihr Wohnverhalten nicht aktiv ändern. Die meisten der in dieser Arbeit untersuchten Massnahmen können, wenn sie einzeln umgesetzt werden, die Steigerungsrate des Flächenverbrauchs zwar verringern, aber den Aufwärtstrend nicht umkehren. Eine flächeneffizientere Zuteilung der Wohnungen auf die Haushalte zeigt eine gewisse Wirkung. Aber nur in Kombination mit anderen Massnahmen, wie der Verdichtung des Gebäudebestands und einer Änderung der Baupraktiken, ist eine signifikante Verringerung der Umweltauswirkungen zu beobachten. Die Umweltziele können nicht ohne die aktive Beteiligung von Eigentümern und Mietern erreicht werden.

SCHLÜSSELWÖRTER: Wohnungswesen, Wohnbau, nachhaltige Entwicklung, Umweltauswirkungen, agentenbasierte Modellierung (ABM)

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List of abbreviations and acronyms

ABM Agent-based model

ABZ (ger.) Allgemeine Baugenossenschaft Zürich, (eng.) Housing Cooperative Zurich

ARI Actual rental income

ASLOCA (fr.) Association suisse des locataires, (ger.) Schweizerischer Mieterinnen-und Mieterverband (MV)

BF Building footprint

BS Building stock

BS_model Building stock model

CCL (fr.) Centrale d'émission pour la construction de logements, (ger.) Emissionszentrale für gemeinnützige Wohnbauträger (EWG)

CO_2-eq CO_2 equivalent

D Demolition

DW / Dw / dw Dwelling

FAR (eng.) Floor area ratio, (ger.) Ausnützungsziffer (AZ), (fr.) Indice d'utilisation du sol (IUS)

FOEN (eng.) Federal Office for the Environment, (ger.) Bundesamt für Umwelt (BAFU), (fr.) Office fédéral de l'environnement (OFEV)

FOH (eng.) Federal Office for Housing, (ger.) Bundesamt für Wohnungswesen (BWO), (fr.) Office Fédéral du Logement (OFL)

FSO (eng.) Federal Statistical Office, (ger.) Bundesamt für Statistik (BFS), (fr.) Office Fédéral de la Statistique (OFS)

HH Household

HH_model Household model

GAPTO (ger.) Anzahl Personen im Gebäude, (eng.) Number of persons in the building

GWS (ger.) Gebäude- und Wohnungsstatistik, (eng.) Building and housing statistics

LCAP (fr.) Loi fédérale encourageant la construction et l'accession à la propriété de logements, (ger.) Wohnbau- und Eigentumsförderungsgesetz (WEG)

LS Land surface

MRI Maximum rent increase

NC New construction

NRI Needed rental income

P Purchase

PAR (eng) Plot area ratio, (ger.) Überbauungsziffer (ÜZ), (fr.) Coefficient d'occupation du sol (COS)

PRIO Priority number of households

R Renovation

RD Rent decrease

RE Reconstruction

REF Reference scenario or Baseline scenario

RI Rental Income

S Sale

SCHL (fr.) Société Coopérative d'Habitation Lausanne, (eng.) Housing Cooperative of Lausanne

SIA (ger.) Schweizerischer Ingenieur- und Architektenverein, (fr) La Société suisse des ingénieurs et des architectes, (eng.) The Swiss Society of Engineers and Architects

SFH Single family house

T Transformation

TC Total cost

TES (eng.) Total effective surface, (ger.) Hauptnutzfläche (HNF), (fr.) Surface utile principale (SUP)

TGS (eng.) Total gross surface, (ger.) Geschossfläche (GF), (fr.) Surface de plancher (SP)

VacDW List of vacant dwellings in each time step

Glossary

BF Building footprint, it is the surface that the building occupies on the land.

BS Building stock, it includes all three owner entities: settlements, buildings, dwellings and their attributes.

FAR (eng.) Floor area ratio, is the maximum permissible floor area, that one can build on a particular plot/piece of land. It is the ratio of all building floor surface (all floor areas of main buildings) to the land surface. (ger.) Ausnützungsziffer (AZ), (fr.) Indice d'utilisation du sol (IUS).

Maintenance Simple regular building interventions, in order to guarantee the structural integrity of the building. (ger.) Instandhaltung, (fr.) Maintenance.

New construction One of the seven owner actions; when a new settlement (buildings and dwellings) is built.

PAR (eng.) Plot area ratio, is the maximum ratio of the permissible building surface to the permissible land area. (ger.) Überbauungsziffer (ÜZ), (fr.) Coefficient d'occupation du sol (COS).

Purchase One of the seven owner actions; when an owner decides to sell a building or settlement.

Reconstruction One of the seven owner actions; it is activated after a demolition of an existing settlement; it describes the construction of a new building on the site of the old one.

Renovation One of the seven owner actions; when owners invest money to their existing building stock in order to improve its condition e.g. façade, insulation, heating system, floor etc. Renovations can be heavy or light, depending on how extensive the renovation works are. (ger.) Erneuerung, (fr.) Rénovation.

Sale One of the seven owner actions; is the maximum ratio of the permissible building surface to the permissible land area.

TES (eng.) Total effective surface, is the total building surface including main usage areas e.g. kitchen, bathroom, other rooms of dwellings and excluding secondary rooms, external walls, elevator, stairs. (ger.) Hauptnutzfläche (HNF), (fr.) Surface utile principale (SUP).

TGS (eng.) Total gross surface, is the total building surface including ground floor, walls, service shafts, elevator, stairs. (ger.) Geschossfläche (GF), (fr.) Surface de plancher (SP).

Tick Time step of the model.

Transformation One of the seven owner actions; is a form of heavy renovation, when the main structure / skeleton of the building is kept intact, but many of the elements of the building are changed e.g. floor plans, number, size of dwellings, façade, materials. (ger.) Gesamterneuerung, (fr.) Rénovation totale.

1 Introduction

Housing is a complex commodity that has many distinctive elements; housing choices entail substantial consequences for health, well-being, wealth, lifestyle, job opportunities and social networks. Unlike other commodities, dwellings have a set of unique attributes. Housing is characterised by: *spatial fixity* as dwellings are constructed in a specific location, are immovable and, thus, depend on a variety of location factors; *heterogeneity* as dwellings have unique characteristics that might be similar to other dwellings but never exactly the same; *durability* as houses exist for many years and are usually occupied for a long period of time (Fallis, 1985; Mulder and Hooimeijer, 1999; Gibb, 2003; Favarger and Thalmann, 2007; Wilhelmsson, 2002). In addition, housing has high start-up and transaction costs, long time delays because it takes time to finance, find land, design and construct (Tu, 2003; Neto, 2005; Quigley, 2003).

Real estate is a tangible asset composed of the land and the building. However, it is much more than that; houses can also be homes (Clapham, 2018; Weidemann and Anderson, 1985). A house is a basic human need, and it provides shelter, freedom, security and privacy (UN-HABITAT, 1991; Nuuter et al., 2015; Iglesias, 2012). People get attached to their home and neighbourhood, and their identity is associated with, and shaped by their environment. Housing is also linked to labour market and public and private amenities, e.g., shops, leisure facilities, schools. A house is as well a symbol of social status and is associated to social cohesion and equity. Housing and health are directly connected. Poor quality housing conditions impact negatively the health and well-being of occupants; higher rates of chronic disease and premature death are connected to housing or lack thereof (APHA, 2020; Ruonavaara, 2017). Adequate and affordable housing is a human right in the international human rights law (UN-HABITAT, 1991). Adequate housing should provide access to: sufficient living surface, sanitation, clean water, security, adequate light and low noise levels. It should ensure access to adequate, safe and affordable housing (UN-HABITAT, 2018).

The housing market and its subset, the rental housing market, follow the principles of supply and demand (Fallis, 1985; Balchin, 1996; MacLennan, 1982). Supply describes the available dwellings with their unique characteristics, e.g., size, rent, location, view, centrality, luminosity, etc. Demand encompasses the households looking for dwellings according to their needs, preferences and budget constraint. Traditionally, producers (developers and property owners) are set to maximise profits and consumers (households) to maximise utility, in a way that the different housing actors search for equilibrium outcomes in the market (Gibb, 2003). Neo-classical economic theory is based on homo economicus that assumes that individuals are ideal decision-makers with complete rationality, perfect access to information, and consistent with self-interested goals (Parker and Filatova, 2008; Tesfatsion, 2006). However, cognitive biases might lead to inaccurate judgement, perceptual misinterpretation and irrationality. Bounded rationality could be a result of human processing limitations, lack of access to information, time inadequacy (Thaler, 2008; Kahneman, 2011; Thaler, 2015). Therefore, humans do not act as if they were following the optimal decision after a cost-benefit analysis (Herbert, 1997; Ariely, 2008; De Bruin and Flint-Hartle, 2003). It has been argued that housing market models that follow rational choice and profit/utility maximisation have failed to explain the behaviour that was observed (Marsh and Gibb, 2011).

The deviations from the neo-classical assumptions imply that the housing market might exhibit particular characteristics in comparison to other commodities. Supply might be inelastic and respond slowly to changes in demand. Housing markets can stay in disequilibrium for long periods of time, due to housing shortage or unaffordability that the market cannot correct on its own. This opens the door to state regulation (Clapham, 2018). Its unique characteristics encourage as well a transdisciplinary approach to the study of housing, as a disciplinary path might not cover adequately all aspects of housing. *"The complexity of housing has meant that it has been examined through the lens of different disciplines, each of which has offered important insights"* (Clapham, 2018). However, at the same time, approaching the subject from various disciplinary lenses has proven to be challenging as it makes it difficult to establish an accepted housing theory (Kemeny, 1992).

Housing demand is determined by the population size and growth, by the gross domestic product (GDP) per capita that depicts the standard of living and the expenditure of housing as part of the household's budget. Housing supply is determined by the total investment of the housing construction sector, and it includes the total of housing units with all their attributes, which corresponds to the number of dwellings built, the size of the dwellings in terms of surface and number of rooms, the age and the state of the housing units. The size of the housing stock is analysed in relation to the population. The relationship between supply and demand defines the housing prices and the transactions. Rental or sale prices are strictly correlated to a variety of factors, such as size, location, clean air, view, centrality, luminosity, etc. (Schläpfer et al., 2015). Housing policy plays an important role to the evolution of housing, to both supply and demand (Paciorek, 2013). Policy instruments, such as lowering mortgage rates, enabling access to funding, decreasing taxes, giving subsidies, etc. stimulate supply and

demand (Balchin, 1996).
Real estate investors can origin either from the public or the private sector, and they can be profit or non-profit oriented, e.g., private individuals, housing cooperatives, institutional investors, banks, insurance companies or pension funds. Depending on their origin, they might have different goals. For example, housing cooperatives are non-profit organizations aiming to provide affordable good quality dwellings to households that are diverse in terms of income, social status, nationality, age, with special focus to families with minor children and single parents (Wüest Partner, 2019*e*; Sotomo and FSO, 2017). Non-profit owners are not aiming at maximising their profit; instead they produce housing units that cover the total investment cost allowing them a small return. As we notice, a large variety of property owners are actors of the housing market; there can be individuals, cooperatives, associations, public-utility organisations or the public sector. *Housing and environment*
"Housing consumes large amounts of energy and raw materials (environmental aspect); it is a major part of the construction industry and financial institutions (economic aspect); and it is a factor of stability linked to the well-being of individuals and families (social aspect)" (Herczeg et al., 2014). Therefore, housing is a key factor to the transition towards sustainability. Factors such as urban sprawl, energy consumption and population growth are changing the direction of housing construction. Housing plays a significant role in resource consumption and is a major driver for economic growth in most countries. Over the past years, the construction of large dwellings, in terms of surface, has been encouraged. In parallel, the size of households has been shrinking because of change of lifestyle, ageing population, declining fertility and increase of single parent households. Consequently, the average number of occupants per dwelling decreases and the floor area per capita steadily increases. This translates into a mismatch between dwellings and households in terms of size, and into an increased level of resource consumption per capita.
On a global scale, buildings and construction activity account for one third of final energy use and almost 40% of CO_2 emissions (UN Environment and International Energy Agency, 2017). Although many steps have been made towards sustainable buildings, they are still not enough to compensate for the growing construction sector and rising energy demand. Building-related CO_2 emissions have continued to increase by approximately 1% per year for the last ten years (UN Environment and International Energy Agency, 2017). The majority of carbon emissions in the built environment are caused by energy consumption (De Feijter et al., 2021). Hence, the energy performance of both new and existing housing is crucial for the transition towards sustainable housing. However, apart from embodied and operational energy of buildings, material consumption and waste management has to be considered. All phases of construction activity, i.e., new construction or renovation or demolition of existing buildings, entail a high level of resource consumption (Wüest Partner and BAFU, 2015).
For that reason, many measures are developed in order to limit the environmental impact

of housing. This can be achieved through various paths: technology and materials improvement, change of construction patterns, renovation of old buildings, fossil fuel heating system replacement, construction of new energy-efficient buildings, etc. (Empa, 2016). Any kind of construction affects the environment and requires resources and energy. Buildings consume materials and land; their maintenance consumes energy and their demolition produces waste (Kytzia, 2004). Environmentally sustainable construction means that environmental impact to the air, soil and water is limited. To accomplish sustainable housing, on the one hand, the construction of new buildings should be avoided as much as possible; on the other hand, renovating and transforming existing buildings should be preferred (FOH, 2006). The waste produced by renovating or demolishing should be limited. The consumption of grey energy for the production and transportation of materials, and the operational energy of buildings (lighting, ventilation, heating, hot water) needs to be reduced. Lately energy efficiency labels are used more frequently or are prerequisite to receive financial help from the state. Buildings with an energy label usually entail increased income for the property owner. Apart from an immediate financial benefit from lower energy expenses, as the dwelling is energy-efficient, the increased energy efficiency is also recognised at the time of sale/lease, which leads to a higher transaction price or rent (Brounen and Kok, 2011).

Apart from the improvement of the housing stock, the allocation of dwellings to households and the housing behaviour of tenants are critical too. People spend a great proportion of their time in buildings, thus, their behaviour influences the environmental impact as well.The contribution of domestic behaviours of households to achieve low carbon energy consumption is essential (Tweed, 2013; Gram-Hanssen, 2010; Jones et al., 2013). The energy consumption of households living in identical dwellings might vary even by 300% (Gram-Hanssen, 2010). This variation in energy consumption is caused by differences in the everyday activities of households, such as heating, cooling, ventilating, lighting, cooking, showering (De Feijter et al., 2021). In order to reduce the impact of housing on the environment, a change of the behavioural patterns of tenants is needed, both among all those involved in construction as well as among those who use the buildings (FOH, 2006).

Finally, apart from changing the construction patterns or the behaviour of tenants, the allocation of dwellings to households plays an important role. The discussion around adequate housing or sufficient housing rises. More and more studies focus on finding ways to estimate an environmentally tenable and globally equitable amount of per person living area (Cohen, 2021; Millward-Hopkins et al., 2020). It is no longer just a question of a minimum net living area, but also of a maximum, in relation to the household size. Housing size is the largest determinant of domestic energy consumption. The larger the floor space is, the greater is the need for energy for heating, cooling, ventilation and lighting (Moreau et al., 2021; Makantasi and Mavrogianni, 2016). Dwelling surface and floor area per capita are considered the largest determinants of environmental impact of housing (Wüest Partner, 2020*a*; IRP, 2020; Heeren and Hellweg, 2019; Saner et al., 2013; Lavagna et al., 2018). The reduction of settlement area consumption per person is considered one of the most important pillars towards sustainable housing (Wüest Partner, 2020*j*).

Housing in Switzerland - unique characteristics

Switzerland is a relatively small country with a surface area of 41,300 square kilometres. Because of its geomorphology, about two-thirds of the territory is not appropriate for building construction. Unlike many countries with market economies, the main form of housing tenure has been historically the rental sector; approximately 60% are tenant households and only 40% of Swiss households own their home (FSO, 2021*e*). The proportion of owner-occupation is the lowest of all European countries (Eurostat, 2020). The homeownership rate has been slowly but steadily increasing since 1970 (Delbiaggio and Wanzenried, 2010).

Since the rental market in Switzerland constitutes such a big part of the housing market, it is worth studying it separately. Almost half of the rental dwellings belong to private individuals; real estate companies, associations and institutions have adopted an increasing role in the rental sector, whereas the public sector owns around 5% and cooperatives represent a bit more than 8% of the rental housing units (WOHNEN SCHWEIZ, 2019). With the public sector owning almost 5% of rental housing, non-profit owners play the role that in other countries is mainly assigned to public housing (Kemeny, 1995; Kemeny et al., 2004).

The construction sector has an important impact on the Swiss national and regional economies (Lawrence, 1996). Construction activity is determined by the issue of land-use planning permits and authorisations, e.g., maximum permittable plot coverage, building heights, distances, etc. This in combination with a mix of policy rules, defined by the confederation, cantons and municipalities set the framework that gives incentives and puts constraints to housing construction. The principle targets of Swiss housing policy sum up to the promotion of (1) homeownership, (2) the construction of affordable housing and (3) the protection of both tenant (lessee) and owner (lessor) through the tenancy law (LOG, 2003; LCAP, 1974; Rohrbach, 2014). Furthermore, in Switzerland, the outstanding natural landscape has led to develop policy measures targeting the preservation of the physical environment, such as strict building codes and zoning restrictions are set by the cantons (Balchin, 1996).

In 2020, the permanent population of Switzerland was 8.7 million (FSO, 2020*d*), and more than half of the population was concentrated in the big cantons (FSO, 2020*a*). Population in Switzerland grows steadily and is expected to exceed 10 million by 2045 (FSO, 2016*b*, 2021*r*). In 1850, there were around half a million households and by 1950, the number of households was estimated to 1.3 million; 50 years later, the number had more than doubled as in 2020, there were 3.8 million (FSO, 2020*j*) households. While between 1850 and 2015 the population grew more than three times from 2.4 million to 8.3 million, the number of households increased even more, almost sevenfold during the same period. The change in the lifestyle of

families, the ageing population and structural changes in families lead to a further shrinking of household size.
In order to reply to the constantly growing housing demand, there are two paths to follow: either to construct new buildings or to use the existing housing stock. Buildable land is expensive and scarce, especially in the urban centres. Available and more affordable land is to be found in the periphery of the cities, but since urban sprawl is not desired, a more efficient exploitation of the existing building stock is preferred (Stadt Zürich, 2020; Rey and Brenner, 2016; Rey, 2014). Therefore, a large potential lies in the "renewal of existing buildings" especially in central areas. The densification process has already started, and it is more intense in large cities like Zurich, where the housing shortage is intense and the land reserves are very low.
Construction activity (either the construction of new buildings or renovation or demolition) entails a large resource consumption (BAFU, 2018). Grey energy refers to the hidden energy associated with the product of a building, and it includes the total energy required by all the transformations undergone by a product throughout its life cycle, from its production to its disposal. In addition to the grey energy, a great part of energy consumption is generated by the tenants during the use phase of a building. It has been estimated that every person living in Switzerland consumes around six thousand Watt of energy for their activities that include mobility and housing (EnergieSchweiz, 2021). Households are estimated to be responsible for 40% of energy consumption (Stadt Zürich, 2011). The vision of a 2000-Watt society predicts that only one third of today's energy will be available in the future, and that three quarters of that energy will have to be generated from renewable sources. This implies a reduction of the primary energy consumption per person to one third of today's level.

This dissertation - research gaps, objectives and questions
This thesis was part of the research project "Shrinking housing's environmental footprint" (SHEF), which was funded by the Swiss National Science Foundation (SNSF) in the context of the National Research Programme "Sustainable Economy" (NRP73). In this project, there were three laboratories involved: the Laboratory of Environmental and Urban Economics (LEURE, EPFL), the Laboratory of Human-Environment Relations (HERUS, EPFL), and the Chair of Ecological Systems Design (ESD, ETHZ).
The aim of this dissertation is to develop measures and recommendations to reduce the environmental impact of housing. In more detail, it examines by which means, and to what extent, the consumption of resources in rental housing can be decreased. It aspires to develop a range of approaches for a wide audience, such as residents, building owners and authorities. The collaboration between the three laboratories offers a transdisciplinary and broader approach to all aspects of sustainable housing. The decision-making processes of property owners of rental dwellings (Economic) are studied by LEURE; the tenants' housing behaviour and residential mobility (Social) are examined by HERUS; the building stock model and its environmental

impact in terms of material and energy consumption (Environmental) is designed by ESD.
A major feature of this research project is the inclusion and close collaboration with three large-scale property owners of rental housing in Switzerland; two housing cooperatives: ABZ in Zurich and SCHL in Lausanne, and the insurer and asset manager Swiss Mobiliar. Their housing stocks, of approximately 10,000 dwellings, are examined in depth and are used as a case study to answer our research questions. In the context of this thesis, the case study is a subset of the Swiss rental housing market.
The rental housing market is a complex system with many actors often trying to fulfil conflicting goals and needs. In the context of this thesis, three major actors are considered: the owners of rental units, the households and the state. The focus of this dissertation lies on the housing supply, specifically on the decision-making processes of owners of a subset of residential rental dwellings in Switzerland. Owners make decisions about their existing and future building stock; it is them who determine whether to produce new dwellings by constructing a new building or to demolish and reconstruct or transform or renovate an existing building. It is them as well who are responsible for the selection of tenants and the allocation of dwellings to the households. On the other side, households need to find a home, and thus, choose dwellings according to their needs and budget. They both meet in the housing market and try to achieve their goals. The decisions made from both actors entail an environmental impact. The housing sector is responsible for a large part of greenhouse gas emissions (GHG), therefore housing is a key component towards a sustainable future.
Housing has been studied through the scientific lens of various disciplines. Economists have developed housing theories that describe in detail the supply and demand of housing markets; they have built models estimating the profitability of investments in housing; they have developed hedonic pricing models for the valuation of real estate assets; they use utility functions to describe household preferences, etc. (Malpezzi, 2003; Wing and Chin, 2003; Christersson et al., 2015). Social scientists and psychologists have studied the behavioural aspects of tenants' dwelling choice and satisfaction; researches have been trying to shed light to the determinants of housing choice and the motives of households that generate residential mobility (Weidemann and Anderson, 1985; Amérigo and Aragonés, 1997). Environmental scientists have developed ways to assess the environmental impact of housing, such as life cycle analysis (LCA) (Saner et al., 2013; Heeren et al., 2013, 2015; Lavagna et al., 2018), ecological footprint calculation (Pfister and Kulionis, 2020), etc. Engineers and architects have been trying to find structural, material and architectural solutions to construct buildings that are: resilient, able to withstand intense natural and manmade disasters; functional, to respond to the needs of the occupants; aesthetically pleasing, to satisfy inhabitants and to harmonise with the natural surrounding; and economic in the sense that investors ensure the targeted financial returns and inhabitants afford renting or buying. Housing has been in the focus of various disciplines (Kemeny, 1992), and there has been little transdisciplinary research in the housing

field. Because of the high complexity that characterises this field, it is needed to find ways to overcome disciplinary fragmentation and to approach the subject more holistically.
Many studies have been published analysing several aspects of investment decision-making of owners (Christersson et al., 2015; Streicher, 2000; Makantasi and Mavrogianni, 2016; Tweed, 2013; Quigley, 2003; Kemeny et al., 2004), and triggers and constraints for housing development (Thalmann, 2008; Paciorek, 2013; Schüssler et al., 2005). Although there are many examples of top-down modelling of the housing market, there is a small number of bottom-up agent-based models simulating the housing market in a holistic way including both real estate owners and households (Picascia and Yorke-Smith, 2017; Axtell et al., 2014; Gilbert et al., 2009; Filatova, 2014). Most studies focus on the behavioural aspects of households related to dwelling choice and residential mobility (Carstensen, 2015; Jackson et al., 2008; Ustvedt, 2016; Lux et al., 2017; Ettema, 2011; Zhuge and Shao, 2018). ABMs have been used relatively frequently for the study of spatial aspects of housing, land price and land use (Magliocca et al., 2015; Ligman-Zielinska and Jankowski, 2010; Parker and Filatova, 2008). However, the simulation of owners of rental dwellings; the management of their building stock, e.g., new construction, demolitions, renovation, etc.; the interaction between dwellings and households are rarely simulated with ABMs. There is need for a bottom-up empirical model that simulates both tenants' housing behaviour and the owners' decision processes regarding their building stock.

In the context of the Swiss housing market, this dissertation tries to provide answers to four main research questions:

- *Research question RQ1*:
  One of the objectives of this thesis is to explore ways to model the housing market choices of both owners and households, and find means to assess their environmental impact, which leads us to the following research question: ***How can the housing market with its actors be modelled in such a way that the environmental impacts of different development scenarios can be compared?***
  This question refers, on the one hand, to the methods used to tackle the problem of describing such a complex system as the housing market, and on the other hand, to the methods for the estimation of its environmental impact. For that purpose we develop an agent-based model. The project combines methodologies from the natural and social sciences. The main reasons for choosing to built an ABM instead of a traditional model are: the complexity of the housing system that comprises various actors; the interrelation (direct or indirect) between the housing actors; the fact that humans (property owners or the tenants) are not acting always in a rational way, as they are limited by bounded rationality and imperfect information. The ABM describes the housing market and aims to examine measures to reduce the environmental impact of housing.

Regarding the evaluation of the model results and the assessment of the environmental impacts, this thesis concentrates on dwelling size and living surface per capita, as housing size is considered as the largest determinant of resource consumption.
This thesis, as part of the SHEF project aspires to develop a transdisciplinary approach that combines the theoretical background and modelling techniques from the engineering, economic and social sciences disciplines. Such an approach is necessary to understand better the potential for influencing the current resource demand increase and environmental impacts.

- *Research question RQ2*:
  The next objective of this thesis is to describe the owners' decision-making processes regarding their housing stock and to better understand the environmental impact of these decisions, which leads us to the following set of research questions: ***How do large scale property owners make decisions about the management of their existing housing stock and its future development? and what is the environmental impact of such decisions?***
  Depending on the type of owner (profit and non-profit), the decisions and the constraints of owners regarding their investment in housing and the management of their building stock might differ. By identifying the investment choices of property owners with multiple objectives and numerous constraints, as well as their housing management practices (maintenance, replacement, dwelling attribution), we plan to develop a systematic representation of the supply side of the housing market. By identifying a set of indicators for environmental impacts, we aim to provide a simple mapping of the management and occupation of a stock of dwellings to its environmental footprint. This is the base for the design of a model that simulates the dynamics between housing actors and estimates he implications for resource use.

- *Research question RQ3*:
  Another main focus of this thesis is to describe and simulate the owners' rules regarding the attribution of dwellings to households and study the environmental impact of dwelling attribution rules, which leads us to the following research question: ***How do property owners allocate their dwellings to households and what is its contribution to the environmental impact of housing?***
  The choice of the tenants and the allocation of dwellings to households is not studied thoroughly. The living area per capita is considered as a major determinant of resource consumption of housing. The floor area per capita depends on the one hand on dwelling size as a result of construction choices, but it depends as well on the housing choices of households. Usually, households choose a dwelling based on their preferences and willingness to pay, and owners or real estate agencies propose or not the dwelling to the

household. However, there are also dwellings that are attributed based on occupancy rules (housing cooperatives or subsidised housing), which affects greatly the floor area per capita. This thesis aspires to examine ideal occupancy measures, and to associate the ideal occupancy to housing sufficiency. In other words, to investigate what is the ideal occupancy of a dwelling, while it still offers sufficient living surface and decent living conditions to tenants. In addition to this, the focus lies to the environmental impact of the application of such occupancy rules.

- *Research question RQ4*:
  The final objective of this thesis is to describe and simulate the household's housing preferences and behaviour and to study its contribution to the environmental impact of housing, which helps formulating the following research question: ***How do households choose a dwelling and what is the contribution of households' housing choices to the environmental impact of housing?***
  Demand and supply are interdependent. Many models have been developed describing the housing behaviour of tenants. In order to model the owners' decisions, it is also needed to simulate the housing choices of households that evolve over time and change in terms of size, income, preferences, etc. By developing the demand side of the housing market, we create a broad description of the context-based housing market. Along with the dynamics of the building stock, we include the development of households throughout their life stages. This allows to investigate the influence of occupants' and owners' decisions on the environmental impacts of the housing stock, which has not been possible in the past. This goal is to built an agent-based model that encompasses all major actors of the under-study housing system and study emergent phenomena from the interaction of both owner and household actors.

Thesis outline

In Chapter 1, the context of the study is introduced. Housing and its main attributes are presented; the unique characteristics of the Swiss housing market are further developed. Furthermore, the research objectives and questions are identified; the value of such research is argued, while the limitations of the study are also discussed. In Chapter 2, the status quo of the Swiss housing market is presented. The key elements, the current major challenges and the future tendencies of housing are portrayed. Additionally, the basic aspects of the Swiss housing policy are reviewed to identify the legal framework of housing. This allows to better understand the unique characteristics of the Swiss housing market, to develop and validate the agent-based model and to assess the simulation results of the model. In Chapter 3, the case study property owners are described. This allows to simulate the context specific decisions-making processes of owners and to build and calibrate the ABM. In Chapter 4, the theoretical framework of the model is presented. The adoption of a qualitative, inductive research approach is justified, and the broader research design is discussed, including its limitations. Specifically, the conceptual framework of the model is presented and the agent-based model (ABM) is described in detail. The decision-making processes of property owners of rental dwellings and the housing preferences of households are modelled. All three sub-models of the ABM: (1) the building stock model, (2) the household model and (3) the matching model are presented. In Chapter 5, the model scenarios are described; the simulation results are analysed and the major lessons learned are discussed. Finally, in Chapter 6, a summary of the research subject and the key findings are outlined.

2 Housing in Switzerland

2.1 Introduction

In this chapter, the Swiss housing market and its special characteristics are described. Firstly, a general layout of the housing market in Switzerland is presented. The focus lies on the characteristics of the dwellings, construction activity, housing land reserves, owners of rental housing, households and the evolution of the population. Furthermore, in this chapter, the residential mobility and the Swiss housing policy is briefly presented aiming to help understand the legal context of housing. Finally, the future tendencies in the housing sector are portrayed. Apart from offering a general description of the Swiss housing market, the aim of this chapter is to capture and analyse the fundamental elements of the Swiss housing market that will be essential for building and quantifying the parameters of the agent-based model in chapter 4. This chapter serves as a reference for chapter 4 and 5, in order to justify the modelling choices and interpret the simulation results.

2.2 Methodology

This chapter is the result of a thorough analysis of the Swiss housing market from sources covering a big diversity of subjects, e.g., housing policies, zoning and land use regulation, land reserves, public utility rental owners, construction activity, tenant's housing preferences, mobility, etc.

2.3 Housing status quo in Switzerland

The population of Switzerland is 8.5 million, 85% live in areas with an urban character and half its population lives in one of the five largest agglomerations[1] (FSO, 2019*d*). Switzerland is a country of tenants; approximately 60% are tenant households and only 40% of Swiss households own their home (section 2.5). The Swiss housing market is a market economy, where the economic decisions and pricing is determined by supply and demand. Public, non-profit, cooperative housing represent a small part of the housing market (section 2.5).
In the 1980s, Switzerland witnessed an urban exodus. However, over the past twenty years, Swiss cities have been attracting progressively more inhabitants. Population growth has also been accompanied by an important increase in the demand for housing. Despite the high level of construction activity, the vacancy rate in Swiss cities has been low for many years. Low vacancy rates have led to an increase in the rental price of urban housing, with the financially weaker sections of the population being pushed to the periphery (section 2.5).
The majority of buildings in Switzerland are single-family houses (57%) (section 2.5). However, only one fourth of the population lives in single-family houses. Larger cities have a smaller proportion of single-family houses. Non-profit housing consists almost exclusively of multi-family buildings, and most of the dwellings are average sized, 3-room and 4-room flats (section 2.5).
The size of dwellings has been increasing steadily; both dwelling surface and room surface has the tendency to increase. On average, the living surface of rental dwellings is significantly lower than the owner-occupied housing units; multi-family dwellings are smaller than single-family houses (section 2.5). Furthermore, household size has been decreasing. As a result, the average living space per inhabitant has been increasing (section 2.6).
The Swiss population is expected to exceed 10 million in 2045 (FSO, 2015*b*). The number of households is increasing faster that the population (Bradbury and Liu, 2014). Therefore the demand for housing will increase significantly. The population's need for housing is the driving force for construction activity (Sartori et al., 2016); the number of dwellings is augmenting in order to accommodate the rising demand (Wüest Partner, 2021*d*). In parallel, dwellings have been growing in size, while household size has been decreasing (Moura et al., 2015; Wilson and Boehland, 2005). The average dwelling surface (m^2/dw), room surface (m^2/room) and floor area per capita (m^2/capita) are increasing, while the number of occupants per room is decreasing (FSO).
In Switzerland, the residential sector accounts for more than one fourth of the greenhouse gas emissions (GHG), mainly in the form of CO_2 (IEA, 2017; FOEN, 2021; Wüest Partner, 2020*h*). They are primarily caused by the consumption of fossil fuels for hot water and heating of buildings (Matasci et al., 2006). Total domestic energy consumption in 2020 was

[1] Zurich, Geneva, Basel, Bern and Lausanne.

determined by space heating (30.9%) and mobility (29.3%) (FSOE, 2020). Almost two-third of the energy consumption of private households was spent for space heating (64.5%) (FSOE, 2021). Dwelling size and floor area per capita play both a very important role in the residential energy consumption; larger dwellings entail an increased need of energy for heating, cooling and lighting (Wüest Partner, 2020*a*). From 1990 to 2005, the living space per person and the energy reference area increased more than the residential population. However, thanks to improved insulation standards in new buildings, the energy efficiency renovation of old houses and the increased replacement of heating oil with natural gas and non-fossil energy sources (such as heat pumps, wood, etc.) for heating buildings (Wüest Partner, 2020*c*; Dascalaki et al., 2010), greenhouse gas emissions per energy reference area decreased steadily (-56.0% from 1990 to 2019) (FOEN, 2021).

Not only energy consumption but also material consumption is proportional to the dwelling surface. To build, demolish or renovate it requires extraction of raw material, use of biomass and generates a large amount of waste. The size of dwellings is a key factor that determines the consumption of resources and energy of housing. Floor area and floor area per capita are considered the largest determinants of environmental impact of housing (Wüest Partner, 2020*a*; IRP, 2020; Heeren and Hellweg, 2019; Saner et al., 2013; Lavagna et al., 2018) *"Reducing demand for floor space by up to 20 per cent compared to the reference scenario could lower material related GHG emissions from the construction of residential buildings by up to 73 per cent by 2050 when emissions savings from recycled building materials used elsewhere in the economy are credited...The residential floor area occupied per person is one of the most important drivers of residential GHG emissions"* (IRP, 2020, p. 33). Switzerland aims for a gradual decarbonisation and transformation of the national energy system that follows the Energy Strategy 2050, which foresees a significant reduction of final energy demand by 54% from 2000 until 2050 (FSOE) (Nägeli et al., 2020). Housing plays an important role toward that direction.

The built environment represents an important capital in the national economy that generates demand for the construction industry and capital income for all economic actors that meet in the housing market (Kytzia, 2004). Housing consists of a plethora of actors, sometimes with conflicting interests; large-scale dwelling owners, private individual owners, rental households, housing cooperatives, financial institutions and other state institutions constitute the basic core of housing.

2.4 Land for housing

Land in Switzerland is scarce; especially inside and near the urban centres buildable land is limited and expensive. The variation of land price per square meter of land and the future rental price of dwellings is very high depending on the location (Wüest Partner, 2021*h*; Credit

Suisse, 2016).

- *Land reserves*

  Housing prices have been increasing, and this is mainly explained by the increases in land price (Ryan-Collins et al., 2017). According to a study among fourteen advanced economies, 81% of house price increases between 1950 and 2012 are explained by rising land prices and the remainder due to increases in construction costs (Knoll et al., 2017) The area of Switzerland is 41,300 km^2; one quarter of this, is so-called unproductive land (mainly lakes, rivers, glaciers, rock and scree). One third of the Swiss territory is agricultural land (36%), and one third is forest land (31%). Due to the continuing growth of settlements as well as scrub encroachment and forestation (in the alpine regions), agricultural land is decreasing. Only 7.5% of the land is used for housing and infrastructure. However, this surface area has increased by more than 23% between 1985 and 2009, with more than 90% of the increase at the expense of agricultural areas (FSO, 2015*a*). Furthermore, forest land has increased as well, but modestly.

  While the resident population grew by 18% between 1985 and 2010, the residential area grew by 44%. This resulted in an increase of the per capita living area. This development goes in parallel with a demand for larger dwellings and a trend toward smaller households: between 1980 and 2020, the average dwelling area per capita increased from 34 m^2 to 46 m^2 and the share of single-person households from 29% to 36%. The total area of the building zones in Switzerland (built and unbuilt areas) is approximately 230,000, ha and currently only 15% of the total building zones is not built yet (a maximum surface of 40,500 ha is estimated not to be built) (UVEK, 2018). Half of the building zones are equally dedicated to working zones, mixed zones, central zones and zones for public use; the other half belongs to housing (approximately 110,000 ha). From this surface dedicated to housing, less than 20% is unbuilt. Available buildable land is even scarcer in the big cantons. Specifically, in the canton of Zurich at most 12% of the building zones is available to be built.

  Reserves of building zones for housing are shrinking rapidly. The scarcity of land, mainly in the city centres in combination with the increasing population that is mainly concentrating in the cities, leads to high demand for buildable land, high competition for this land and high land prices. It is estimated that if the population growth, building activity and density continues with the current rhythm, the reserves could accommodate 1-1.7 million persons additionally (ARE, 2017).

  In Switzerland, building land is scarce and especially in city centres. In a study, commissioned by ARE and carried out by Fahrländer Partner AG in 2008, land reserves available at the time were compared with the foreseeable demand up to 2030. The study concluded that building zone reserves are too large in some regions and that they are often poorly located: they are often located in rather rural areas where demand is comparatively low (Fahrländer et al., 2012). In densely populated agglomerations with high growth dynamics and correspondingly high demand, however, available land is a scarce commodity (ARE, 2017).

- *Land price*
  For example, the price range for a m^2 of land to construct a multi-family house in Zurich is 4,880 CHF/m^2 for an inexpensive plot, 7,980 CHF/m^2 for an average priced plot and 13,180 CHF/m2 for an expensive plot[2]. The respective values for the Lausanne region are 2,210 CHF/m^2, 3,340 CHF/m^2 and 5,000 CHF/m^2; for Geneva 2,980 CHF/m^2, 5,090 CHF/m^2 and 8,270 CHF/m^2 (Wüest Partner, 2021*h*). On average, the land price in Switzerland is 553 CHF/m^2 for an inexpensive land, 972 CHF/m^2 for an average-priced plot and 1,512 CHF/m^2 for an expensive plot. There is a big variability of land prices depending on the location. Land availability and land price is a big challenge in the housing sector in order to offer affordable rent prices, in the case of cooperatives; and in order to generate higher rental income and maximize profit in the case of profit-oriented owners.
  According to the statistical office of canton Zurich, the average land price for residential housing is 800 CHF/m^2, while in more central areas the price is higher than 3,000 CHF/m^2 (ZKB, 2017). There are considerable differences depending on the location. Based on a hedonic regression model that ZKB has developed to estimate the land price in the canton of Zurich, the most important factor is the travel time to Zurich and to the centre of the economic area. However, tax rates and other accessibility aspects, such as the distance to workplace clusters and local infrastructures (shops and schools) or the quality of accessibility by public transport, also play a significant role. Landscape aspects are also of considerable importance for land pricing. There is a high willingness to pay for land near Lake Zurich, but also for land with good mountain and lake views. Other factors such as noise pollution, calmness or building regulations, influence as well the price of land (Stadt Zürich, 2017*c*).

2.5 Dwellings

- *Building category*
  The majority of buildings in Switzerland are single-family houses (57%) (FSO, 2021*b*). Non-profit housing consists almost exclusively of multi-family buildings, and most of the dwellings are average sized, 3-room and 4-room flats. However, only one fourth of the population lives in single-family houses. Larger cities have a smaller proportion

[2] Inexpensive plots are defined by the lower 10% of the prices, average price is the median value and expensive plots are plots whose price is in the upper 90% of the prices.

of single-family houses. For example, 25% of the buildings in the city of Zurich are single-family houses, 24% in Lausanne, 27% in the city of Bern and 9% in the city of Geneva (FSO, 2019*a*, 2021*b*).

- *Number of dwellings*
  In Switzerland, there are 1.8 million buildings and 4.5 million dwellings, among them 3.5 million are exclusively used for housing; almost one million (23%) are single-family houses and 2.5 million (77%) are apartments in multi-family houses (FSO, 2020*e*). In the canton of Zurich, there are approximately 700,000 dwellings and in Vaud 370,000 (FSO, 2020*f*).

- *Size of dwellings*

  – *Dwelling and room surface*
  The size of dwellings has been increasing steadily. The average floor area of dwellings is 99 m^2, and it tends to increase. The average floor area of rental units is 83 m^2, while for owner-occupied it is 134 m^2. Additionally, almost one third of dwellings have a living surface more than 120 m^2. Additionally, the average room surface of rental dwellings is 27.6 m^2 and 29.4 m^2 of owner-occupied dwellings. Rental dwellings are significantly smaller, almost 40% smaller in comparison to owner-occupied. The same applies for the average room surface, as shown in Table A.3 in the appendix.

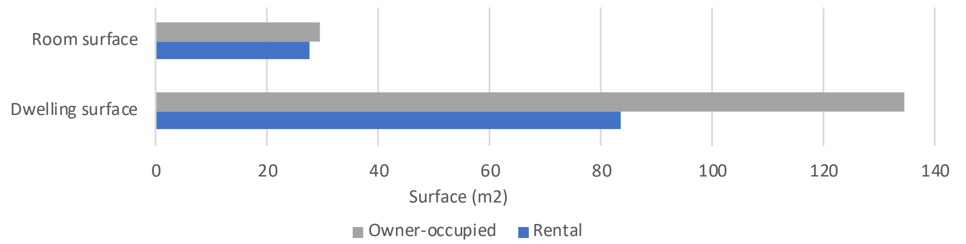


Figure 2.1 – Swiss housing - Dwelling and room surface by tenure type

Single-family houses have an average surface of 142 m^2, and dwellings in multi-family houses have a significantly lower surface of 87 m^2 (see Table A.1 in the appendix) (Wüest Partner, 2021*g*; FSO, 2020*g*,*l*). Furthermore, young dwellings, built after 2000, have larger average surface of almost 130 m^2 (FSO, 2020*l*). In Figure 2.2 and Figure 2.3, the average dwelling surface and room surface by dwelling size for rental and owner occupied dwellings is illustrated. The larger the dwelling, in terms of number of rooms, the smaller the room surface is; small sized dwellings (1-room) the highest room surface (see Figure 2.3).

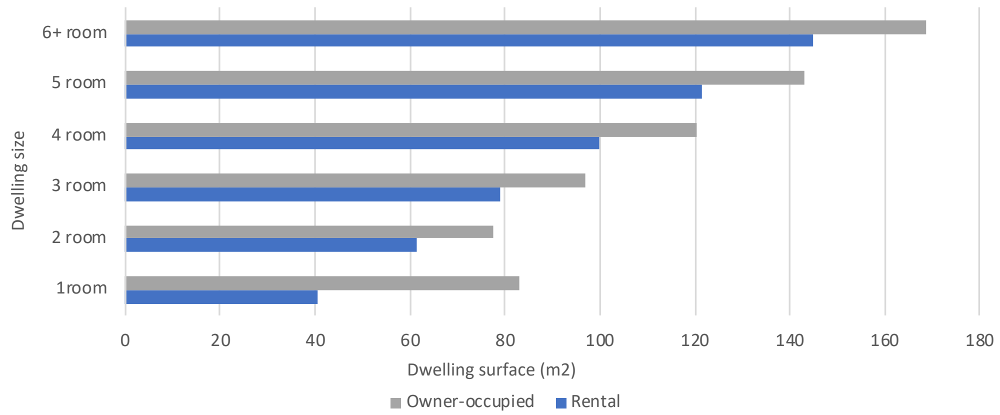


Figure 2.2 – Swiss housing - Dwelling surface by dwelling size and tenure type

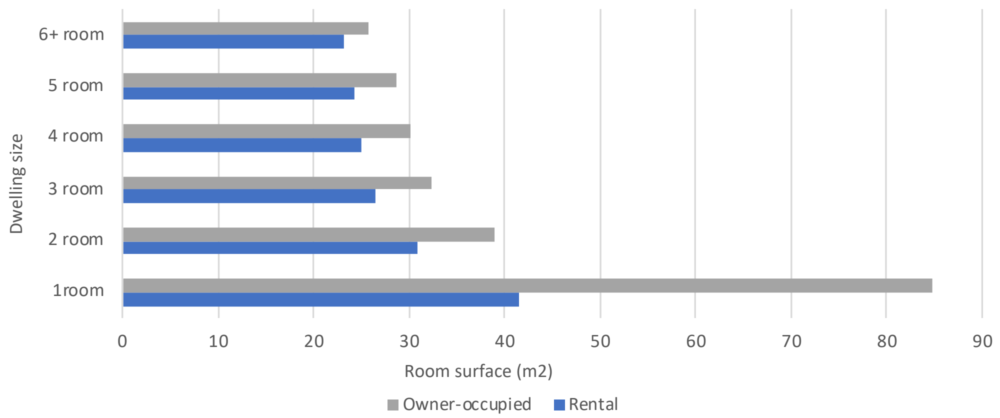


Figure 2.3 – Swiss housing - Room surface by dwelling size and tenure type

– *Number of rooms*

The majority of the housing market (55%) consists of medium-sized, 3-room and 4-room dwellings (27% and 28% of the total building stock respectively). Only a small percentage of small, 1-room and 2-room dwellings (6% and 14% accordingly) (FSO, 2020*g*). In the Swiss cities, smaller dwellings are more numerous; in the city of Zurich, small dwellings (1-room and 2-room) represent 35% of the total dwellings (12% and 23% respectively). The majority of owner-occupied dwellings (86%) are average sized (four or more rooms), while small apartments (one and two rooms) are rarely occupied by their owners. In general, housing cooperatives, in comparison to the Swiss average, have more medium size (3-room to 4-room) apartments than small or big. More specifically, 9.3% of the medium sized dwellings of all Switzerland belong to a housing cooperative.

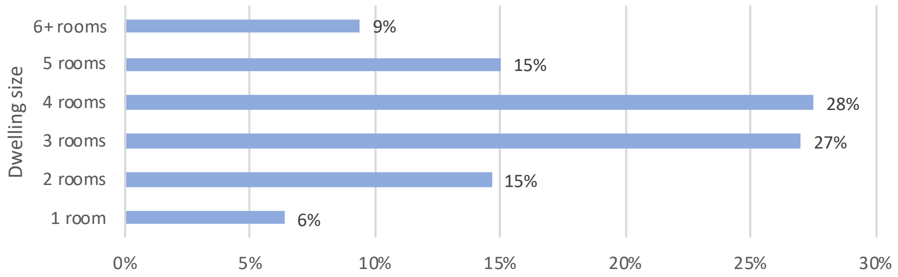


Figure 2.4 – Swiss housing - Dwelling size (number of rooms)

- *Age of the building stock*

  Almost than one third of the buildings in Switzerland (30.3%) were built before 1945, more than one third (38%) was built during the last 40 years, after 1980 (FSO, 2021*a*). Multi-family dwellings built after 2000 represent almost 23% of the total housing units and 40% were built after 1980 (FSO, 2021*h*). One fourth of the dwellings were built before 1945, as shown in Figure 2.5. Public utility housing is relatively younger with 60% of its buildings constructed between 1945 and 1980 (FSO, 2020*h*).

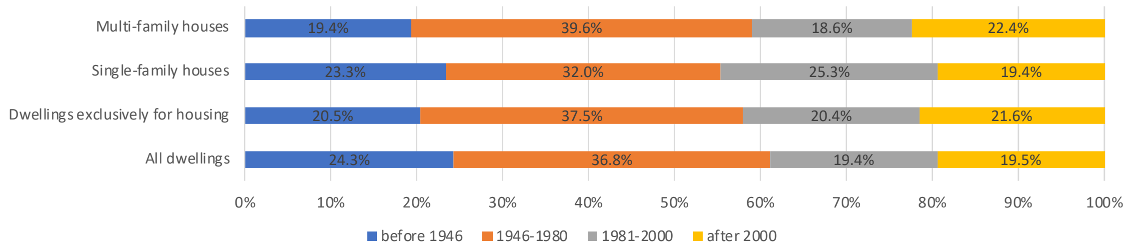


Figure 2.5 – Swiss housing - Age of dwellings by building category

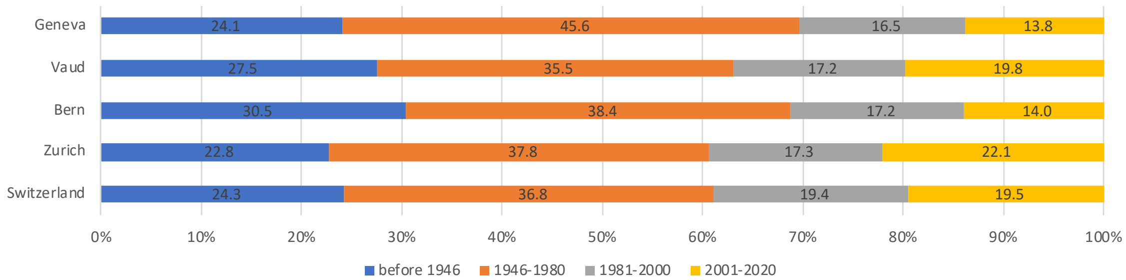


Figure 2.6 – Swiss housing - Age of dwellings by canton

Specifically, the canton of Zurich has relatively younger buildings, especially in comparison to the cantons of Geneva and Bern (see Figure 2.6). In canton Zurich 22% of the dwellings were constructed after 2000 and almost 40% after 1980; the respective percentages are 14% and 30% in the cantons of Geneva and Bern, which means that 70% of their dwelling were constructed before 1980 (FSO, 2020*h*).

Furthermore, old dwellings built before 1945 are occupied by higher social classes with higher income, buildings constructed after the war and until 1970 are occupied by lower class households and younger buildings are mainly occupied by middle class households[3] (Wüest Partner, 2020*e*).

- *Owners of rental dwellings*

  Private individuals are the principal owners of rental dwellings (50%); however, we notice that private companies have become a big player in the housing sector owning 42% of the dwellings that were constructed after 2000 (FSO, 2020*o*). Public sector owns 3.8% of the building stock, and housing cooperatives are owners of 8% of the rental dwellings in Switzerland. Zurich has a great number of cooperative rental dwellings (16%), significantly higher than the Swiss average.

Figure 2.7 – Swiss housing - Type of owner of rental dwellings

- *Tenure type*

  Switzerland is a country of tenants; approximately 60% are tenant households and only 40% of Swiss households own their home (FSO, 2021*e*)[4]. Moreover, the majority of households have a preference for rental dwellings[5] (Wüest Partner, 2020*d*).

  Homeownership rate in Switzerland has been constantly increasing since 1970 (Delbiaggio and Wanzenried, 2010). However, it is still the lowest compared to the countries in the European Union where on average 70% of the households own their home. In countries like Romania, Hungary, Slovakia, Lithuania, Croatia, etc. the homeownership reaches even 90% (Eurostat, 2020).

[3] This can be partly explained by the fact that older buildings have a certain charm but also have high maintenance costs; buildings built between 1945 and 1970 have old fashioned floor plans, small rooms and low ceilings.

[4] In Swiss urban centres the proportion of tenants is even higher, with 74% tenant or cooperative households, while owner occupancy represents only 25% of the households. The number is even higher in the big Swiss cities, with approximately 87% of the households being on rent (BFS and Städteverband, 2021).

[5] Small households of one and two persons without children prefer renting their dwelling. The main reasons for this preference, are the feeling of flexibility and independence when one is on rent and the fact they do not have responsibility for the rental dwelling. Families with children have a slight preference for owning their home.

The majority of the dwellings (2.2 million dwellings) are rental housing units, which represents 60% of all building stock (FSO, 2021*c*). The percentage of rental dwellings is even higher in the big cities, for example in Zurich 70% of the dwellings are rental housing units. The urban cantons of Basel-City (84%) and Geneva (78%) have the highest shares of rental housing, while the cantons of Jura (42%) and Valais (39%) have the lowest.

- *Non-profit housing sector*
  Non-profit housing sector plays an important role in providing housing for population groups that are disadvantaged for economic or social reasons. Approximately 4% of the housing stock in Switzerland is owned by public utility owners (Wüest Partner, 2019*e*; Sotomo and FSO, 2017). Their distribution throughout the country is not even; in the big cities of Switzerland, the share of public utility housing is around 11%, which is well above the national average (BFS and Städteverband, 2021). It is remarkable how homogeneous cooperative buildings and dwellings are in terms of number of dwellings per building, size of dwellings and living space per person, regardless of the spatial context (Lawrence, 1996).
  The public utility dwelling owners, such as cooperatives, foundations and other associations are non-profit dwelling owners and charge cost-based rents, which means that the rental income is used to cover the investment and maintenance costs (Sotomo and FSO, 2017; Wüest Partner, 2019*e*; Kemeny, 1995). Housing cooperatives receive help from the state in the form of interest-free loans, sale or lease of land at an advantageous price below the usual market price, etc. (Pattaroni and Marmy, 2016; Lawrence, 1996; Cuennet et al., 2002). This allows them to offer affordable dwellings with an average net rent approximately 15 - 20% lower in comparison to the rest of the market (Sotomo and FSO, 2017; Wüest Partner, 2019*e*). Location and tenure type seems to affect significantly the rental prices (Wüest Partner, 2019*g*). In central, expensive locations, cooperative rents might be even lower, 30 - 40% lower than conventional dwelling rents. Apparently, the cost-based rent principle is particularly effective in locations that allow commercial developers to charge higher rents (Vorburger, 2018).
  Furthermore, the majority of the cooperative dwellings[6] are offered based on strict occupancy rules, defined by each owner, sometimes following the suggestions of the canton or municipality (Wüest Partner, 2019*b*). As a result, the relation between the number of persons in the household and the size of the dwelling is stronger in the case of cooperative housing. Currently, the room rule dominates as an instrument for controlling occupancy. Regarding the occupancy in terms of specific space consumption, i.e. defining the maximum living space per person, only 2% of non-profit owners regulate space consumption (square metre rule). Furthermore, regarding the income and wealth

[6]Approximately 70% of all non-profit rental housing is subject to occupancy requirements (Blumer, 2012).

criteria, more than two-thirds of the housing developers surveyed say that they rent their affordable housing primarily to low-income households (Blumer, 2012)
Although cooperatives are to some extent outside the market logic, the dwellings they offer are characterised by higher occupancy density. Owner-occupied dwellings exhibit the highest living space per person, higher than rental dwellings, which is even higher than the public-utility dwellings (see Table A.1 and Table A.2 in the appendix). There is a problem with controlling whether the household size complies with the occupancy rules after the moments of the lease agreement. However, the occupancy rules introduced by the public utility owners are achieving their goal. Living space per capita is an important indicator of the environmental impact of housing (Wüest Partner, 2020*a*; Heeren and Hellweg, 2019); land usage per capita provides even more information. From this point of view, cooperative housing uses 25% less land than rental housing[7] and even 60% less than owner-occupied housing (Sotomo and FSO, 2017).

- *Vacancy rate*
  The housing market of Switzerland is saturated and is characterised by a very low vacancy rate of 1,72% in 2020 (FSO, 2020*i*), which is even lower in the big urban centres: 0.72% in the canton of Zurich, 1.35% in the canton of Vaud, 0.14% in Zurich city and 0.35% in the city of Lausanne (FSO, 2021*i*).

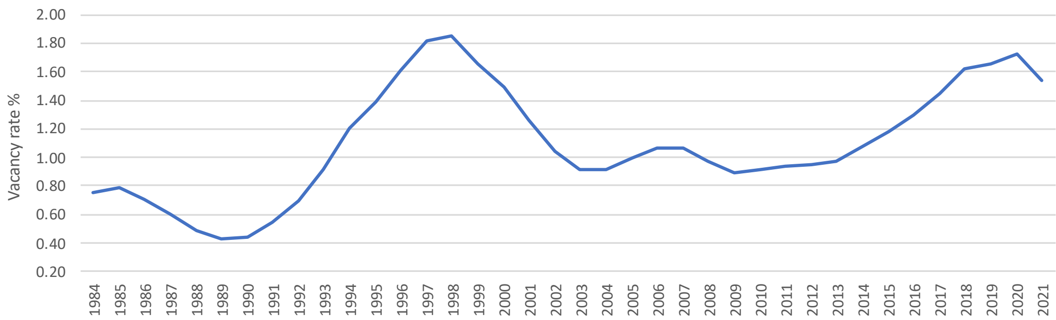


Figure 2.8 – Swiss housing - Vacancy rate evolution 1984-2021

The vacancy rate in Switzerland has been decreasing until 2009, when it reached a low value of 0.90%, and since then is slowly growing, with a growth rate of 5% per year, to reach 1.72% in 2019 (FSO, 2020*i*). Zurich is the only canton where the vacancy rate declined even stronger. The above vacancy rate corresponds to the total of the building stock (for sale and for rent); the large majority (80-90%) of vacant dwellings are for rent (FSO, 2021*e*). Despite the high level of construction activity, the vacancy rate in

[7] If we focus only on big cities, the difference between cooperative and rental housing is smaller, namely only 8%. This can be explained by the fact that in urban centres, land is scarce and very expensive; this pushes owners of rental dwellings to exploit land surface intensively.

Swiss cities has been low for many years (FSO, 2020*i*). Low vacancy rates have led to an increase in the rental price of urban housing, with the financially weaker sections of the population being pushed to the periphery (BFS and Städteverband, 2021; Credit Suisse, 2015). Although vacancy rate is very low In Switzerland, the market is in equilibrium(stable real rents), when the vacancy rate is between 1% and 1.5% and between 2% and 2.5% when we take into consideration only rental housing (Thalmann, 2012).

- *Net rent*

  - *Monthly net rent*

    The average net rent in Switzerland[8] amounts to 1,362 CHF (FSO, 2021*i*). The highest average net rent is observed in the canton of Zurich (Figure 2.9) (FSO, 2021*k*). One fourth of the households that rent in the free market pay less than 1,000 CHF, 42% under 1,200 CHF and 58% under 1,400 CHF. The respective percentages of the cooperative dwellings are 40% under 1,000 CHF, 60% under 1,200 CHF and 75% under 1,400 CHF (FSO, 2020*c*).

    Rental prices for apartments and other premises in Switzerland depend on various factors such as construction cost, age, previous renovations, dwelling surface, location, tax rates view, vicinity to other amenities, etc. (Schläpfer et al., 2015). The highest average rents are found in three cities of the Zurich "Goldküste", where the average net rent can even reach 2,200 CHF. The rent is negatively correlated with the dwelling's age; especially dwellings that are young and are constructed within the last 10 years have a higher rent by approximately 10% in comparison to older dwellings (FSO, 2021*m*).

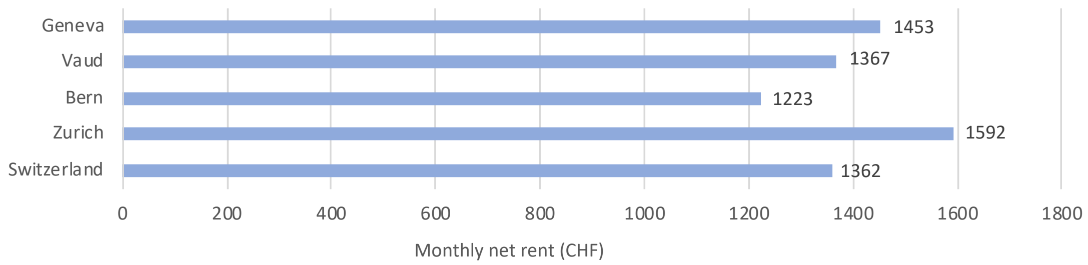


Figure 2.9 – Swiss housing - Net rent by canton

[8]The average net rent in the city of Zurich is 1,590 CHF, in Lausanne 1,270 CHF and in Bern 1,320 CHF.

- *Monthly net rent per living surface*
  The average net rent per floor area in Switzerland[9] is 16.4 CHF/m^2 (FSO, 2021*l*); the smaller the dwelling in terms of number of rooms, the higher the average net rent per floor area. The country's average amounts to 19.3 CHF/m^2 for 1-room dwellings, 18 CHF/m^2 for 2-room dwellings and progressively drops to 15.6 CHF/m^2 for 5-room dwellings.

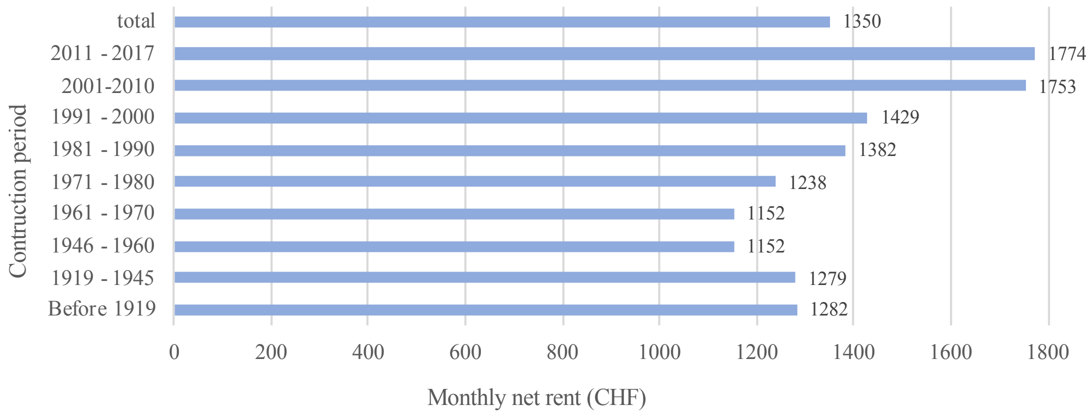


Figure 2.10 – Swiss housing - Net rent by construction period

- *Construction activity*
  Construction activity in Switzerland is high; newly constructed dwellings on a yearly basis, account for 1% of the building stock (Rey and Brenner, 2016). Available data about the yearly demolitions is limited; on average a yearly demolition rate of approximately 0.3% - 0.4% is estimated. After 2000, the demolition rate increased slightly, and it is expected to increase even more due to the ageing building stock and the densification trend.
  Analysing renovations and renovation frequency is very challenging. There is limited information about the renovation type, the renovated elements and the age of the building at the time of the renovation. In principle, the renovation cycle is estimated at 30 years (Gerheuser, 2004; Volland et al., 2020). The proportion of renovated rental flats is similar to that of owner-occupied flats. Cooperatives are very active renovating their building stock; among the owners of rented flats, cooperative tenants have by far the highest rate of flats that are renovated (Riser et al., 2017). The lowest renovation rates are found in buildings owned by real estate funds and insurance companies; this could be partly explained by the comparatively high proportion of younger flats they own. Due to the lack of reliable renovation data, the existing standards for construction and housing are a better source of information. According to CRB, the operating life of a building

[9]The average net rent per floor area in the canton of Zurich is 19.2 CHF/m^2, in Vaud 17.6 CHF/m^2, in Bern 15 CHF/m^2 and in Geneva 19.5 CHF/m^2.

is estimated to a maximum of 120 years. However, renovations are estimated after the first 40 years. Regarding the technical parts of the building, their life is estimated to 15-50 years, e.g., electrical installations, lights, security system, alarm, video surveillance and fire-alarm system, etc. Heating, ventilation and air-conditioning systems have on average 20 years life expectancy; boiler, circulation pump, fireplace, heat pumps, 20 years; floor heating 30 years and radiators 50 years (CRB, 2012).

In 2019, the construction of residential buildings in Switzerland decreased by 1.0% compared to the previous year. The construction of single-family houses dropped by 2.5% compared to 2017. In contrast, the number of new dwellings constructed increased by 6.0%. Regarding the spatial distribution of new construction, most of the newly constructed dwellings were built in the greater Zurich region (+20.9%) and the Lake Geneva region (+12.4%) (FSO, 2021*e*). In 2018, the construction of residential buildings increased by 0.6%, and the number of new dwellings rose by 7.5% in comparison to the previous year (FSO, 2020*b*).

In 2018, more than 13 billion CHF was invested in new housing construction, which represents almost 40% of the total investment in housing construction. In urban centres, 6% of the investments is dedicated to public utility housing. In 2018, approximately 58,000 new dwellings were constructed (FSO, 2020*k*). In 2019, investments in new buildings in Switzerland decreased by 2.7%, while in the previous year, in 2018, they had increased by 0.8%. However, investments in transformation works increased by 4.7% compared to 2018.

The last years, the liquidity of the Swiss rental housing market remains stable although the construction activity is high and the population is not growing as fast; this is partly explained by the shrinking of households and the demolition and reconstruction of existing buildings (Wüest Partner, 2021*f*).

- *Reference rate*

  The reference interest rate is based on the weighted average interest rate for mortgages in Switzerland, which is determined every quarter. Article 269 of the Swiss Code of Obligations stipulates that in the event of considerable fluctuations in the reference interest rate, landlords may increase rents, while tenants may demand a reduction. Tenant organisations inform interested parties about changes in mortgage rates and about the rights and duties of landlords and tenants. Among these organisations is the Swiss Tenants' Association (ASLOCA).

  The reference rate has been decreasing over the last years (see Figure 2.11). This has generated construction activity and led to an increase of homeownership. In long term, a stabilisation or slight increase of the average interest rate is expected. However, the reference rate is expected to remain at 1.25% until 2026 (ZKB, 2021*b*).

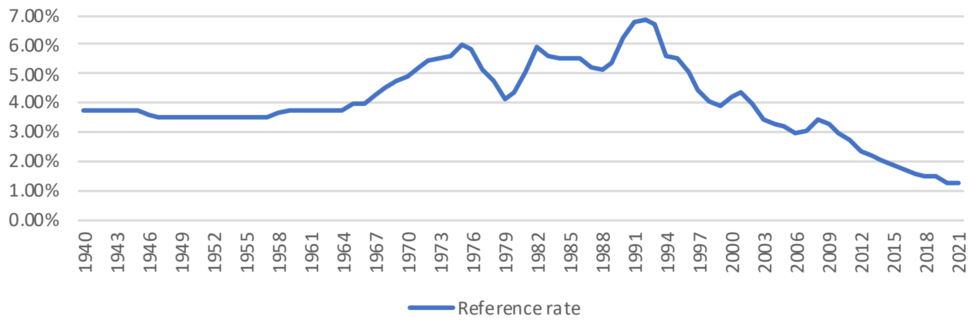


Figure 2.11 – Swiss housing - Reference rate evolution 1940-2021

2.6 Households

- *Number of households*

  In 2019, the permanent population of Switzerland was 8.6 million (FSO, 2018*a*) and more than half of the population was concentrated in the big cantons[10]. In 1850, there were around 500,000 households in Switzerland, and they were slowly but steadily augmenting. At the beginning of the twentieth century, the number of households started increasing more rapidly. By 1950, the number of households was estimated to 1.3 million; 50 years later, the number had more than doubled; in 2019, there were 3.8 million (FSO, 2018*b*) households[11]. While between 1850 and 2015 the population grew more than three times from 2.4 million to 8.3 million, the number of households increased even more, almost seven times more during the same period. The growth was particularly high at the end of the 20^{th} century. During that period, a structural change was observed; the number of small households increased sharply, while the number of large households decreased. This explains the disproportional increase of the number of households. However, another important factor is the demographic growth of the last 20 years due to migratory flows to Switzerland. In the context of this thesis, the number of households is equal to the number of occupied dwellings and not counted based on the principle of separate budgets.

- *Size of households*

  In Switzerland, the average number of persons per household is 2.2 (FSO, 2021*p*), and all big cantons follow the same pattern[12], while in cities like Zurich, Lausanne and Bern it

[10]The population of Canton Zurich was 1,492,744, Canton Bern 1,015,007, Canton Vaud 783,298 and Canton Geneva 475,948.

[11]The number of households in Canton Zurich was 680,791 and in Canton Vaud 349,158, in the municipality of Zurich 201,252 and in the municipality of Lausanne 68,940.

[12]Canton of Zurich had 2.19 persons per household, Canton of Bern 2.16, Canton of Vaud 2.24 and Canton of Geneva 2.38.

is lower, close to 2.0. The highest household size averages are observed In the cantons of Appenzell Innerrhoden (2.4), Fribourg(2.34) and Geneva (2.34)(FSO, 2021*o*). The highest household size is noticed in certain municipalities of Geneva[13] with even 2.9 persons per household (FSO, 2019*e*). The majority of households (70%), are small households consisting of one or two persons.

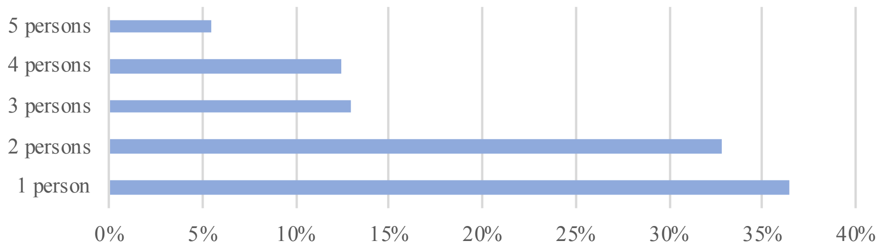


Figure 2.12 – Swiss housing - Household size

Almost half of the population lives in small households of one- or two-person households. Two thirds of Swiss households are small households (36% and 33% respectively). At the beginning of the 20^{th} century, households of six or more persons were the majority, and there were relatively few one-person households. From 1960, the number of small, one-person households, began increasing, and by the end of the century, they became the dominant household size category. Concerning the two-person households, they grew steadily during the 20th century. However, their growth slowed down during 1990 and resumed at the beginning of this century. Looking at the evolution of three-person and four-person households since 1920, their number increased steadily until 1980. Both types of households remained relatively stable afterwards. Finally, we observe a slight increase of households of five and six persons until 1970, then a decline since the end of the last century.

- *Type of households*

  Already by the end of the 20^{th}century, the household size had been shrinking, thus the demand for smaller dwellings was rising. This structural change can be explained in many ways. Firstly, the size of households depends on demographic factors, for example, declining fertility and increasing life expectancy. Indeed, as women gradually gave birth to less children, the number of children per household gradually declined, and as the elderly lived longer, the number of older people living mostly alone increased. Secondly, other factors, such as the number of marriages and divorces and the share of unmarried

[13]Among the first ten Swiss municipalities with the highest household size, the seven are located in the canton of Geneva (the municipalities of Genthod (2.98), Vandoeuvres (2.98), Chancy (2.97), Hermance (2.96), Bellevue (2.92), Collogne-Bellerive (2.91), Anières (2.90)). The municipality with the highest household size is observed in the municipalities of Vaux-sur-Morges (3.2) and Chavannes-des-Bois (3.05), which are located in the canton of Vaud.

people influence the household size and typology.
In addition, people tend to have children later than before, when they are older. This leads to a decrease in the share of married couples with children. The latter combined with the fact that people have more often children outside of a marriage results in a decrease of the percentage of married couples with children. Finally, due to relatively high divorce rates (13% in 1960 to 40% in 2015)[14], single-parent families have increased significantly. In 2019, 36% of the households were single-person households (which represents 29% of the permanent resident population) and 27% couples without children. Couples with or without children are the most numerous groups, representing 45% of the households (FSO, 2019*f*) (see Figure2.13).

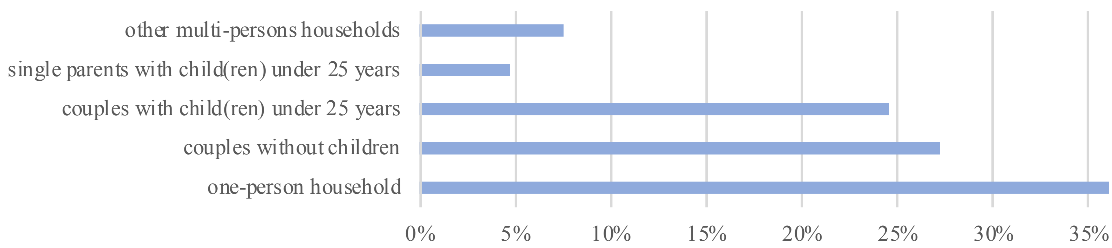


Figure 2.13 – Swiss housing - Household type

- *Occupancy*
  - *Number of occupants per dwelling*
    Over time dwellings became more spacious in terms of dwelling size; they also became more comfortable because of the decrease of the number of occupants per dwelling. In Switzerland, the average number of persons per private household is 2.2 (FSO, 2021*p*). The larger the dwelling, the higher the number of occupants per dwelling.

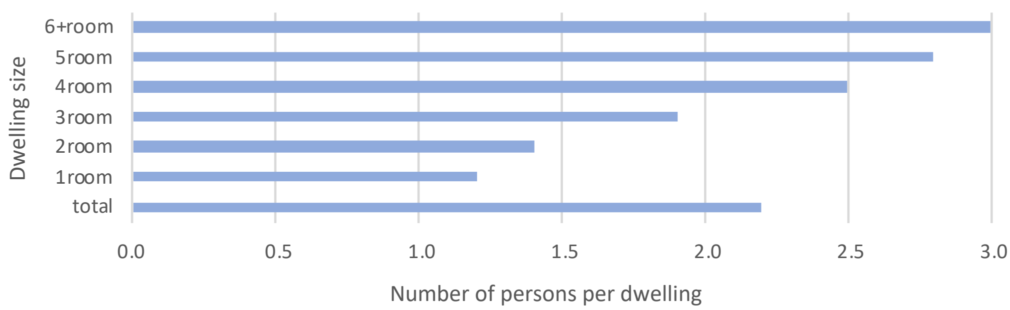


Figure 2.14 – Swiss housing - Number of occupants per dwelling by dwelling size

[14]FSO, 2019

Table 2.1 – Swiss housing - Number of occupants per dwelling by dwelling size and period

Number of occupants per dwelling							
Year	Total	1room	2room	3room	4room	5room	6room +
1970	2.9	1.3	1.9	2.7	3.4	3.7	4.3
1980	2.6	1.2	1.6	2.3	3	3.3	3.8
1990	2.4	1.2	1.4	2	2.7	3	3.3
2000	2.3	1.2	1.4	1.9	2.5	2.8	3.1
2020	2.2	1.2	1.4	1.9	2.5	2.8	3
Source: FSO 2020							

– *Number of occupants per room*

There is a steady decline of the average occupants per room. In 2020, there were 0.59 occupants per room in Switzerland (FSO, 2021*p*). The respective value for Swiss households is even lower, namely 0.53, for foreign households it is 0.71 while for Swiss-foreign households it is 0.82.

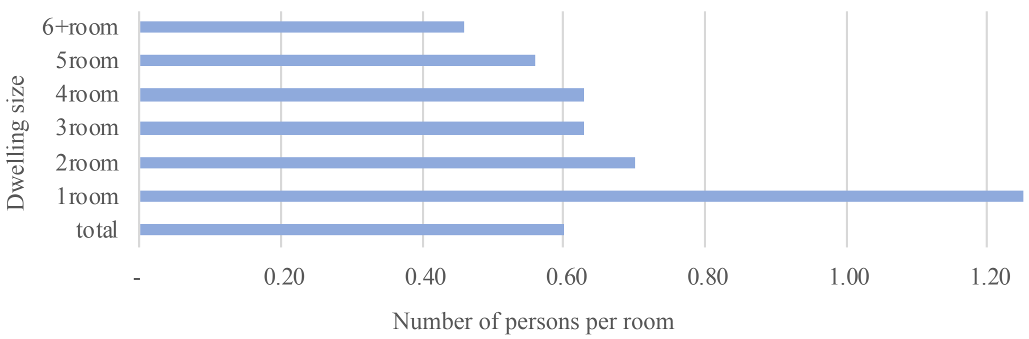


Figure 2.15 – Swiss housing - Number of occupants per room by dwelling size

Furthermore, public utility housing offers dwellings with significantly less living space per person. For example, the average floor area/capita of a 5-room apartment is 47 m^2, the respective value in a public utility housing unit is 32 m^2. For 6-room apartments, the difference is even greater, 60 m^2 versus 38 m^2 (Sotomo and FSO, 2017). This can be explained on the one hand by the fact that public utility apartments are subject to certain occupancy rules on the other hand that public utility housing has older buildings with smaller rooms.

Table 2.2 – Swiss housing - Number of occupants per room by dwelling size and period

Number of occupants per room							
Year	Total	1room	2room	3room	4room	5room	6room +
1970	0.79	1.23	0.93	0.87	0.82	0.72	0.59
1980	0.7	1.12	0.76	0.75	0.75	0.64	0.55
1990	0.63	1.18	0.71	0.67	0.68	0.6	0.49
2000	0.59	1.19	0.66	0.61	0.62	0.56	0.46
2020	0.59	1.22	0.68	0.63	0.62	0.55	0.45
Source: FSO 2020							

– *Rooms per person*
In 2020, more than one out of two households was living in a dwelling with more than two rooms per person (FSO, 2021*p*). In detail, 53% of households live in a very spacious dwelling, 42% live in a relatively spacious dwelling and only 5% live in a crowded dwelling[15].

– *Floor area per capita*
In 2020, the average surface per person was 46 m^2 (FSO, 2020*m*) for all Swiss dwellings[16]. Furthermore, the average living space per inhabitant has increased from 44 m^2 in 2000 to 46 m^2 in 2019 (Wüest Partner, 2021*i*) and it has an increasing trend since.
The average surface per person increases as the dwelling gets bigger (in terms of number of rooms). In 2019, it was 30 m^2/capita for 1-room dwellings; 43 m^2/capita for 2-room to 4-room dwellings, and it increases strongly for larger dwellings reaching even 60 m^2/capita (see Figure 2.16).

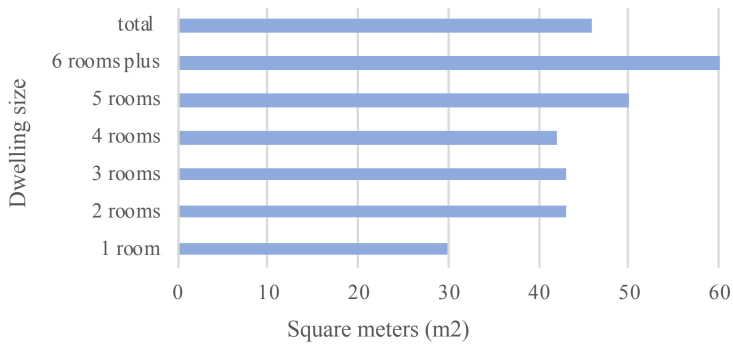


Figure 2.16 – Swiss housing - Floor area per capita by dwelling size

Furthermore, the average floor area per capita increases, the newer the dwelling is (see Tabel A.1 in the appendix). Specifically, for dwellings built before 1919, the average floor area per person is high, around 47 m^2/capita; for dwellings built between 1920 and 2005 it grows from 45 m^2/capita to 50 m^2/capita; for dwellings constructed after 2005, it declines again to 47 m^2/capita (FSO, 2020*n*).
Additionally, floor space per capita depends on the tenure type; tenants occupy on average 20% less surface than people that live in their own house (Gerheuser, 2004). Moreover, it is significantly higher in single-family houses than in multi-unit

[15]According to FSO categorization: very spacious (2 and more rooms per person), spacious (1 or fewer that 2 rooms per person and crowded (less than one room per person).
[16]The average floor area per capita in canton Zurich was 45 m^2 and in canton Vaud 43 m^2, source: FSO, 2020, https://www.bfs.admin.ch/bfs/en/home/statistics/construction-housing/dwellings/housing-conditions/floor-area-person.html

buildings (54 m^2/capita versus 43 m^2/capita) (FSO, 2020*k*). In Switzerland, 25% of the population are foreigners; the proportion of foreigners is even higher in the big urban centres: in Zurich it is 32.5%, in Lausanne 42.5% and in Geneva 48%. The average surface per person drops to 31 m^2 when all members of the household are foreigners.

- *Tenancy and ownership*
  A distinction can be made between owner-occupied households and tenant households. Switzerland is a country of tenants, 57% of the households are renting their dwellings, 3% are living in a housing cooperative and 40% live in their own dwelling (FSO, 2021*c*). This tendency is more intense in the cities, where tenants represent an even higher part. For example, in the city of Zurich almost 75% of the households are tenants and an additional 16% are tenants of a cooperative; this means that the vast majority of households rent their dwelling. The same applies for the city of Lausanne with 87% of the households being tenants and 2% living in a housing cooperative (FSO, 2019*b*).

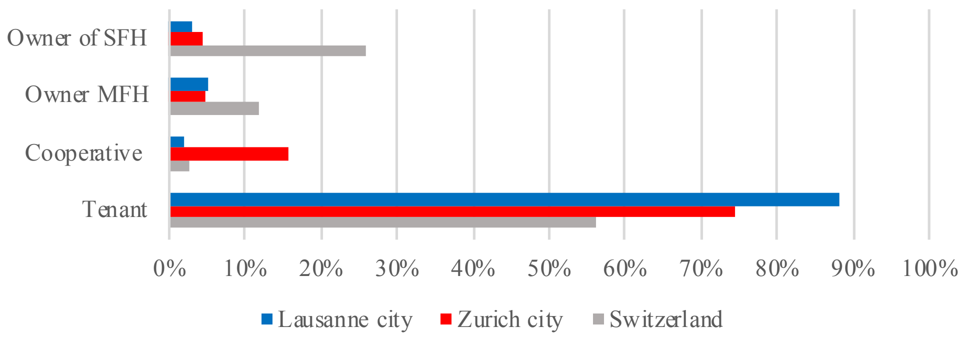


Figure 2.17 – Swiss housing - Tenure type

The typologies that rent the most are single-person households and single-parent households, while households with typologies couples with or without children tend to live more in their own houses (FSO, 2021*d*). Almost three-quarters of one-person households live in rented accommodation. More than half of households comprising four and more people own the home they occupy. In addition, the younger the people are, the higher is the probability that they are renting their flat. Furthermore, owner-occupied dwellings tend to be more spacious than rental dwellings. This applies to the surface area of the dwelling, the number of rooms and the floor area per capita. In 2018, the average per capita living space was 56 m^2 for owner-occupied dwellings. This is 12 m^2 more than for rental dwellings (44 m^2).

2.7 The example of Zurich

Buildable land is scarce as mentioned before; this implies that there is not sufficient land for new construction (ZKB, 2008). The city of Zurich manages to offer shelter to its growing population (Stadt Zürich, 2017*a*) through the extended use of existing buildings, either by demolishing and replacing them with new ones or by using old industrial or non-residential buildings and transforming them into residential buildings. Brownfield sites are becoming rare as well; this means that an important housing potential lies dormant in the demolition and reconstruction of existing buildings. Most parcels are less densely developed than it would be possible under the current building and zoning regulations (Bau- und Zonenordnung, BZO) (Stadt Zürich, 2014). According to Rey, in the case of a demolition, the reconstructed building has the potential to add on average 36% more dwellings, 102% more living space and to accommodate 77% more persons (Rey, 2014). Since 2018, studies estimate that on average every demolished dwelling is replaced by 1.7 new dwellings (70% densification degree), living surface has increased by 112% and the number of residents by 90% (Rey and Brenner, 2016). Demolitions are expected to increase in the near future. This is already evident in Zurich, where a change in the construction pattern is noticed; until 2000, most of the new construction was on undeveloped land. Since then, demolition and reconstruction has become much more important. Only 10% of newly constructed dwellings are built on undeveloped land and almost 2% of all dwellings are renovated every year (Stadt Zürich, 2020). Specifically in Zurich, the yearly average renewal rate for the period 2001-2015 is estimated to 1.5%, and it includes transformations and demolitions (ZKB, 2017). In the following years, it increased even more reaching a renewal rate of 2% yearly in 2016 (among it, 1.6% was dedicated to transformations and 0.6% to demolitions). Although demolitions are still more rare, their number has doubled since 1990. The increasing densification is particularly visible in the buildings of the public sector and housing cooperatives (Rey and Brenner, 2016). Today, reconstructed dwellings account for more than half of the total residential construction activity in Zurich (Rey and Brenner, 2016). Additionally, since land is scarce, finding land through the demolition of an existing building becomes more and more frequent. In the meanwhile, about a third of all land traded in the canton is demolition land (ZKB, 2017).

Regarding the energy source in the housing stock, renewable energies are on the rise in the city of Zurich. Almost half of all flats in Zurich are heated with natural gas, a quarter with heating oil and the last quarter with renewable energy sources. The big change can be seen in the comparison of buildings built around 1990 with those built in the last ten years. Almost 70% of the dwellings built between 1990 and 2000 are heated with gas and another 6% with heating oil. Most of the remaining quarter is connected to the municipal district heating network. The situation is quite different for buildings constructed after 2010, where half of the dwellings are heated with a heat pump. In addition, 37% of the dwellings are heated via a district heating network and 2% with wood. Another 10% of the flats are connected to the municipal gas network while oil heating practically no longer exists in the new buildings (Stadt Zürich, 2020). Zurich has the largest number of cooperative dwellings. Approximately 15% of the dwellings belong to a housing cooperative, whereas the national average is 4% (section 2.5). Cooperatives attribute their dwellings to the households according to a set of occupancy rules that define the minimum and maximum number of occupants based on the dwelling size. In Table 2.3 the occupancy regulations of a selection of housing cooperatives in Zurich are presented[17]. Some housing cooperatives even penalise households in case of under-occupancy. For example, ASIG cooperative imposes a fee if the dwelling is under-occupied; the household is obliged to pay a monthly under-occupancy contribution. The monthly rent increase amounts to 1/9 or 11.11% of the net rent and it increases every year by the same amount (the net rent which increases by 11% every year) up to the statutory maximum of 2/3 or 66.66%. Should there still be an under-occupancy after the eighth year in a row, the tenancy will be terminated after exclusion from the cooperative. The occupancy rate is determined periodically by surveying the tenants.

Table 2.3 – Swiss housing - Occupancy rules of housing cooperatives in Zurich

Minimum occupancy - Minimum number of occupants										
Number of rooms	Kraftwerk1	MBGZ	Linth-Escher *	ASIG **	BAHOGE ***	BGF Frohheim	BGSJ S.	Sunnige Hof	ABZ	SCHL
1-1.5room	1	1	1	1	1	1	1	1	1	1
2-2.5room	1	1	1	1	1	1	1	1	1	1
3-3.5room	2	2	2	1	1 if <72m^2	2	2	2	2	2
4-4.5room	2	3	3	2	2 if <82m^2	3	3		3	3
5-5.5room	3	4	4	3	4	4	4	*****	4	4
6-6.5room	4		5	4					5	5
7-7.5room	4									
8-8.5room	6									
Source: Own work based on the rental regulations of the cooperatives										
* Linth-Escher has a rule of min number of occupants = number of rooms - 1 ** ASIG has a rule of min number of occupants = number of rooms – 2 *** BAHOGE has an occupancy rule partly based on the dwelling surface **** For permanent cohabitation with at least one child ***** For permanent cohabitation with at least two children										

2.8 Residential mobility

This term refers to the action of households to change residence, to relocate either in the same city or between cities, agglomerations and cantons [18]. Residential mobility in Switzerland

[17] We conducted a search of the occupancy regulations of the main housing cooperatives in Zurich. Information was collected for the cooperatives that had this information available online (MBGZ, 2013; Kraftwerk, 2010; Linth-Escher, 2020; ASIG, 2019; BAHOGE, 2017; BGF, 2010; BGSJ, 2016; Sunnige Hof, 2019). The cooperatives were found in the site of city of Zurich: https://www.stadt-zuerich.ch/sd/de/index/erschliessung/izs/wohnen/baugenossenschaften.html#SocialServicesListResults

[18] Yearly mobility rate includes the installation of new households to Switzerland coming from abroad. However, the share is very small; in 2010, the vast majority of relocations (88%) were within the limits of the country (internal

refers mainly to internal residential mobility. Households might want to move out of their current dwelling for a plethora of reasons, e.g., new job, income change, marriage, birth of a child, household size increase, renovation, etc. The share of tenants in the Swiss housing market is very high, and since tenants are more mobile than owners, the mobility rate in Switzerland is very high. As in most European countries, also in Switzerland, the mobility of households has been gradually augmenting and remains in high levels (Pattaroni et al., 2009; Homegate, 2020).

On average 500,000 households relocate every year (Wüest Partner, 2020g; Homegate, 2010). The Swiss housing market has a dynamic character with high relocation rates. On average 12% of the housing stock changes hands every year; this tendency is especially high in the urban centres. For example, in the city of Zurich, it is estimated that one fifth of the dwellings change hands every year. In 2018, the mobility rate was 11.3% in the canton of Geneva, 15,2% in the canton of Zurich and 11% in the canton of Vaud (Homegate, 2010). This translates into an even larger number of persons relocating every year; according to estimates, 800,000 persons change dwelling every year (La Poste, 2020). This accounts for almost 10% of the population. During the COVID-19 pandemic, especially the first months, relocations decreased. Particularly high was the decrease in the cantons of Geneva and Vaud. However, after the end of the restrictions, households continued relocating. In 2019, the relocation rate was estimated to 9.3%; it means one out of eleven households changed dwelling (Homegate, 2020).

The Swiss post office conducted in collaboration with MOVU[19] a thorough survey to study the relocation processes of households[20]. Based on this study, on a yearly basis, 10% of the population and approximately 500,000 households relocate; half of the people that relocate are under 40 years old[21]. People relocate more in the cities and agglomerations of St. Gallen, Winterthur, Fribourg and Zurich.

Among the most important reasons that trigger people to move were: (1) in order to move to a bigger dwelling (31%), this was particularly relevant for younger people, older tenants more than 50 years old moved in order to live in a smaller dwelling; (2) because of a change in the family status (25%); (3) as a result of leaving the parental home (16%) and (4) for other reasons (11%), e.g., coming from abroad, closer to work, renovation.

Based on the results of this survey, more than 55% of the households relocated within the same municipality or city, and 86% stayed in the same canton, only one out of seven households

mobility) (Homegate, 2010).

[19] MOVU Schweiz is one of the largest moving platforms in Switzerland, part of the Baloise Insurance Company , source: https://www.movu.ch/en/

[20] In April - May 2021, the Swiss post office in collaboration with MOVU organized (1) a survey analysing 450,000 relocation cases (based on households that announced the relocation to the Post) and (2) an online survey to 1,300 participants who had recently moved. They also (3) collected and analysed information from MOVU from their archives of relocating households.

[21] Younger people tend to move more; among the moving households, 24% belong to the age group 18-30 years and 25% belong to the age group 31-40 years.

moved to another canton[22] (La Poste, 2020). In 2019, almost three quarters of the relocations were within the same municipality or another municipality in the same agglomeration; (Wüest Partner, 2020*f*).
The frequency of relocating varies and depends on several factors. Nationality seems to play an important role; foreigners tend to relocate more often in comparison to Swiss citizens (in 2017, 15.4% of foreigners moved in contrast to 9.5% of Swiss citizens). This can be explained by the fact that foreigners are not attached to their place of residence and also because the homeownership rate among foreigners is lower[23]; as a result, they change dwelling more often. (Wüest Partner, 2020*g*). Cities that have a big share of foreign population, such as Zurich and Lausanne, have higher mobility rates. Therefore, location also plays an important role; the frequency of moving differs among regions. Urban centres, e.g., Zurich, Bern and the region around lake Geneva, exhibit strong relocation rates, even higher than 13% (Wüest Partner, 2020*f*).
Furthermore, construction activity seems to be positively correlated to relocation frequency. The availability of dwellings influences strongly the mobility rate. In regions where the number of new constructions per inhabitant increases, the mobility rate tends to be higher. It is also observed that mobility decreases where new construction is lower than the average (Wüest Partner, 2020*f*). The increasing supply of new dwellings, with the decline in rents that follows, stimulates relocation. This is confirmed by the fact that more people move within the same municipality. However, increasing supply is not the only reason that generates movement; demand grows because there is a larger choice of dwellings. In general, when housing supply is high, the willingness of the households to move is high. The last years, there was high construction activity and high relocation rates have been observed. (Homegate, 2020).
Zurich is the city with the highest liquidity, where dwellings are very quickly absorbed by the market. The city continues to attract people because of its location, in terms of work and education. This is also why construction is concentrated there (Homegate, 2020). As a result, the mobility rate is very high and half of the relocations take place within the city limits; this translates into an average tenure of 7 years (Homegate, 2020).
Another factor that determines relocation is the job market; job opportunities trigger residential mobility. Moreover, availability of public transportation, good connection to transportation, vicinity to urban green spaces and leisure activities seem to influence the relocation rate. In addition, a determinant factor for relocations is the life stages of a person or household. Events such as finding a job, marriage or separation, having a child or losing a family member and other family reasons trigger residential mobility. Change of life phases are related to the age of a person; the younger the person is, the more probable it is to move more often.

[22]The results of this survey showed that 7% of the households moved into a dwelling in the same building or street, 28% in the same postcode, 20% in the same city but other postcode, 31% in the same canton but other city and 14% in another place in Switzerland.
[23]16% of foreigners have a property, while 44% of Swiss own their home.

People belonging in the age group 23 - 33 years, move the most; one fourth of people in this category move at least once every year (Wüest Partner, 2020*f*). Persons that are older than 30 years move as well. However, the relocation distance is smaller as they tend to move closer to their initial dwelling. In 2019, more than half of the relocations happened within a radius of 5 kilometres. Age of the tenants is inversely proportional to the relocation distance (Wüest Partner, 2020*f*). Understanding the relocation mechanisms allows to better understand the needs and preferences of households and thus design and construct residential dwellings that are closer to what the population (housing demand) prefers or needs.

2.9 Swiss housing policy

Housing policy in Switzerland was set up after the World Wars to deal with the shortage of housing caused by the freeze in construction. At the beginning, it included tenant protection, rent control, and construction incentives designed to promote housing construction as well as to boost the economy. Housing is a complex system that is composed of various actors, thus, housing policy deals with delicate relationships and actors who might even have conflicting interests.

The main objectives of housing policy are to ensure that all people have a decent and affordable dwelling to fight inequality, discrimination and segregation. According to article 41 of the Swiss Constitution, it is stated that among the social objectives of the country, it is the responsibility of the federal and cantonal governments to provide complementary assistance to families struggling to find affordable homes. In 1973, this obligation was more clearly defined in article 108 of the Swiss Constitution. It was then that the promotion of housing construction was identified as a clear governmental target. However, certain cantons and larger cities continued their own, independent promotion of housing construction. The Federal Office for Housing (FOH), in Grenchen in the canton of Solothurn, is responsible for administering the instruments provided by the law.

Housing policy in Switzerland is based on three pillars: (1) promotion of housing supply, (2) promotion of homeownership and (3) tenancy law; it is addressed by all three administrative levels: (1) federal, (2) cantonal and (3) municipal. There are two main axes of intervention: (1) housing aid[24] and (2) tenancy law[25]. The former refers to measures taken to encourage construction and renovation, and the later tries to ensure a balanced relationship between tenants and landlords.

The Swiss Confederation promotes the construction of housing units, homeownership, and the activities of non-profit residential owners; in the center of attention are families, the elderly and persons with disabilities (WOHNEN SCHWEIZ, 2019; Thalmann, 2001). The federal

[24] Aide au logement (fr.), Wohnraumförderung (ger.).

[25] Droit du bail (fr.), Mietrecht (ger.)

government has developed a set of financial instruments in the form of loans, guarantees, subsidies, etc. There are also measures whose impact is not exclusively financial, such as land use regulation, advice, or support for innovative housing projects. Public authorities take measures to promote the construction or renovation of housing, particularly low-cost housing, to enable households who wish to become homeowners, and to reduce the rent of existing rental units (Thalmann, 2003*b*; Cuennet et al., 2002).

In order to achieve this, a set of measures is developed. Firstly, housing policy aims to encourage housing construction by offering incentives to investors to build dwellings and by establishing a stable framework that allows for an appropriate return without undue risk. Additionally, it should protect both lessee and lessor. Furthermore, many people who are renting their home aspire to own it. A lack of equity or a slightly low income can be compensated for by public aid. For families who own their own home, the big issue is taxation, how their home is taken into account in the calculation of their income and wealth.

Housing is responsible for a high percentage of energy consumption, mainly for heating. To make sure that the Swiss energy and climate objectives can be attained, various policies for reduced use of energy and increased use of renewable energy are being implemented. There are several incentives given to enhance the energy performance of existing buildings (renovation) or of new constructions.

- *Construction aid and personalised aid*

  In the field of housing policy, a distinction is made between the financial support for construction and support for individuals. Through the housing aid, the public authorities support the construction and maintenance of affordable housing, but also provide financial support to people of modest means in their search for housing, so that they can find adequate accommodation (OFL, 2018).

  Construction aid ("Aide à la pierre") aims to promote investment in housing. It can take different forms: grants, loans or subsidies paid directly to the beneficiaries, aid delivered to financial institutions in order to lower the mortgage rate of loans, tax exemptions, tax reductions, sale of land in an advantageous price, or land lease. It can be granted either for construction or for renovation. Construction aid decreases the initial cost and such a lowering of the investment can significantly reduce the rent needed to cover the costs, and thus the final net rent.

  On the other hand, personalised aid ("aide à la personne") is addressed to tenants and ensures that rental costs are decreased to a level that the household can bear; this is like a rate that relates the rent to the household income (Cuennet et al., 2002). The financial help by the state is the difference between the rent considered to be bearable and the actual rent. Personalised aid refers to housing subsidies in the form of personal allocations (Lawrence, 1996). In addition, personalised aid can take the form of tax benefits for homeowner households; it can be considered as an individual support instrument (Wüest Partner, 2019*a*).

Furthermore, this allows the authorities to impose conditions on the occupancy rate of the dwellings, i.e. the number of rooms should not exceed the number of occupants. While Construction aid aims at lowering rents, personalised aid increases the purchasing power of the less privileged households. The former supports the supply side, whereas the latter the demand side.

- *Laws LCAO and LOG*

  Between 1975 and 2001, the federal government promoted housing construction and homeownership under the federal "Law encouraging housing construction and accession to home ownership" (LCAO)[26] (LCAP, 1974). In 2003, LCAO was replaced by the federal "Law for the promotion of affordable housing", the housing law LOG[27] (LOG, 2003). The purpose of both these laws has been to increase the number of affordable rental flats for the economically weaker households and to facilitate access to homeownership. A third objective of LOG is the promotion of alternative and innovative types of housing. The difference between LCAO and LOG is found not so much in their objectives but mainly in the policies applied.

  LCAO[28] helped tenants finding an affordable dwelling and homeowners who often lacked the necessary start-up capital to build a home. The state acted as a guarantor for the acquisition of land and the construction of the building by public authorities or social housing developers. It guaranteed for mortgage loans up to 90% of the cost price (Lawrence, 1996).

  LCAO offered a refundable advance to reduce initial rents, but it progressively changed, so that rents rose smoothly until the initial subsidies were fully paid back with interest. This aid was given for entire buildings. However, there was the possibility to obtain additional non-refundable subsidies for individual dwellings occupied by eligible tenants (low-income families or persons with special needs). All types of owners could apply for housing aid, as long as they accepted rent control until the subsidy was paid back. They were restrictions on housing construction costs, and they had to respect conditions of quality, which mainly referred to room size. Finally, the rents should have a normal

[26]Here we tratranslated and refer to as Law encouraging housing construction and accession to home ownership (LCAO) (eng.), Loi fédérale encourageant la construction et l'accession à la propriété de logements (LCAP) (fr.), Wohnbau- und Eigentumsförderungsgesetz (WEG) (ger.).

[27]Loi fédérale encourageant le logement à loyer ou a prix modérés (Loi sur le logement (LOG)) (fr.), Bundesgesetz über die Förderung von preisgünstigem Wohnraum (Wohnraumförderungsgesetz (WFG)) (ger.).

[28]Until the end of the programme in 2001, approximately 110,000 dwellings received financial aid under the LCAO law; among them almost one third were owner-occupied. In about 30% of the cases, the aid was for renovation. Thus, an estimated 87,000 dwellings were built with federal aid. About half of the rental units were owned by cooperatives, foundations or other public bodies, the rest by private individuals or institutional investors. It is estimated that, in this period, one out of 12 dwellings benefited from LCAO (Cuennet et al., 2002).

return on the owner's equity, which was tied to mortgage interest rates (Kemeny et al., 2004). LCAO was not only available to non-profit owners, however, there was additional aid available for this type of owners, such as subsidies to buy land and a few small tax advantages.

Under the housing law (LOG), the federal government promotes the construction or renovation of rental housing for low-income households and encourages homeownership. The main principles of the support measures of LOG are: (1) the construction must be of good quality, (2) resources such as energy and land must be used economically and rationally, (3) dwellings and its immediate environment must be adapted to the needs of families, children, young people and the elderly or disabled, and (4) social diversity should be promoted (LOG, 2003). In contrast to LCAO, LOG focuses more on interest-free or low-interest loans. Additionally, it promotes the activities of organisations involved in the construction of social housing and housing research. On the basis of this law, the Confederation has a fund dedicated to grant loans at favourable interest rates for construction and renovation projects of non-profit owners. It also provides guarantees to finance the construction of affordable dwellings. It mainly supports the CCL, which enables its members to obtain long-term financing on favourable terms, and whose loans are guaranteed by the Confederation (Swiss Confederation, 2020). Direct and indirect support is available, however, direct loans from the Confederation have been suspended since 2003. As a result, support measures are limited to indirect support for housing cooperatives and other public utility developers.

LOG also intends to increase the proportion of homeownership, for which it provides two types of support. Firstly, similar to the system that applies to the construction of rental housing, interest-free or low-interest loans can be granted to financially weaker owners. Another support targets the households who, exclusively based on their income, are able to afford their mortgage payments in the long run, but who do not have the necessary equity capital to acquire real estate.

In the context of LOG, financial instruments benefit directly or indirectly households with a market disadvantage. However, financial aid is linked to specific housing objects, and therefore benefits only those who live in such flats. Switzerland's housing policy does not provide support to tenants affected by high rents in the large unsubsidised market sector.

- *Mountain areas - LALM*

  Since 1951, the Swiss government has been encouraging cantonal actions to improve the housing situation in mountain areas. The federal help LALM[29] is in the form of subsidies for low-income homeowners in mountain areas. These subsidies are promoted by

[29] Aide fédérale dans les régions de montagne (LALM) (fr.), Bundeshilfe in Berggebieten (WS)

regional planning policies and primarily benefit owners who live in their own properties. Since 2008, the Confederation is no longer responsible for housing renewal in mountain areas according to LALM. The responsibility passed to the cantons; the cantons of Valais, Vaud, Graubünden, Uri and Obwalden have developed a successor law that continues to support housing renovations. The focus is primarily on renovation work to residential buildings and flats.

- *Non-profit housing*
  The promotion of public-utility housing construction is a constitutional commitment and a clear objective of housing policy. However, without a concrete national policy for the provision of affordable housing, finding appropriate housing is left to private individuals and depends on local programs and policies of the municipalities and cities (FOH, 2006; Glaser, 2017). In contrast to owners who offer profit rental housing and seek to maximise their profits, non-profit rental housing offers lower rents, calculated to cover the costs and any surplus made should be reinvested to the building stock (for more detail see section 2.5). The non-profit sector usually offers lower rents, better quality of dwellings and greater security of tenure. Non-profit housing in Switzerland includes mainly private initiative (cooperatives) and a few municipalities. Non-profit providers always had to compete with profit providers for scarce land, construction, loans and even subsidies (Kemeny et al., 2004).
  Both the LCAO and the LOG provide(d) special incentives for public utility housing investors (Pattaroni and Marmy, 2016). They are the ones who benefit more from the subsidies for housing (Gerber, 2015; Kemeny et al., 2004), in comparison to other types of owners. With the public sector owning almost 5% of rental housing (see Figure 2.7 in section 2.5) (WOHNEN SCHWEIZ, 2019; Kemeny, 1995), non-profit owners play the role that in other countries is mainly assigned to public housing (Kemeny, 1995). But still, non-profit renting is weakly influencing the Swiss housing market (Kemeny et al., 2004).

- *The role of the cantons*
  In 1973, with the introduction of LCAO, the promotion of housing construction became a permanent task of the Confederation. Several cantons are also active in housing policy and run their own promotion programmes (Hilber and Schöni, 2016). Firstly, they are free to supplement the federal housing subsidy and the regulations of the tenancy law. However, in practice, few of them do so (Cuennet et al., 2002). When they do, they generally adapt their measures to the framework provided by federal policy (Lawrence, 1996). For example, they can apply occupancy rules, like in the case of Geneva[30] (RGL, 1992) or

[30] The canton of Geneva is a notable exception as it has an independent housing policy.

Vaud[31]. Additionally, cantons play an important role by defining the tax policy and the framework of zones and land-use regulations. The role of the federal government and the cantons in regulating the housing market is very important.

- *The role of the municipalities*
  Usually municipalities don't have their own housing policy. The federal and cantonal legal framework[32] limits their freedom (Glaser, 2017). For example, regarding the rent, the communes cannot issue rules that would derogate from the tenancy law. Municipalities have a certain freedom when it comes to promoting the development of low-cost housing. Most municipalities seek to create affordable housing for defined target groups, often low-income households. In order to ensure the allocation of housing to the households in need, they can set some conditions, e.g., determine a minimum number of persons per flat, choose based on criteria such as age, income or wealth (FSO, 2014).
  Furthermore, municipalities could collaborate with other actors in the local housing market. For example, they can impose quotas for low-cost housing in its land-use plans, directly finance the construction of housing, or give subsidies to households to lower the rent. They can also sell or lease land to third parties at preferential prices for the purpose of building low-cost housing. An active land policy, such as the targeted purchase or exchange of land, has enabled, in the past, many municipalities to increase their influence on the local housing market (Cuennet et al., 2002). Furthermore, municipalities can get involved in negotiations and convince landlords, developers and investors to get involved in the creation of low-cost housing (OFL, 2018). In some of the subsidised dwellings occupancy rules apply. Occupancy conditions imply a control by the municipality and the landlord. In practice, no landlords other than non-profit landlords apply such rules. In general, urban municipalities are more active because they deal with more housing problems, e.g., high demand, housing shortage, high rents (WOHNEN SCHWEIZ, 2019).

- *Promotion of construction*
  As mentioned above, the promotion of housing construction has been one of the main targets of the Swiss housing policy (LCAO, LOG). Although the provision of adequate housing is primarily left to the private sector, however, there are legal structures to promote housing construction. In this context, cantonal and municipal planning laws,

[31] For buildings built with state subsidies, there may be some rules, mainly income criteria related to the size of the household, the number of children and the size of the dwelling. For subsidised dwellings that are exclusively available to households entitled of a subsidy, the rules are stricter and households are controlled on a yearly basis to verify whether they still conform with the income and size requirements set by the canton (Canton Vaud, 2015; RCOL, 1991; RCOLLM, 2007; LL, 1975).

[32] The main aspects of the tenancy law, land use regulations, spatial planning are defined at the federal or cantonal level.

construction regulations and zoning plans play an important role (Lawrence, 1996; Cuennet et al., 2002). The state provided all types of owners with a set of financial housing aid to promote construction (with LCAO between 1975 and 2001); it continues to promote housing and especially affordable housing provided by non-profit owners since 2002 with LOG, as described above in section 2.9.
"In Switzerland, public authorities rarely build, they try to encourage other developers, e.g., cooperatives, foundations, real estate companies and individuals who, in exchange, agree to submit to certain conditions concerning the profitability of the buildings, the socio-economic characteristics of the tenants or the level of the rents. The question of profitability is particularly important, since the subsidy is often reserved for public utility developers. These are companies - usually cooperatives or foundations - whose objective is not to seek the highest possible return on investment but to provide housing at attractive conditions. In principle, the excess profit must be reinvested in housing." (our translation) (Cuennet et al., 2002).

- *Rental housing aid*
  In a free rental market, the type of dwelling a household can have is determined by the rent it is willing to pay. This amount depends on the financial capacity (income and wealth) of the household, as well as on its preferences and the importance attached to the quality of the housing. Swiss households spend on average 15.5% of their budget for housing (FSO, 2019*c*). Housing affordability is usually described by the common ratio of rent to income. However, it doesn't allow to understand whether housing affordability problems are the result of high rents or low income (Thalmann, 2003*a*). To support households that don't have enough money to pay their rent, the state can either build exclusive housing for low-income households (public housing), or encourage the construction of social housing (construction aid), or increase their purchasing power (personalised aid).
  In general, public and social housing offers good quality affordable housing. This is possible because of the subsidies and the fact that rents have to cover costs and only a small margin of profit is allowed. However, only a small part of the population can benefit from it. All other tenants are dependent on profit-oriented landlords.

- *Promotion of homeownership*
  Switzerland is a country of tenants. Because of the comparatively low proportion of dwellings used by their owners, a housing policy promoting homeownership is particularly important. In the past fifty years, various policies to promote this segment have been developed (Balchin, 1996) .
  LCAO and LOG both aim(ed) to enable tenants to become owners, targeting the change

of ownership and not the transition to better quality housing. This has also been controversial as it is difficult to justify using public money to enable some households to improve their living conditions (Thalmann et al., 1997). *There is hardly any good economic reason to promote home ownership* (Thalmann, 1999*b*).Another question is also how to identify the households that are entitled to such a help (Thalmann, 1999*a*). Households that aspire having their own home have to deal with very high purchase prices and usually lack equity to buy a property. The role of the state in order to enable access to property, is the same as in the case of rental housing (LCAO and LOG). The Confederation can guarantee the mortgage loan as a secondary guarantee. This guarantee makes it possible to raise the total amount of credit to 90% of the cost price and, thus, allows households to become homeowners with little equity. Equity had to cover 10% of the total price, usually credit institutions generally require a minimum of 20% (Lawrence, 1996; Cuennet et al., 2002). Additionally, households wishing to buy their own home have the option to withdraw a part of their compulsory occupational pension assets (second pillar) to finance the purchase or construction of a home. Ownership is also indirectly encouraged through favourable tax treatment (Kemeny et al., 2004; Thalmann, 2008). Each canton has a different tax system, which makes it difficult to describe the situation in Switzerland in detail.

- *Tenancy law*
  Strict rent controls were first instituted in Switzerland in 1936; the monitoring of rents by the government was introduced in 1962, and liberalised later on. The escalation of rents that followed, led to the need of further legislation, which was introduced in 1972 and 1989. Based on this, rent increases were allowed if they corresponded to rising costs, e.g., higher mortgage-interest rates, renovation costs, etc., and if they were in line with local rent levels (Balchin, 1996).
  Housing supply responds slowly to an increase in demand. Land is scarce and the construction of housing units requires time and resources. This could lead to shortage and a sharp increase of rents, which makes households spend a very high proportion of their budget on housing. There are many measures authorities could take to avoid this, e.g., freeze the rents, set an adequate return on the landlord's equity, etc. Until 1960, the rents were controlled, however, since 1960, Switzerland stopped controlling the rents and gave landlords some flexibility. At the same time, it offered to tenants the right to challenge the level of their rent. The authority acts as an arbitrator between the landlord and the tenant and determines whether the rent charged is abusive or not (Cuennet et al., 2002).
  In Switzerland, concern about rising rents led to the strengthening of rent control in 1990. Article 109 charges the Confederation with the task of legislating to prevent abuses

in the rental sector. Relevant regulations were integrated into the Swiss Civil Code during the same period. The tenancy law is a powerful market regulator that regulates the tenancy conditions in a non-subsidised private rental property. The main targets of the tenancy law are the protection against abusive rents and against the dismissal of residential and commercial leases. Unfair dismissals are annulled on appeal.

The tenancy law assumes that landlords want to push rental prices up and that tenants are in a weaker position. Tenant protection is used to counterbalance market forces when scarcity drives rents up (Cuennet et al., 2002). It ensures an equilibrated relationship between tenants and landlords, in a country where the majority of dwellings are rental. The target of the tenancy law is, on the one hand to enable the property owner to obtain a sufficient return on his investment and on the other hand to protect tenants from paying very high rents or getting evicted. Breaking a contract entails high costs for the tenant (time and cost of moving, double rent for one or more months, psychological cost), but also for the property owner (loss of rent, costs of repairing the property, administrative cost). The vacancy rate is very low and the demand is very high resulting in housing shortage; this justifies the necessity of the tenancy law (Rohrbach, 2014).

In Switzerland, rental contracts are usually for a fixed term. They are renewable unless one of the parties announces to break the contract. At each renewal of the agreement, the landlord can change the rent. It is up to the tenant to contest this change. For renovations, the tenancy law allows the landlord to increase the rent when the renovations improve the comfort or the energy performance of the building, but not when they are just a refurbishment. In the case of a new contract, the tenant has the right to contest the initially agreed rent after the signing of the tenancy agreement if the new rent is higher than the previous rent. The tenancy law protects the tenant from a sharp increase of the rent and prevents the tenant getting pushed out of the house in case of disagreement about the new rent.

But how is it determined whether a rent is abusive or not? The law makes reference to cost-based rents and market rents. In order to control rent increases, the case law has developed two methods: the absolute and relative method (Rohrbach, 2014). The first method determines the permissible increase in absolute terms; the rent is not only examined in relation to the previous rent. In contrast, the second method assesses the rent adjustment only in comparison with the previous rent. In practice, the relative method is used more often because it is easier to apply than the absolute method (Cuennet et al., 2002; Rohrbach, 2014). The tenancy law of 1 July 1990 is mainly based on the principle of charging costs. Rent adjustments are permissible as long as they are based on a change in the costs incurred by the landlord. The variations of the rent should reflect changes in costs (Rohrbach, 2014). The law contains market-related elements such as the usual local rent. Furthermore, the lease is not dissolved in the case of change of ownership. The new owner simply becomes the new lessor. The owner can only terminate the contract by claiming an urgent need for himself or a relative, but nonetheless she/he must respect the legal terms.

2.10 Future tendencies

Population in Switzerland grows steadily and is expected to exceed 10 million by 2045 (FSO, 2016*b*, 2021*r*) (for more detail, see section 2.10). In order to reply to the constantly growing housing demand, there are several paths to follow: (1) use the existing housing stock and accommodate more people in the same dwellings; (2) transform the existing stock, add dwellings by increasing the floors of buildings or subdivide dwellings or transform non-residential to residential dwellings; (3) densify the built area either through the demolition of existing buildings and the construction of new buildings or by building in empty plots; (4) extend the built area by increasing the available land reserves for housing. Buildable land is expensive and extremely difficult to find, especially in the urban centres. Affordable land and available land are located in the periphery of the cities, but since urban sprawl is not desired, a more efficient exploitation of the existing building stock is preferred (Stadt Zürich, 2020). Therefore, a large potential lies in the renewal of existing buildings especially in central areas. The majority of these areas are overbuilt so that the creation of additional floor space must take place through renewal and densification of the existing stock (Rey and Brenner, 2016; Rey, 2014).
This target could be achieved by renovating, transforming or even demolishing and rebuilding[33] the existing building stock. That way not only the building energy performance is upgraded, but also density could increase. Especially in the case of a demolition-reconstruction or transformation, the new building might have higher total surface or a better layout, allowing more people to live there. As a result, the density increases, which means that more people will make use of the same land surface. However, this might result to an increase in property values and rents[34] (Credit Suisse, 2019; ZKB, 2021*b*). Special attention should be given to avoid gentrification and displacement phenomena. In addition, the redevelopment of brownfields and in general of previously developed land is a big opportunity; most of the brownfields are located in urban Mittelland and could accommodate approximately 200,000 people (FOH, 2006).
The pandemic of COVID did not decrease the demand for residential property. Households' desire to own their own home is even stronger, however prices are very high. Due to high

[33] Demolition is an interesting solution in the case when the floor area ratio (FAR) is not used to its maximum; this means there is a potential for densification and better use of the land surface by building more building square meters and accommodate more people per land surface persons/m^2 land.

[34] When it is possible to build more square meters on the same land area, the price of the land increases.

property prices in central locations, residential property buyers are often drawn to more rural areas. Additionally, the constraints to entry to home ownership are leading to a further increase of the demand for rental apartments (Credit Suisse, 2021; FOH, 2021*a*). Currently there is a tendency to look for housing outside of urban centres, but after the end of the pandemic how will this continue?

- *Population*
  Based on the FSO analysis for the evolution of the population, the Swiss population will keep growing and ageing. The population growth over the next few decades will depend almost entirely on the level of migration. There are several scenarios developed by FSO; the reference scenario indicates that the number of permanent residents in Switzerland will reach 9.5 million in 2030 and 10.2 million in 2045; the “low” scenario predicts a population of 9.3 million; the “high” scenario predicts a 11 million population by 2045. The population aged 65 and higher will increase from 1.5 million in 2015 to 2.2 million in 2030 and to 2.7 million in 2045 (FSO, 2016*b*). The ageing population is growing faster than the total population.

- *Household number*
  According to the reference scenario for the future development of households, the number of private households will continue to increase over the next decades. Between 2017 and 2045, the number of households will increase by 23% from 3.7 million to 4.6 million. According to the "low" and "high" scenarios, the number of households is expected to be between 4.2 million and 4.9 million in 2045 (FSO, 2015*b*).

- *Household size*
  In the reference scenario, the number of two-person households will increase between 2017 and 2045. They will rise from 1.2 million to 1.5 million, an increase of 26%. The number of one-person households will increase by 31%, from 1.3 million to 1.7 million. Larger households will grow less rapidly. Three-person households will grow by 12%, four-person households by 9%, five-person households by 10% and households of six or more persons by 14% (for more detail see Table 2.4). The increase in life expectancy will lead to an increase in one- or two-person households. As mentioned before, the relatively low fertility observed will lead to an increase in small households of young adults (FSO, 2021*r*).
  The proportion of one-person households will increase from 35% in 2017 to almost 38% in 2045. The share of two-person households will increase slightly from 33% to 34% between 2017 and 2045 (FSO, 2016*b*). The proportion of households with three or more people will decrease from 32% to 29%. Based on these future projections, a higher housing demand is anticipated especially for smaller dwellings. However, due to

the COVID-19 pandemic and teleworking, more people start working from home, and thus, looking for bigger apartments. This has led already to a growing demand for larger dwellings (3 to 4.5-room); the demand for small dwellings is expected to continue to be strong but less dynamic than before (Wüest Partner, 2021*i*; ZKB, 2021*a*).
In 2021, the demand for larger dwellings and the prices to buy a dwelling increased significantly. The pandemic is probably the real reason for the strong price increases. People are still reflecting more intensively on their own housing situation and are looking for larger or more comfortable flats (ZKB, 2021*b*). Moreover, the size of the households is shrinking and the living surface per capita is expected to increase even further after the COVID-19 pandemic (Wüest Partner, 2021*c*).
In Switzerland, the average number of persons per private household will continue decreasing from 2.20 in 2019 to 2.16 in 2045 (FSO, 2021*n*, 2016*b*, 2018*b*). The average size of private households is expected to decline in almost all cantons; the decrease will be more intense in the rural regions of Switzerland. In urban regions, such as Geneva, it is expected to decline but remain close to the current level.

- *Household type*

  Until 2045, the percentage of couples with children in private households is expected to decrease. This will lead to an increase not only in the number of older couples without children but also in the number of young adults living in couple without children or alone.

Table 2.4 – Swiss housing - Household evolution predictions

Evolution of households in Switzerland 2020-2050 - reference scenario			
	2020	2050	Evolution
Swiss population	8,676,100	10,152,200	↑
Household size			
1 person	35%	38%	↑
2 persons	33%	34%	↑
3 persons	13%	12%	↓
4 persons	13%	11%	↓
5 persons	4%	4%	
6 persons+	2%	2%	
Household type			
one-person	36%	38%	↑
couples with children	25%	22%	↓
couples without children	27%	28%	↑
single-parents	4%	4%	
other multi-person	8%	8%	
Occupants per dwelling	2.22	2.15	↓
Source: FSO, 2021			

According to the reference scenario, the percentage of couples with at least one child will thus fall from 25% to 22% (FSO, 2021*f,g*). This trend implies that the number of couples with no children will increase significantly. Their percentage in private households will increase from 27.5% to almost 29%. The number of single-parent families will increase slightly; their percentage will remain close to 4%. In 2017, nearly 45% of people living in private households will live in a couple household with at least one child under 25. By 2045, 41% will be living in a couple household (FSO, 2021*f*).

- *Construction activity*
  Construction activity is expected to continue growing. However, the net augmentation of dwellings is lower than what the construction activity suggests. This implies that the replacement of existing buildings with new ones, especially in the urban centres, will be intense (Stadt Zürich, 2020; Stadt Zürich, 2015; Rey and Brenner, 2016). In the cities, almost half of the permits are already for demolition and reconstruction projects (Wüest Partner, 2021*c*). This trend is expected to continue because although more dwellings are needed, urban sprawl has to be limited and the densification of the existing building stock seems to be the solution.

- *Dwellings*
  Dwellings are expected to grow even more; both the size of the dwellings and the room size will grow further. In combination with the shrinking size of households, it results in an increase of the average floor space per capita; currently, the average value is 46 m^2/capita and according to négaWatt report, it is expected to reach 54 m^2/capita by 2050 (Moreau et al., 2021).
  Furthermore, the Swiss building stock is not prepared for the climate change. Although a lot of efforts have been done in replacing fossil fuel heating systems, the majority of the buildings are not equipped with a cooling system (Wüest Partner, 2021*b*). In the future, the need for the cooling of the buildings will increase, and thus, we expect an adaptation of the construction of buildings to natural and artificial cooling. Apart from technology solutions, this could be achieved by a proper choice of orientation and geometry of the building, the enhancement of the insulation, creating facades with vegetation, etc. (Wüest Partner, 2021*a*). According to Wüest Partner, a decrease of 14% is expected to the heating costs of buildings till 2060 (Wüest Partner, 2021*j*). However, this decrease of heating costs will be probably compensated by an increase in cooling costs.

3 Case Study

3.1 Introduction

This chapter presents the case study, the dwellings and the tenants of the project partners. The building stock of the partners is described in detail e.g. settlement size, dwelling size, rental prices, construction year, past renovations, etc. The limited available information about the occupants is presented at the end of the chapter. The reason for providing such a thorough analysis of the case study is because it constitutes the initial building stock of the agent-based model, as we will see in the next chapter.

In SHEF project, there are three collaboration partners that are also considered the case study for the research of the environmental footprint of housing. Among them, two are housing cooperatives, ABZ[1] (Allgemeine Baugenossenschaft Zürich), SCHL[2] (Société Coopérative d'Habitation Lausanne) and Mobiliar[3] (Die Mobiliar), which is an insurance company, institutional investor with a diversified portfolio. They are large-scale owners of rental housing in Switzerland, altogether they own more than 11,000 dwellings all over the country. Housing cooperatives are non-profit investors, while Mobiliar is a profit-oriented investor. They all offer rental dwellings in the housing market; these dwellings are heterogeneous rental units and have different physical (living surface, height, floor plan), financial (net rent, gross rent, additional costs) and spatial characteristics (location, orientation, centrality, urban/rural).

Housing cooperatives mainly supply the housing market with free-market[4] dwellings, however, they also have some subsidized dwellings, which can only be rented by households that are entitled to a subsidy; Mobiliar on the other hand offers dwellings exclusively to the

[1] https://www.abz.ch

[2] https://www.schl.ch

[3] https://www.mobiliar.ch

[4] In the context of this thesis, free-market dwellings are considered all rental units that are not subsidized. They are available for rent to all possible tenants with no constraints, in contrast to subsidized dwellings that were partly built with subsidies, they have stricter occupancy rules and only households that are entitled to a subsidy can rent them. Both cooperative and Mobiliar dwellings can be free-market dwellings.

free-market. All three owners are active in the housing sector for approximately 100 years, and they are experts in the rental housing market. They have various departments e.g. financial, administrative, construction, tenancy, which allows them to function autonomously, decide about their tenants and about future investments, evaluate the state of their building stock, undertake construction / renovation projects, etc. All three owners want to continue growing their building stock either by constructing new buildings or buying existing ones; however, it is more common to undertake new construction projects. They are very interested in maintaining their building stock in a good condition; for that reason they evaluate on a regular basis the state of their buildings and decide about ways to intervene, either to maintain the building or enhance the building's condition. More information regarding the strategies, characteristics and main targets of the project partners can be found in the summary of the Owner Workshops, organized in 2019 (see section C.2 in the appendix).

3.2 Methodology

In order to describe in detail the building stock, the tenants and the decision-making processes of the owners, several methods and sources are used:

- *Data gathering*
  The data for the description of the partner's building stock and its tenants was gathered from various sources between 2018 and 2019. The data describes the building stock from that period; because the building stock and the households are evolving, any changes since 2019 are not taken into consideration. Data sources include the partner's yearly reports (ABZ, 2018, 2019, 2020, 2021), (SCHL, 2018*a*, 2019, 2020, 2021) and other publications of the partners (ABZ Forum Magazine, 2020), (Banz et al., 2016), (SCHL, 1995), (Riser et al., 2017), rental and building stock archives, digital datasets provided by the partners, and direct access to the working platform (Mobiliar). The type of gathered data can be found in the appendix, Table A.21.
  We created an extended dataset of the building stock of the partners that consists of 224 settlements and 11,112 rental dwellings (as in 2019). These inventories provide a thorough description of the rental dwellings of the partners and an overview of their characteristics e.g. age, location, size, net rent, gross rent, etc. Furthermore, analysing the data allowed to study the decisions of the owners regarding (1) their building stock, e.g. past renovations, renovation frequency, demolitions (if any), construction rate, construction preferences and (2) the choice of the households that occupy their dwellings.

- *Group meetings with tenants*
  In 2018, SHEF team organised group meetings with a small sample of tenants of the project partners. The purpose of these workshops was to come in contact with the

tenants, understand the way they choose a dwelling, the important attributes they look for in a dwelling, when do households decide to move out and in general create a framework for the housing preferences and needs of households. This helped design the questionnaire for the SHEF survey.

- *SHEF Survey*
  The availability and quality of tenancy data of the three owners was very poor. Owners don't update the information about their tenants after the time of the contracts. Thus, they do not have up-to-date knowledge of the dwelling's occupancy. Additionally, tenancy data from the population census and FSO turned out to be difficult to gather and especially to relate to the specific dwellings. In autumn 2019, SHEF team conducted a tenant survey; the survey was addressed to 1,000 representative households that rent a dwelling from one of the partners. The aim of the survey was to investigate in more detail the housing preferences of tenants. Conducting this survey allowed not only to demystify the housing preferences of households but also to fill in the missing data about the households.The results of this survey have been used to construct the agent-based model, to populate the agents and to initialize the simulations. For more details about SHEF survey, see chapter 4, section 3.5.

- *Owner Workshops*
  In spring 2019, we conducted three owner workshops, one with each partner. The aim of these workshops was to discuss with the head of the departments of finance, management, sustainability, administration, construction and tenancy. The workshops followed a pre-defined set of questions focusing around five pillars: (1) strategy, (2) construction activity, (3) funding and rental income, (4) sustainability and (5) tenancy. The full set of questions and a summary of the owner workshops can be found in the appendix (section C.1 and section C.2).

- *Regular meetings with owners*
  Regular meetings were organised with various employees of the three partners e.g. head of departments, engineers, architects, accountants, managers and admins. At the beginning, the meetings focused on data gathering; next, discussions evolved around owner decision-making processes regarding the building stock and the tenants; at a later stage, the focus lied on the verification of the model choices and the preliminary results of the research. We aimed to include our project partners as much as possible in all stages of our research, despite the imposed difficulties due to the corona virus pandemic.

- *Swiss housing context*
  In the previous chapter, the Swiss housing market and its main characteristics were

studied. The results of the analysis of the building stock and tenants of the partners were always "seen" in the context of the Swiss housing status quo.

- *Software*
  The data was cleaned and analysed with Excel, SQL, SPSS, R and Python.

3.3 Building stock

The housing system we are studying comprises the dwellings and households of the three project partners. ABZ is the largest owner of this housing system and also has the largest settlements in terms of number of dwellings; dwellings have on average 78 m^2 surface and rooms 22.5 m^2. SCHL has smaller settlements; the average dwelling surface is 75 m^2 and the average room surface is 24.8 m^2. Mobiliar has the highest number of settlements, however, they are smaller in terms of number of dwellings; the average dwelling floor area is 88 m^2, which is significantly higher than in the cooperative dwellings.

Table 3.1 – Case study - Key figures of the building stock

Key figures of the building stock - Case study - Initialization					
Variable	**ABZ Free-market**	**SCHL Free-market**	**Mobiliar**	**ABZ Subsidized**	**SCHL Subsidized**
Number of dwellings	4770	1792	4059	161	330
	Average values				
Number of dwellings per settlement	160	100	55	128	61
Number of dwellings per building	12	43	16	13	38
Number of buildings per settlement	17	3	4	11	2
Dwelling floor	2.8	2.3	2.1	2.2	1.8
Number of rooms	3.5	3.1	3.6	4.2	3.0
Dwelling surface (m2)	78	75	88	98	76
Square meters per room	22.5	24.8	24.7	23.8	25.3
Net rent (CHF)	1006	1030	1556	1023	904
Net rent per square meter	12.9	13.4	18.3	10.7	11.8
Additional costs (CHF)	99	132	226	87	168
Additional costs per m2	1.3	1.8	2.6	0.9	2.2
Gross rent (CHF)	1146	1157	1782	1104	1018
Gross rent per m2 (CHF/m2)	14.8	15.1	20.9	11.7	13.1
Reference year	1970	1976	2000	2007	1967
Source: Own analysis based on the partner's data					

The average monthly net rent amounts to 1,006 CHF for ABZ, 1,030 CHF for SCHL and 1,556 CHF for Mobiliar; the respective values for net rent per square meter are 12.9 CHF/m^2, 13.4 CHF/m^2 and 18.3 CHF/m^2.[5] Housing cooperatives have older buildings, with the average construction year for both of them in the 1970s, while Mobiliar has a very young building stock with average construction year in 2000. In the following sections, the most important building

[5] The above mentioned values correspond to the free-market dwellings of the cooperatives, for more detail about the subsidized dwellings see Table 3.1.

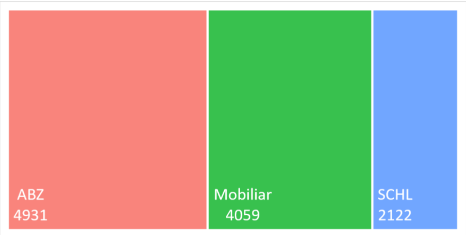
stock characteristics are described in more detail, and we aspire that it works as a reference for analysing the model results in chapter 5. Additional detailed information can be found in the appendix in Table A.8 and Table A.16.

3.3.1 Building stock size

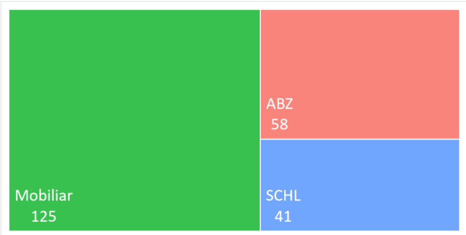
The building stock inventory consists of three levels of analysis: (1) settlements, (2) buildings, (3) dwellings and their characteristics. ABZ is the largest owner, with almost 5,000 dwellings, Mobiliar follows with approximately 4,000 dwellings and SCHL has 2,000 apartments, as shown in Table 3.2. All dwellings are rental housing units in Switzerland in multi-family buildings; there are no single-family houses included. Although ABZ (4,931 dwellings) has more dwellings than Mobiliar (4,059 dwellings), it has half the number of settlements. This means that the settlements of ABZ are larger; ABZ has on average 85 dwellings per settlement, SCHL has 51 dwellings per settlement and Mobiliar 32 dwellings per settlement.

Table 3.2 – Case study - Number of settlements and dwellings by owner

Description of building stock - number of settlements, buildings & dwellings - Case study		
Owner	**Number of settlements**	**Number of dwellings**
ABZ	58	4,931 (4,770 free-market, 161 subsidized)
SCHL	41	2,122 (1,792 free-market, 330 subsidized)
Mobiliar	125	4,059
Total	*224*	*11,112*
Source: Own analysis based on the partner's data		



(a) Number of dwellings



(b) Number of settlements

Figure 3.1 – Case study - Number of settlements and dwellings by owner

3.3.2 Settlement size

The housing cooperatives have bigger settlements and as mentioned above, ABZ has more dwellings per settlement. The size of a settlement can be diverse, as shown in Table 3.3 below. There is a big range of number of dwellings per settlement; it can be for example a small settlement with one small building of five or eight dwellings or it can be a big settlement with many buildings having even up to 371 dwellings. In Figure 3.2 (and Figure B.1 in the appendix), the settlements and their size (number of dwellings) are illustrated in a chronological order according to their construction year. We notice that in all three cases, settlements became larger (more dwellings) over time. The size and shape of the settlement depends on the one hand on the land, the zone, the applicable land use regulations, the coefficient of utilization and on the other hand on other factors such as architectural choices, floor plans and demand characteristics.

Table 3.3 – Case study - Settlement size by owner

Settlement size - Number of dwellings per settlement - Case study			
Owner	**Minimum number of dwellings per settlement**	**Maximum number of dwellings per settlement**	**Average number of dwellings per settlement**
ABZ	8	371	85
SCHL	8	233	51.8
SM	5	225	32.5
Source: Own analysis based on the partner's data and FSO			

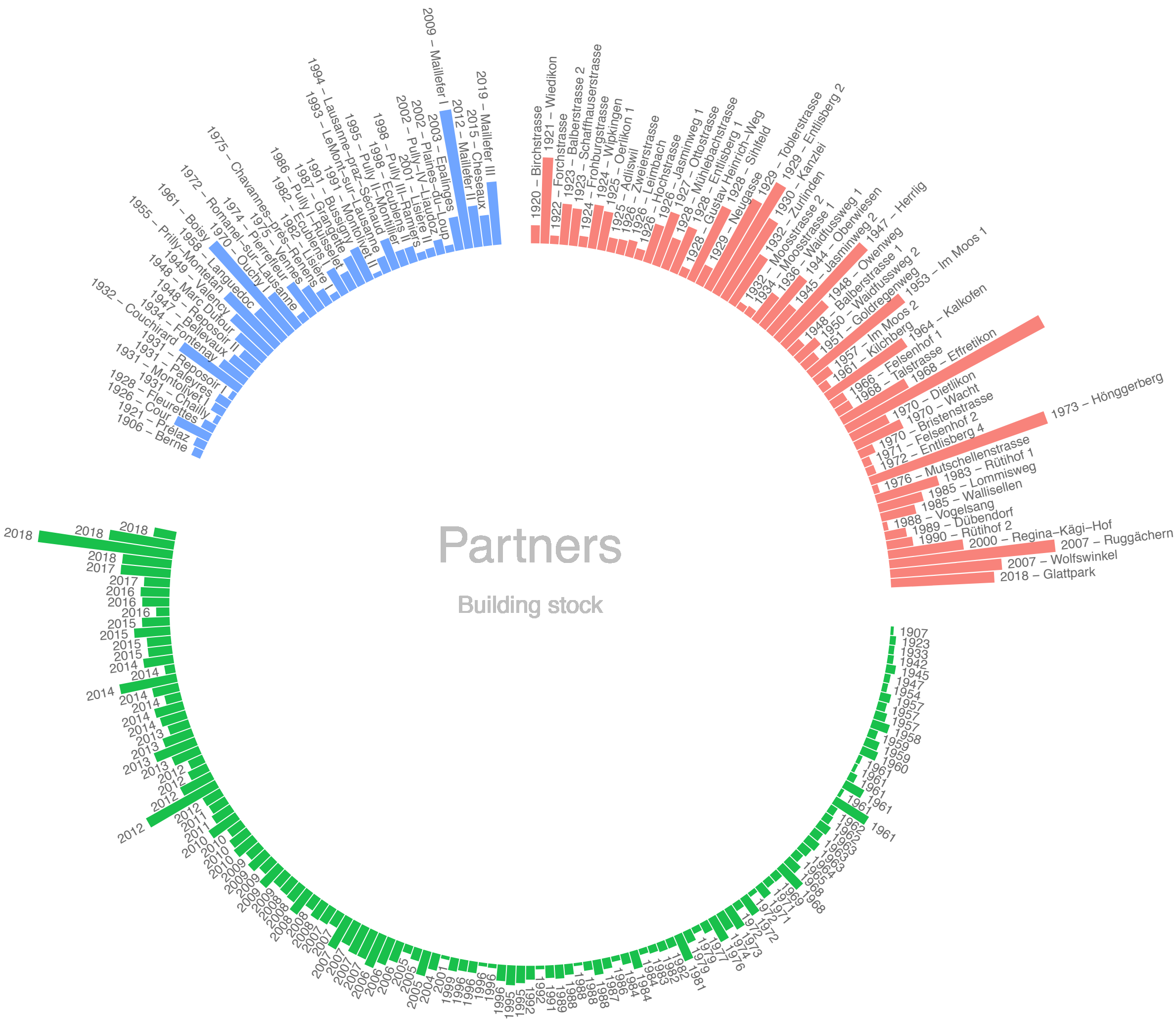


Figure 3.2 – Case study - Settlements

3.3.3 Dwelling size - Number of rooms

All three owners offer a big variety of dwelling sizes, they vary from 1-room to 8-room dwellings. However, we group them into five categories (1-room to 1.5-room, 2-room to 2.5-room, 3-room to 3.5-room, 4-room to 4.5-room, 5-room plus) to facilitate the analysis. All three owners tend to have similar dwelling size distribution; the majority (70%) of the dwellings are medium sized dwellings (3-room to 4.5-room), with 3-room dwellings represent approximately 40% of the stock. The housing cooperatives don't have many (3-4%) small apartments (1-room to 1.5-room), Mobiliar offers slightly more dwellings of this type (5%), as shown in Table 3.4 and Figure 3.3. The results from the case study descriptive statistics about the dwelling size are very similar to the Swiss average; in Switzerland, the majority of rental dwellings are 3-room dwellings; the latter together with the 4-room dwellings represent more than 70% of the total rental units (FSO, 2020g).

Table 3.4 – Case study - Dwelling size by owner and market type

Dwelling size - Number of rooms - Case study										
Dwelling size	**ABZ Free-market**		**ABZ Subsidized**		**SCHL Free-market**		**SCHL Subsidized**		**Mobiliar**	
1-1.5 room	164	4%	2	1%	53	3%			204	5%
2-2.5 room	812	17%	39	24%	391	22%	93	28%	778	19%
3-3.5 room	1976	41%	22	14%	795	44%	133	40%	1522	38%
4-4.5 room	1467	31%	55	34%	487	27%	99	30%	1302	32%
5+ room	351	7%	43	27%	66	4%	5	2%	253	6%
total	*4770*	*100%*	*161*	*100%*	*1792*	*100%*	*330*	*100%*	*4059*	*100%*
Small (1-2.5 room)	976	21%	41	25%	444	25%	93	28%	982	24%
Medium (3-4.5 room)	3443	72%	77	48%	1282	72%	232	70%	2824	70%
Large (5+ room)	351	7%	43	27%	66	4%	5	2%	253	6%
Source: Own analysis based on the partner's data										

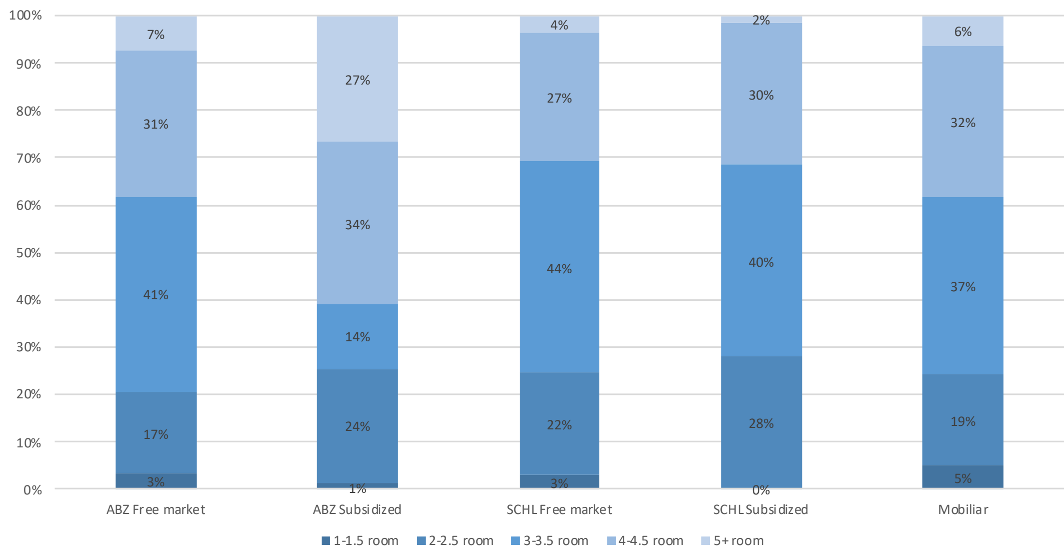


Figure 3.3 – Case study - Dwelling size by owner and market type

3.3.4 Dwelling size - Dwelling surface (m^2)

The living surface of all dwellings is a very important indicator for the environmental footprint of housing. The average floor area of all case study dwellings is 81 m^2, which is lower than the Swiss average (Switzerland: 99 m^2, Canton Zurich: 97 m^2, Canton Vaud: 95 m^2 (FSO, 2020*l*))[6]. However, the Swiss average of 99 m^2 includes all dwellings (rental and owner-occupied), the respective size for rental units is lower (83 m^2). As seen in the following figure (Figure 3.4), the average dwelling surface of all ABZ dwellings is 79 m^2, of SCHL is 76 m^2, of Mobiliar relatively higher 88 m^2. The dwelling size difference between Mobiliar and the housing cooperatives could be explained by the fact that the latter tend to build smaller dwellings (m^2) and exploit the land surface more efficiently.
We notice that the average surface per room is 23 m^2 for ABZ and 25 m^2 for both SCHL and Mobiliar. This is lower than the Swiss average for rental dwellings (27 m^2) and for owner-occupied (30 m^2) (FSO, 2020*l*). We would expect a slightly larger room surface in the case of Mobiliar. However, we have to take into consideration that the way rooms are calculated differs among owners and cities.

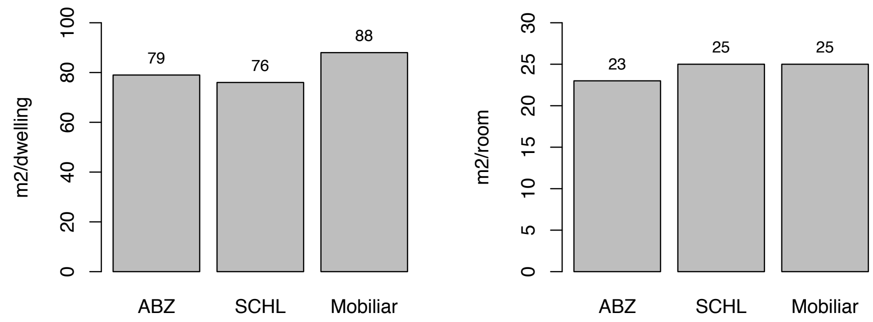


Figure 3.4 – Case study - Dwelling and room surface by owner

In the box-plots that follow (Figure 3.5, Figure 3.6), the size of the dwellings (m^2/dw) and its range is illustrated. The housing cooperatives have similar sized dwellings and Mobiliar has clearly larger dwellings, in terms of square meters. As shown in Table 3.4, Mobiliar doesn't have more large dwellings than ABZ, the percentages are comparable. This means that dwellings belonging to Mobiliar are larger in terms of m^2 and that the size difference is not a result of more large dwellings in terms of number of rooms, they just construct more square meters. Based on the box-plots of Figure 3.5 and Figure 3.6, Mobiliar has more outliers, especially upper outliers. After investigation of the values of the outliers, they are not considered error entries, but instead they are extreme values and represent very large dwellings that do exist in the market. Therefore, we decided not to remove them from the data base; only in the

[6] Based on FSO statistics 2020.

calculation of the basic descriptive statistics, we cleaned the data, to make sure that the extreme values don't affect the average values.
Subsidized dwellings have higher average floor area because medium and large sized dwellings are more numerous, specifically in the case of ABZ, 61% of the subsidized apartments are 4-room plus dwellings. Also, subsidized apartments have almost no outliers. In Figure 3.6, the dwelling's surface according to room size category is illustrated. Dwellings of ABZ exhibit larger surface range, especially in comparison to SCHL and almost all outliers belong to Mobiliar. Furthermore, over time dwelling size increased significantly. The increase is higher in the medium-sized dwellings. Younger dwellings tend to have larger living surface, although the increase is moderate in comparison to the Swiss dwellings size evolution, because of the cooperative effect: cooperative dwellings increased their size over time, but since they follow stricter design rules regarding the size of rooms and dwellings, the increase is not that sharp (appendix, Figure B.6).

3.3.5 Location

The dwellings of ABZ are located in the canton of Zurich and 76% of them in the municipality of Zurich. All SCHL dwellings are located in the canton of Vaud and more specifically in the agglomeration of Lausanne, 67% of the dwellings are situated in the municipality of Lausanne. The dwellings of Mobiliar are scattered all over Switzerland, 20% of the dwellings are located in the canton of Zurich, 15% in the canton of Bern, 14% in the canton of St. Gallen, 10% in the canton of Vaud and 10% in the canton of Fribourg. A detailed list with the location (canton, municipality, postcode) of the dwellings for each owner can be found in the appendix in Table A.8.

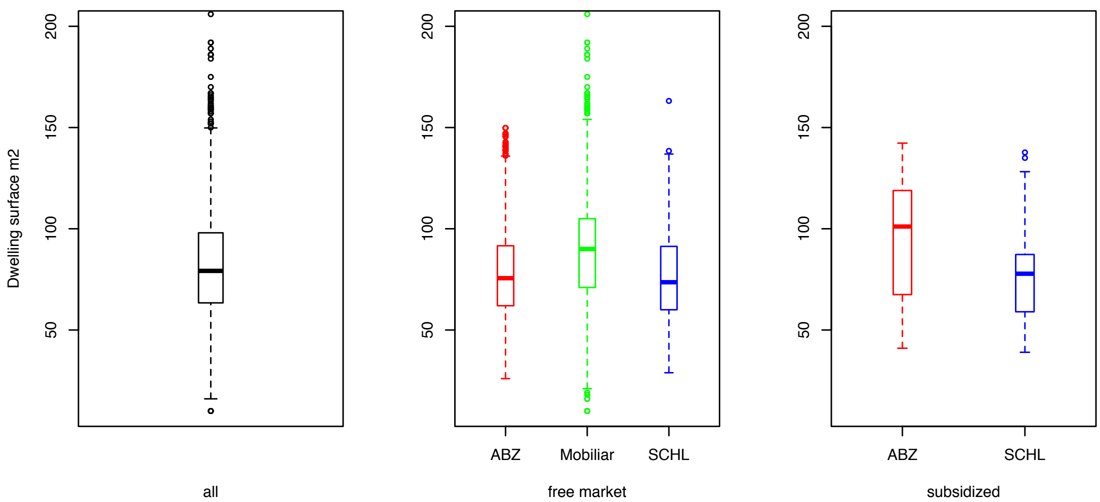


Figure 3.5 – Case study - Dwelling surface by owner and market type

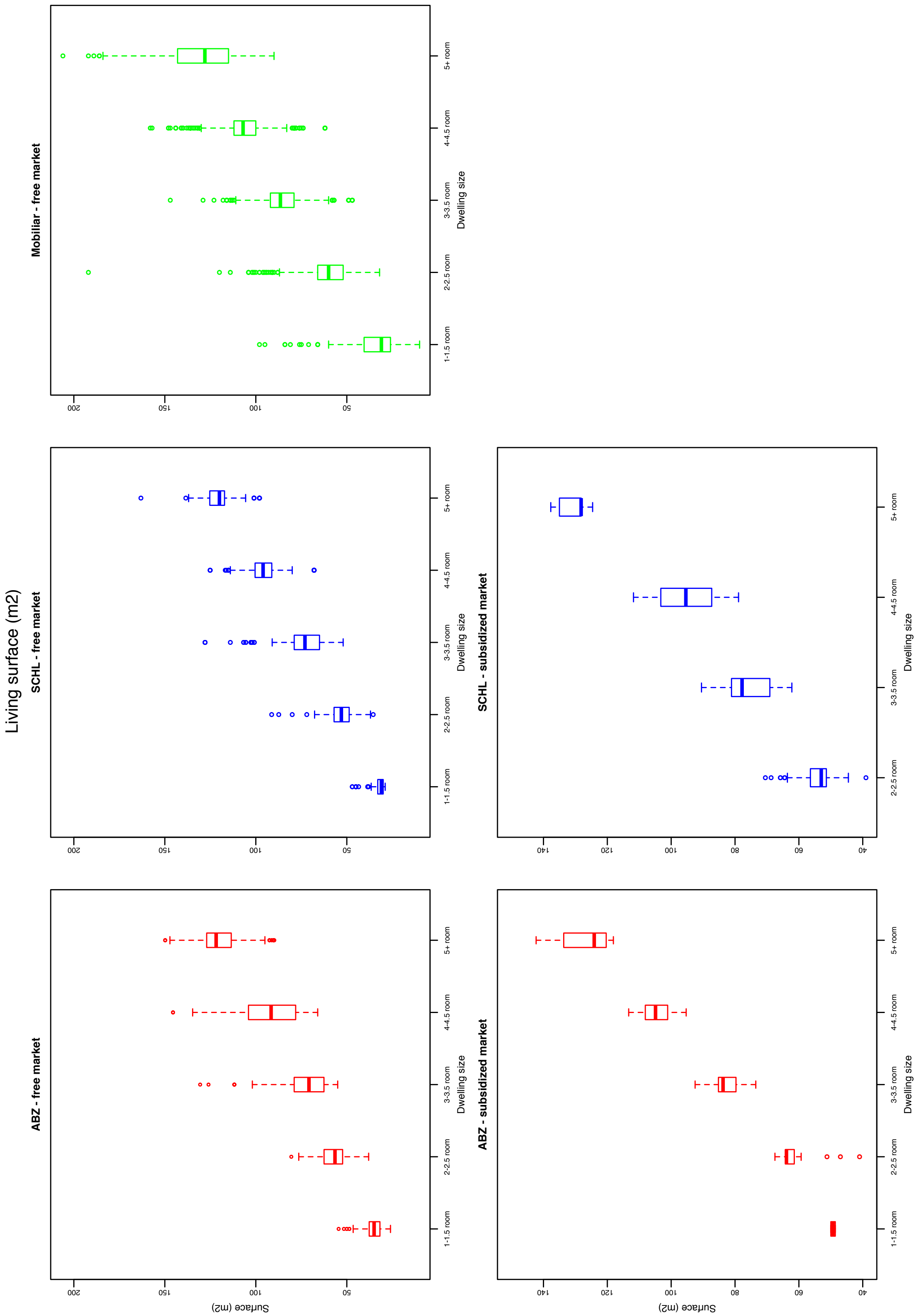


Figure 3.6 – Case study - Dwelling surface by owner, market type and dwelling size

3.3.6 Market type (Subsidized or Free-market)

The housing cooperatives offer dwellings not only to the free-market but also subsidized apartments to households that are entitled to a subsidy. More specifically, ABZ has 161 subsidized dwellings (3.3% of its building stock) scattered in various settlements. Subsidized and free-market rental units can be mixed in one settlement. SCHL has 330 subsidized apartments (15.6% of its building stock) that are all located in exclusively subsidized buildings. SCHL has stopped building subsidized buildings, thus their number will stay stable in the following years. Mobiliar has no subsidized dwellings.

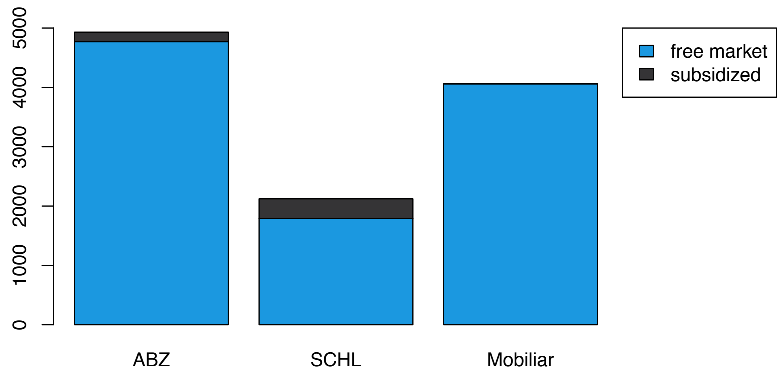


Figure 3.7 – Case study - Number of dwellings by owner and market type

3.3.7 Age

In Table A.10 and in the figures that follow (Figure 3.8, Figure 3.9), the age of the existing building stock of the partners is presented (as in 2019). The average construction year of ABZ dwellings is 1971, of SCHL 1975 and of Mobiliar 2000. The stock of Mobiliar is very young, two thirds of its stock was built after 2000 and almost the total of its stock after 1946; one third of SCHL dwellings were built after 2000 and half of its stock dates back to before 1980; the stock of ABZ is even older with only one fourth of its stock built after 2000. Cooperative dwellings are relatively younger than the Swiss average (see chapter 2 section 2.5). However, the ageing stock of the cooperatives could be a trigger for future renovations, transformations or demolitions. Thus, we would expect these two owners in the future, to invest more into their existing building stock instead of constructing new settlements.

3.3.8 Renovations

All three owners are interested in maintaining their building stock in a good condition, either just in order to keep the buildings in a good state and offer their tenants good quality dwellings (housing cooperatives) or to enhance the dwelling's state in order to make it more attractive to

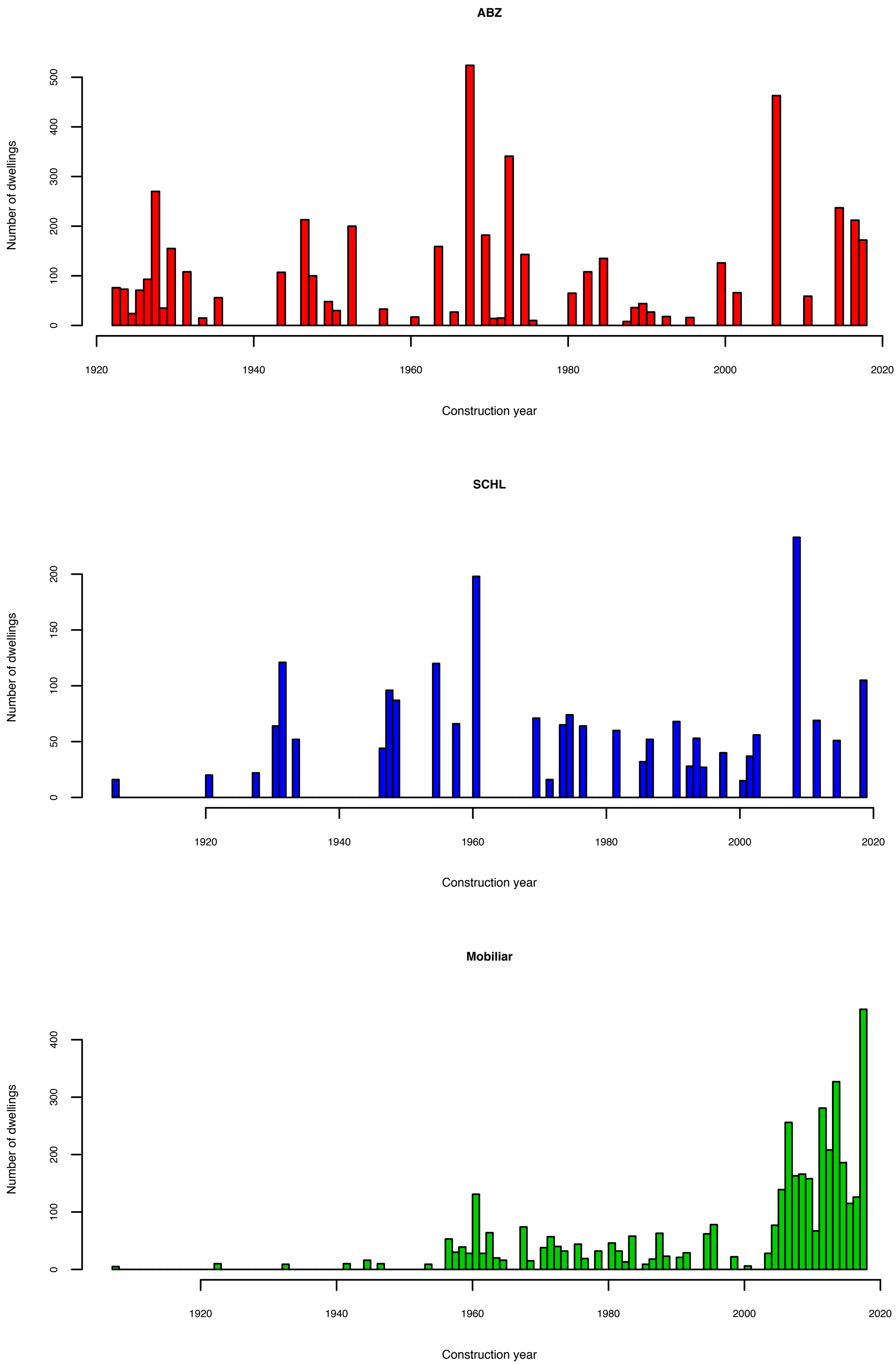


Figure 3.8 – Case study - Age of the building stock by owner

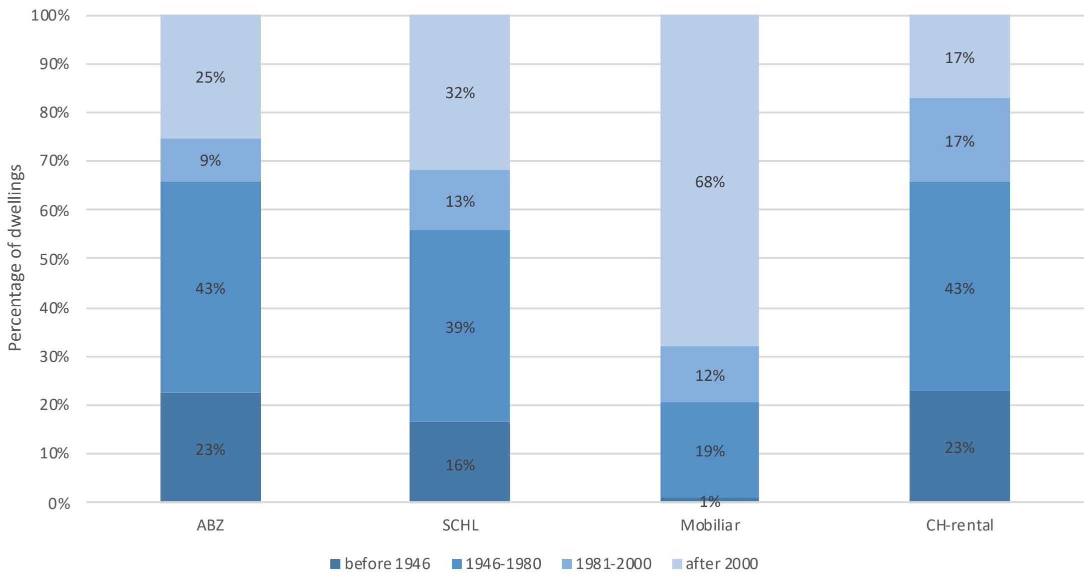


Figure 3.9 – Case study - Age of the building stock by owner and construction period

potential tenants, increase the rent and maximize the rental income (Mobiliar). Therefore, they conduct a yearly evaluation / diagnostics of their building stock and/or a market analysis and decide whether to proceed to a renovation (heavy or light), transformation or demolition. After analysing the data provided by the project partners, the first renovation takes place on

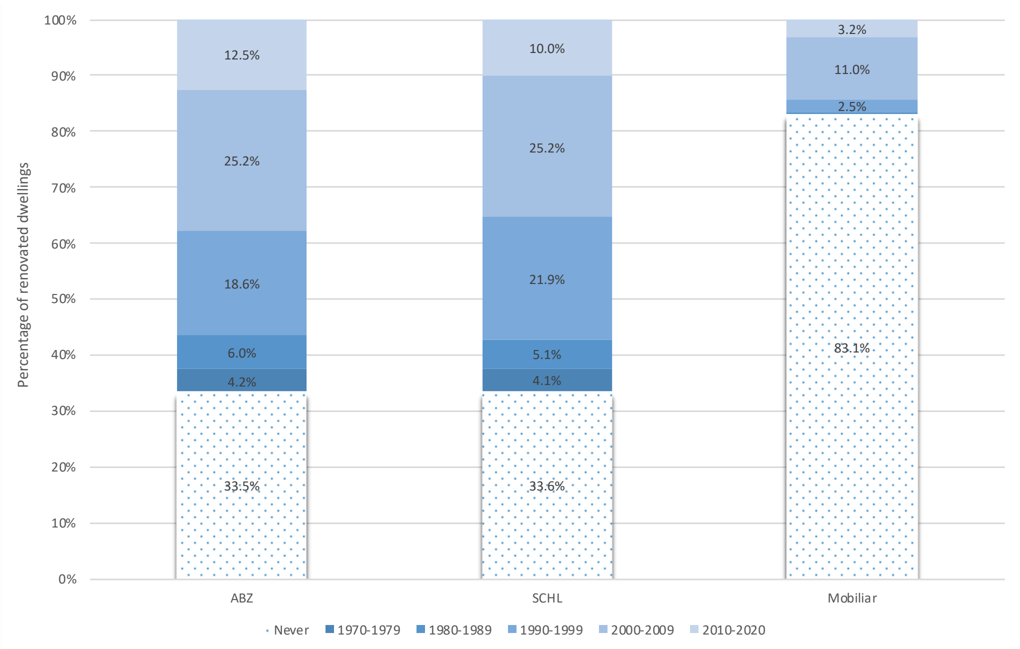


Figure 3.10 – Case study - Renovation history of the building stock by owner

average 40 years after the construction of a new building; there is a renovation on average every 20 years (Riser et al., 2017; Sartori et al., 2016). One third of the cooperative dwellings have never been renovated (see Table A.9 in the appendix). This is explained by the fact that 30-40% of their dwellings were constructed after 1980 (see Table A.9 and Figure B.2 in the appendix) and that the first renovation of a building takes place after 40 years on average. Furthermore, approximately one third of the cooperative dwellings were renovated before 2000 (we refer to the last renovation that took place in a building); it is rational to expect a high rate of renovations of the cooperative dwellings in the next years.

3.3.9 Net rent (CHF)

In Table 3.5 and Figure 3.11, the average monthly net rent of the dwellings according to their size is illustrated. The average net rent for all dwellings of ABZ is 1,006 CHF, SCHL 1,030 CHF, Mobiliar 1,556 CHF, while the Swiss average rent in 2019 was 1,362 CHF[7] (FSO, 2021*j*). The housing cooperatives offer dwellings at a lower price in comparison to Mobiliar; this difference is larger in small and medium sized dwellings (35-45% lower net rent) and smaller the bigger the dwelling is (10-30% lower net rent in 5-room dwellings). In comparison, Mobiliar has more upper outliers of net rent (see Figure 3.11), which can be explained by the fact that there are some dwellings with very high rent, probably situated in expensive central locations, with view, renovated, etc.

Table 3.5 – Case study - Average monthly net rent by owner and market type

Average monthly net rent per owner (CHF) - Case study					
Dwelling size	Free-market			Subsidized	
	ABZ Free-market	**SCHL Free-market**	**Mobiliar**	**ABZ subsidized**	**SCHL subsidized**
1-1.5 room	600	450	799	659	-
2-2.5 room	798	696	1267	751	621
3-3.5 room	905	955	1558	948	894
4-4.5 room	1167	1384	1758	1026	1150
5+ room	1568	1772	2000	1321	1593
All dwellings	*1006*	*1030*	*1556*	*1023*	*904*
Source: Own analysis based on the partner's data					

3.3.10 Net rent per floor area (CHF/m^2)

For a thorough understanding of the rent prices of the housing stock of the partners, we need to study the net rent per floor area. This allows to compare the rental prices of the partner's dwellings among them and in relation to the Swiss average. The average net rent per floor area of ABZ free-market dwellings is 12.9 CHF/m^2, of SCHL free-market dwellings 13.4 CHF/m^2,

[7]The average net rent in Zurich city was 1,584 CHF, in Lausanne 1,266 CHF and in Bern city 1,323 CHF (FSO, 2021*j*).

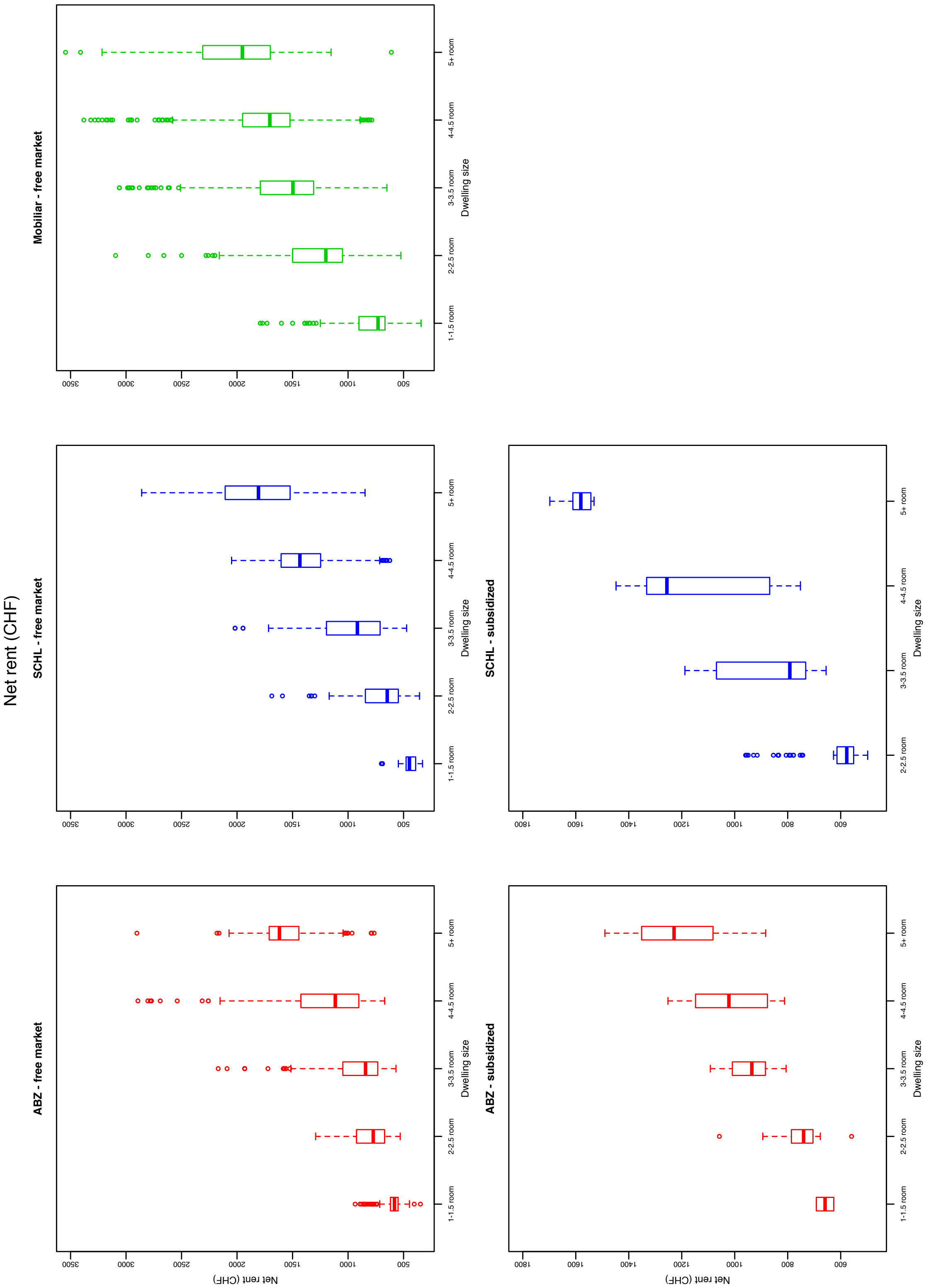


Figure 3.11 – Case study - Net rent by owner, market type and dwelling size

and of Mobiliar 18.3 CHF/m^2 (see Table 3.6). In comparison to the Swiss average[8] (16.4 CHF/m^2), the cooperatives offer significantly lower rent per floor area. The subsidized apartments are offered at a lower price than the free market dwellings; more precisely, ABZ subsidized dwellings have an average rental price of 10.7 CHF/m^2, which is 17% lower than the average rent of ABZ free-market dwellings; SCHL subsidized dwellings have an average net rent of 11.8 CHF/m^2, which is 12% lower than the average rent of SCHL free-market dwellings. In addition, the range of net rent per floor area of the dwellings belonging to Mobiliar is very large, ranging from 7 CHF/m^2 - 35 CHF/m^2, ABZ has a net rent/m^2 range of 7 CHF/m^2 to 23 CHF/m^2, SCHL 7 CHF/m^2 to 22 CHF/m^2 (see Table 3.6, Figure 3.12, Figure 3.13); in subsidized dwellings, the range of net rent per square meter is not that wide, ranging from 7 CHF/m^2 to 17 CHF/m^2 .

Table 3.6 – Case study - Net rent per square meter by owner and market type

Range & average net rent per square meter (CHF/m^2) per owner - Case study				
Owner	**Minimum CHF/m^2**	**Maximum CHF/m^2**	**Average CHF/m^2**	**St. dev.**
Free market				
ABZ	6.8	22.6	12.9	2.003
SCHL	7.2	21.6	13.4	2.965
Mobiliar	6.8	35.1	18.3	4.594
Subsidized				
ABZ	7.4	16.5	10.7	1.758
SCHL	9.1	16.8	11.8	1.614
Source: Own analysis based on the partner's data				

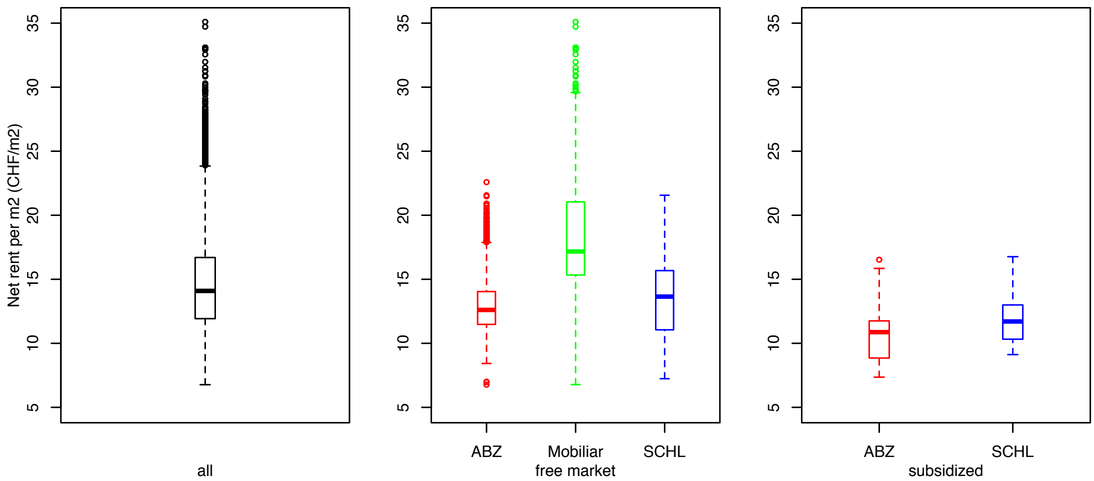


Figure 3.12 – Case study - Net rent per square meter by owner and market type

[8]The average net rent per floor area in the canton of Zurich was 19.2 CHF/m^2 and 17.6 CHF/m^2 in 2019. Source: FSO data, 2019

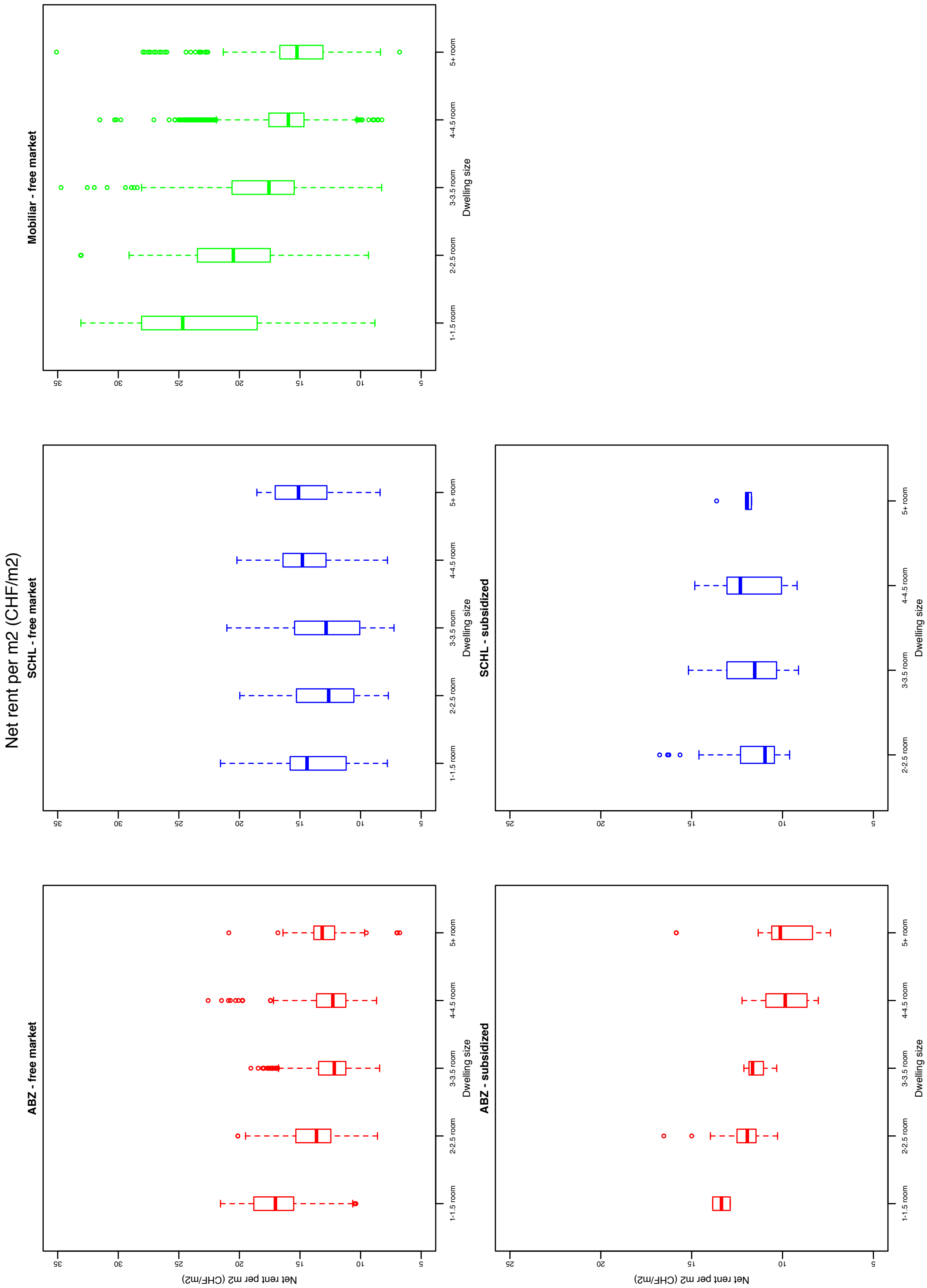


Figure 3.13 – Case study - Net rent per square meter by owner, market type and dwelling size

3.3.11 Evolution of the building stock - Number of dwellings

All three owners have been active in the housing market for more than 100 years and they have been steadily growing their building stock. In the following figure (Figure 3.14) the evolution of the number of dwellings for each owner is illustrated. It represents the building stock (number of dwellings) of each owner over time, based on the year they acquired the dwelling, not the year the dwelling was constructed. The housing cooperatives have a relatively steady growth

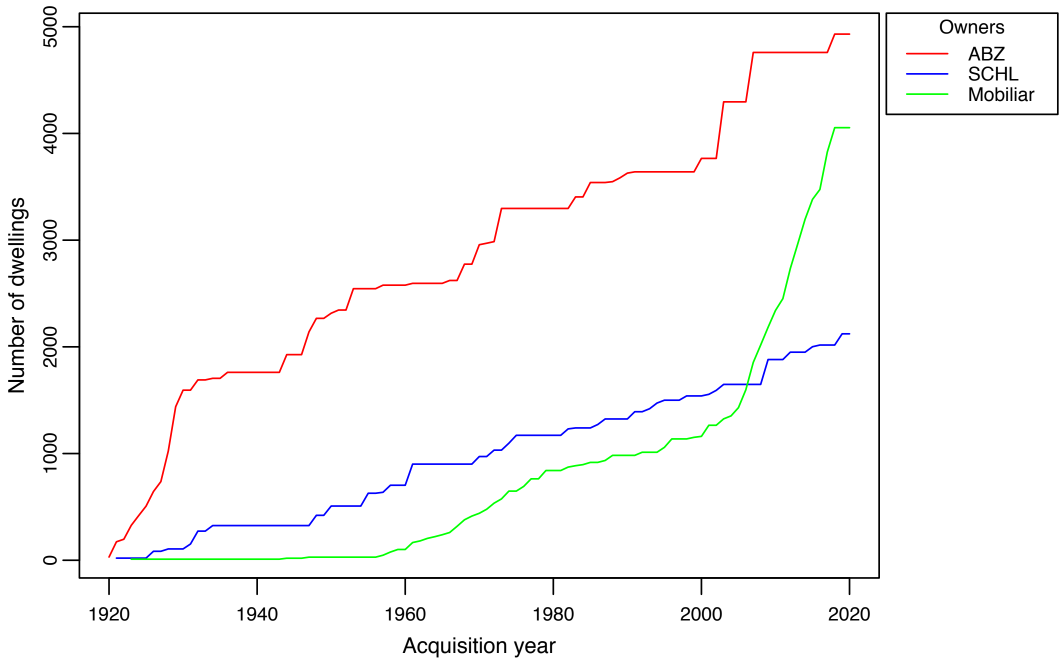


Figure 3.14 – Case study - Evolution of the building stock - Number of dwellings

rate, on average 50 new dwelling additions per year for ABZ and 20 dwelling additions per year for SCHL, which represents a yearly growth rate of approximately 1%. Mobiliar exhibits an intense increase of dwelling number after 2000. In the case of Mobiliar, the vast majority of new dwellings are the result of new construction, which means that Mobiliar, because of a change in strategy started growing its real-estate portfolio over the past 20 years. As a result it has a very young building stock, as we mentioned above in the age section. In the case of the cooperatives, newly added dwellings are a result of new construction, while purchase is very low. For a detailed description of whether the change in the number of dwellings is a result of new construction, demolition, reconstruction, purchase or sale, see Figures (B.4 and B.5) in the appendix.

3.3.12 Evolution of dwelling size - Number of rooms

The following figure 3.15 illustrates the evolution of the size of dwellings in terms of number of rooms per dwelling. In all three cases, there is a strong pattern of increase in the 3 to 3.5-room and 4 to 4.5-room dwellings; this size category follows the same trend over time and increases more than the rest of the dwelling sizes. The small (1-room) dwellings do not follow this pattern, and they increase slightly over time. In the case of SCHL, there is a clear decrease of constructing 2-room dwellings, in favour of larger dwellings. In addition, after 2000 there is a steady increase of the number of large dwellings (>= 5-room).

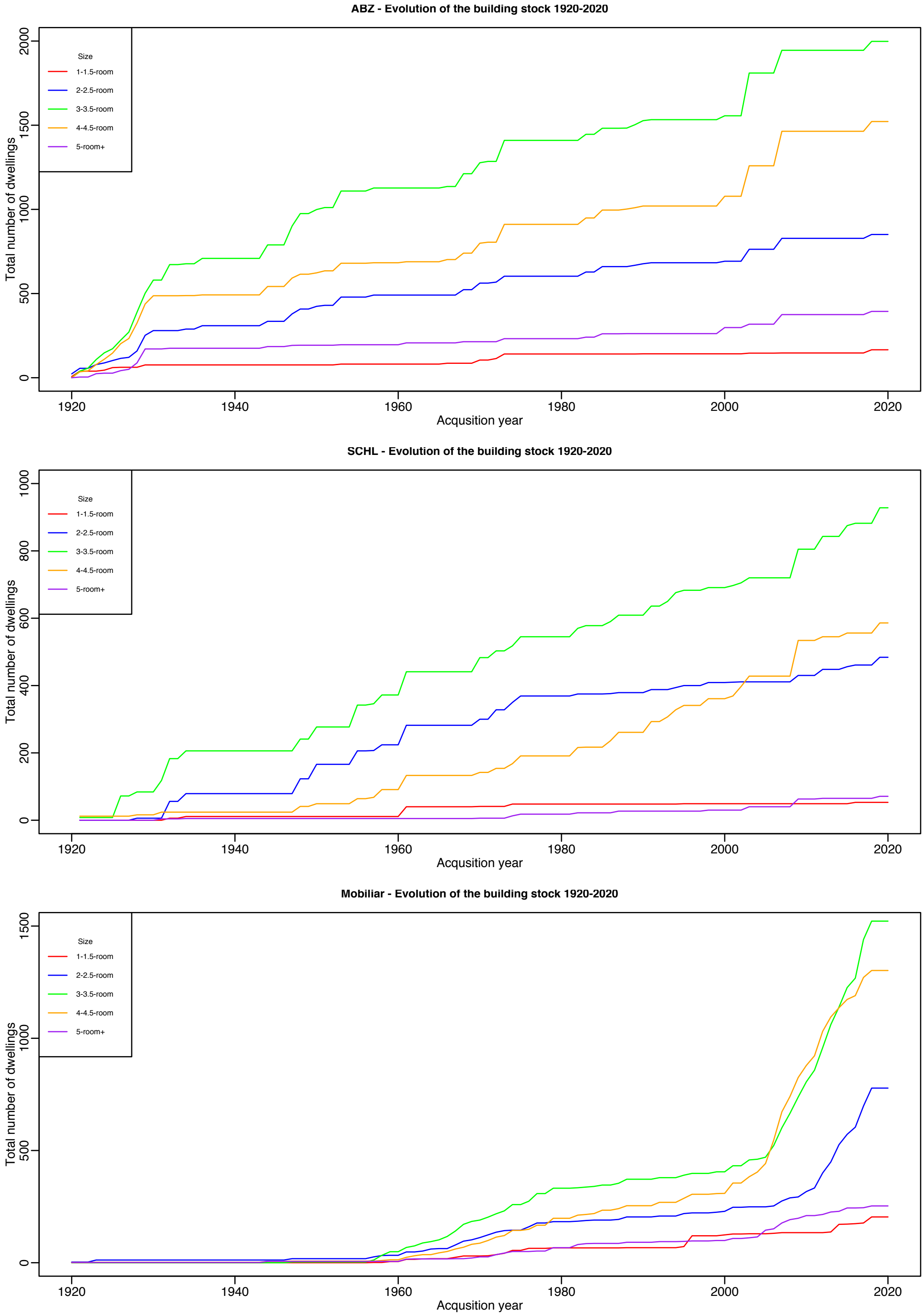
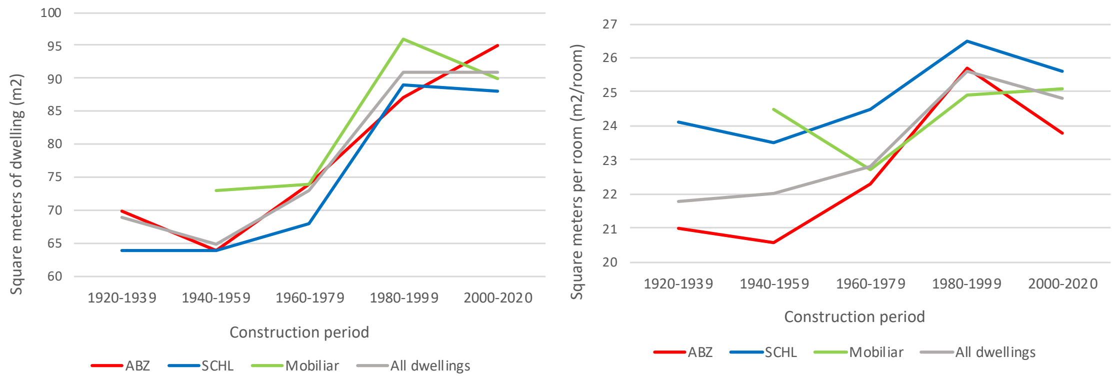


Figure 3.15 – Case study - Evolution of the dwelling size by owner 1920-2020

3.3.13 Evolution of dwelling size - Floor area (m^2)

The average living surface of dwellings grew remarkably over time; younger dwellings have on average larger living surface. This could be explained on the one hand because the average surface per room increased over time, on the other hand because owners increased the proportion of large dwellings over time. As shown in Table 3.7, Figure 3.16 and Table 3.8, both the size of the dwellings and the size of rooms were steadily increasing. More specifically, an augmentation from 21.8 m^2/room for the dwelling build before the war, to 24.8 m^2/ room nowadays. In Figure 3.15, we notice that with time there was a small rise of small dwellings and a clear rise of the percentage of larger dwellings (4-room and 5-room dwellings); in the 1930s only 1% of the building stock was 1-room apartments, while in 2010 it reached 3% of the stock; respectively 4-room dwellings augmented from 23% to 35% of the total stock; 5-room dwellings grew from 5% to 9% and 2-room dwellings remained the same representing 20% of the stock. The same pattern is observed for all owners. Not only is there a clear augmentation of the large dwellings, but there is also a clear rise in the average room surface. This explains the augmentation of the average living surface per dwelling. For more detail, see Table A.12 and Table A.11 in the appendix.



(a) Dwelling surface (m^2/dw)

(b) Room surface (m^2/room)

Figure 3.16 – Case study - Evolution of the dwelling and room surface by owner 1920-2020

Table 3.7 – Case study - Dwelling surface by owner and construction period

Evolution of dwelling size (m²/dw) - Case study				
Construction period	**ABZ**	**SCHL**	**Mobiliar**	**All dwellings**
1920-1939	70	64	99	69
1940-1959	64	64	73	65
1960-1979	74	68	74	73
1980-1999	87	89	96	91
2000-2020	95	88	90	91
total	*79*	*76*	*88*	*81*
Source: Own analysis based on the partner's data				

Table 3.8 – Case study - Room surface by owner and construction period

Evolution of surface per room (m²/room) - Case study				
Construction period	**ABZ**	**SCHL**	**Mobiliar**	**All dwellings**
1920-1939	21.0	24.1	29.6	21.8
1940-1959	20.6	23.5	24.5	22.0
1960-1979	22.3	24.5	22.7	22.8
1980-1999	25.7	26.5	24.9	25.6
2000-2020	23.8	25.6	25.1	24.8
Source: Own analysis based on the partner's data				

3.4 Households

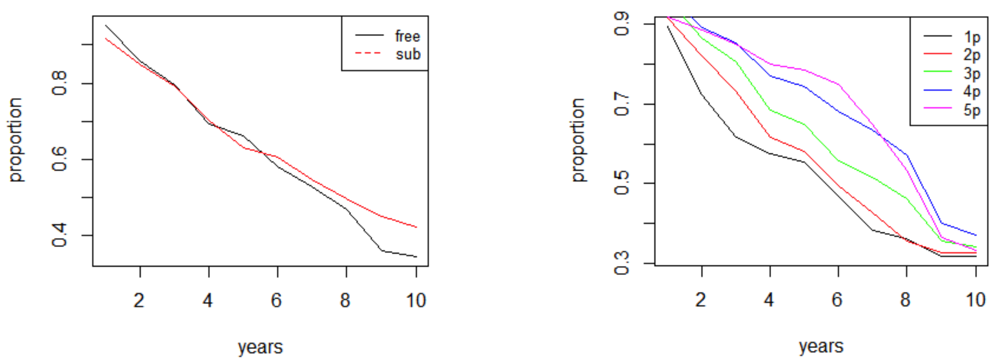
Gathering information about the occupants of the specific dwellings has proven to be very challenging. Although the building owners have a good overview of the occupants of a dwelling at the moment of the contract, updating the occupancy over the years of tenancy is very difficult. Therefore, owners do not have a clear image of who is occupying their dwellings over time; as a result, they could not provide us with such information.
For that reason, we contacted the Building and Housing Statistics (GWS[9]) and asked for the number of persons registered in the buildings of our interest (GAPTO 2013-2017[10]). Every building in Switzerland can be identified based on the EGID number, a unique ID number for each building in the country; this number is related to the number of households and tenants that live there. However, due to data limitations, we could not obtain the number of occupants per building for all the buildings of the project partners. Based on the EGID numbers, we could only identify 449 ABZ buildings and 75 SCHL buildings. For Mobiliar it was not possible to acquire the necessary information. The results of the analysis of this data can be found in Table 3.9 . On average, from 2013 to 2017, the number of people per dwelling varies from 2.1 to 2.3; the number of persons per room varies between 0.62 to 0.72. The average living surface per occupant varies between 34 to 36 square meters per person.
In 2009, SCHL conducted a tenant's satisfaction survey (SCHL, 2009). Based on this survey, as shown in Table A.14 (in appendix), 65% of the households were small size households of one and two persons. Based on the SCHL yearly report 2017 (SCHL, 2018*a*), the tenant rotation rate was 9.9%. Internal exchanges among members of the cooperative accounted for 31.7% of the cases, 15.9% were for family-related reasons and 12% were due to death. In addition, tenants claimed to be sensitive to the problem of energy saving and sustainable development and more than one person out of two would be ready to pay a rent 5 to 10% higher to live in a Minergie-labelled dwelling. However, their behaviour in favour of the environment remains insufficient (only 2% make actual efforts).
There is limited information about the residential mobility of tenants. From the archives of the

[9]Building and housing statistics, (ger.) Gebäude- und Wohnungsstatistik (GWS)
[10]Number of persons in the building, (ger.) Anzahl Personen im Gebäude (GAPTO)

housing cooperatives, the yearly mobility is estimated to 10% (internal[11] and external). This implies that 10% of the cooperative dwellings change hands every year. The available data for the cooperatives allowed to calculate the average years that tenants stay in the same dwelling; for small dwellings (1-room) the average stay is 4.2 years, which is significantly smaller than for the other sizes of dwellings with an average of 7.2 years. In general, the biggest percentage of dwellings (70%) change hands after 8.5 years. Figure 3.17 illustrates the years for which households have not moved to other dwellings; in the y axis the proportion of households who haven't moved yet from the dwelling after x years is represented. For example, after the first two years, approximately 10% of the households have moved out, while 90% hasn't moved yet. The tenancy data for the cooperatives can be found in the following tables and in Tables A.13 and A.14 in the appendix. However, the quality of the data doesn't provide the necessary information to populate the model. Therefore we conducted a survey to the tenants of the three owners.

Table 3.9 – Case study - Occupant statistics

Occupants statistics – Case study					
	2013	**2014**	**2015**	**2016**	**2017**
Number of persons per dwelling					
ABZ	2.27	2.27	2.28	2.29	2.25
SCHL	2.19	2.21	2.10	2.11	2.08
Square meters per person (m^2/person)					
ABZ	34.24	34.18	34.03	33.93	34.56
SCHL	34.23	33.96	35.63	35.44	35.97
Number of persons per room (persons/room)					
ABZ	0.63	0.63	0.63	0.63	0.62
SCHL	0.72	0.72	0.69	0.69	0.68
Number of rooms per person (rooms/person)					
ABZ	1.59	1.59	1.58	1.58	1.60
SCHL	1.40	1.39	1.46	1.45	1.47
Source: Own analysis based on the GWS data					



(a) By market type

(b) By number of rooms

Figure 3.17 – Case study - Years staying in the same dwelling

[11] Internal mobility refers to the residential mobility within the dwellings of the same owner i.e. households moving to another dwelling in the same building or changing buildings but remain to a dwelling belonging to the same owner. External mobility refers to households moving out of the cooperative or new households arriving in the cooperative.

3.5 SHEF Survey

In 2019, SHEF team conducted a tenant survey with a sample of tenants of the three housing owners. The questionnaire was available in two languages (French and German), and it was reviewed by the three laboratories (HERUS and LEURE from EPFL and ESD from ETHZ) as well as from the housing owners (ABZ, SCHL and Mobiliar)[12]. The survey took place from 16 to 28 of November 2019; LINK[13] collected the answers through an online questionnaire addressed to the main tenant of each household. In total 3,000 households were contacted. All households received a personal code to allow access to the on-line questionnaire; households unable to fill in the online survey were contacted by phone. The final number of participants was of 968, which translates into a 32% response rate.
After cleaning the data, there are 945 clean observations, apart from the questions related to the household's income with only 734 valid observations. The descriptive statistics for the SHEF survey dataset are summarized in Table A.18 and Table A.19 in the appendix. The majority of the households (74%) are tenants of a housing cooperative (34% from ABZ and 40% from SCHL), while only 26% are tenants of a private owner; the vast majority (94%) of the tenants live in a free-market dwelling and 6% live in a subsidized apartment. The final sample consists of 54% French speaking and 46% German speaking respondents, among them 53% were female and 47% male. The average age of the respondents that live in an ABZ dwelling is 53 years ($SD = 14$), in SCHL 54 years (SD=16) and in Mobiliar 47 years ($SD = 16$); respondents under the age of 40 represent 40% for the tenants of Mobiliar, while the respective percentage is lower for the cooperatives (25% for ABZ, and 20% for SCHL). Table A.18 and Table A.19 in the appendix describe the results of the survey in detail.

- *Composition and size of households*
  Regarding the composition of the households, couples with at least one child constitute almost 40% of the households, for Mobiliar this typology of households corresponds to a smaller number of observations (29%) but it remains the most frequently observed household type. Additionally, one third of the households are one-person households. More than one fourth of Mobiliar households are couples with no children (28%), whereas the corresponding percentages in the cooperatives are almost half (ABZ 13% and SCHL 16%). Households have on average 1.9 children; the vast majority of households of the private owner (95%) have two or less children; the corresponding value for the cooperative households is 82%. Cooperatives seem to have more and bigger families. The majority of the respondents (50%) are married or in a couple and the

[12] The questionnaire was submitted and approved by the Human Research Ethics Committee of EPFL (HREC) because the participants were tenants and the questionnaire had to be in accordance to the HREC rules. The survey was also tested among members of EPFL.

[13] https://www.link.ch/en/

cooperatives have significantly less single and more divorced or widowed tenants than Mobiliar. Two thirds of the households are small-sized households of one or two persons and in the case of Mobiliar 74% of the dwellings are occupied by small households; this means that only one fourth of the dwellings are occupied by households larger than two persons.

- *Gross income of households*
  The gross income of the households was grouped into five categories; the cooperative households with low income, earning under 60,000 CHF per year constitute 40% of the sample, while the respective percentage is 16% for Mobiliar. Almost 75% of the cooperative households earn less than 88,000 CHF per year, whereas the respective percentage for Mobiliar is 39%. Furthermore, 61% of Mobiliar households earn more than 88,000 CHF per year. In general, almost half of the respondents are working full-time, and in the case of Mobiliar this percentage is almost 66%; the cooperative respondents who work part-time are double than the ones of Mobiliar.

- *Monthly gross rent*
  The average monthly gross rent is 1,360 CHF; for the housing cooperatives it is approximately 1,200 CHF and for Mobiliar 1,800 CHF. The average monthly gross rent per living surface for all owners is 16.5 CHF/m^2 (min = 7.4 CHF/m^2, max = 32 CHF/m^2, SD = 4.1); in the cooperatives it is 15 CHF/m^2 and in Mobiliar 20.8 CHF/m^2. Most of cooperative households pay a monthly gross rent between 1,000 -1,499 CHF (41% ABZ, 35% SCHL, 17% Mobiliar). Most of Mobiliar households pay 1,500 -1,999 CHF (41% Mobiliar, 27% the cooperatives). A gross rent higher than 2,000 CHF per month is very rare for the cooperatives (7% ABZ and 4% SCHL) but is very common for the private owner (38%). One third of the cooperative households pay less than 1,000 CHF but the respective percentage is only 4% in Mobiliar.

- *Residential mobility*
  Regarding the residential mobility, one third of the cooperative tenants never changed dwelling over the past 10 years (18% for Mobiliar); In general, 60% of the cooperative households have changed apartment in the last 10 years and 85% during the last 20 years, whereas 60% of the tenants of Mobiliar changed in the last 5 years and 80% in the last 10 years. On average cooperative households occupy the same dwelling 11 years, while the ones of Mobiliar 7.6 years. In addition, medium-sized dwellings (3-room to 4.5-room) are occupied from the same household for a longer period, especially in the case of the cooperatives; 5-room Mobiliar apartments have the longest occupancy. Small dwellings exhibit high rotation rate. The majority of cooperative households (50%) were previously living in another dwelling of the same cooperative before moving to their current apartment; 8% of ABZ households and 10% of SCHL moved in a dwelling

in the same building.
Households of Mobiliar seem to be waiting less time before finding a dwelling, 68% had to wait less than three months in order to find a dwelling (40% for the cooperative households).

- *Satisfaction with current dwelling*
  The majority of households (80%) claim to be satisfied or strongly satisfied with their current dwelling. Almost half of the cooperative households seem to be very satisfied with the dwelling.

Table 3.10 – Case study - SHEF Survey - Household satisfaction level

Satisfaction level of households			
	ABZ	SCHL	Mobiliar
Very unsatisfied	9%	6.3%	4.5%
Mainly unsatisfied	8.4%	6.1%	8.6%
Neutral	3.7%	6.3%	7.4%
Mainly satisfied	32.6%	38.3%	50.4%
Very satisfied	46.3%	43%	29.1%
Source: SHEF Survey			

- *Occupancy (floor area per capita, rooms per capita)*
  As already mentioned, there was lack of reliable data regarding the occupants of the case study dwellings. The SHEF survey is a valuable source of information about the tenants, their preferences and most importantly about the occupancy of the building stock. On average, there are 2.2 persons per dwelling and this number is higher in the case of ABZ (2.5 persons/dwelling). The average living area per person is approximately 46 square meters (min = 9 m^2, max = 140 m^2, SD=21.3); for ABZ it is 40 m^2/person (min = 9 m^2, max = 111 m^2, SD = 18.3); for SCHL 47 m^2/person (min = 16 m^2, max = 119 m^2, SD = 20.4); and Mobiliar 52 m^2/person (min = 18 m^2, max = 140 m^2, SD = 24.3). In addition, 1.9 rooms correspond to each person; for the cooperatives the number is similar around 1.8 rooms/person (ABZ) and 1.9 rooms/person (SCHL), whereas Mobiliar offers more rooms per person (2.2 rooms/person). The average living surface of the dwelling is 82 square meters; the cooperatives have smaller dwellings (approximately 80 m^2) and Mobiliar more spacious dwellings with an average surface approximately 90 m^2.

- *Occupancy (Under- and over-occupancy)*
  According to the results of the survey, 72% of the dwellings are efficiently occupied, which means that: number of occupants = number of rooms ±a (with a taking the values: a = -1, 0, 1). Over-occupied are 0.4% of the dwellings (number of occupants ≥ number of rooms + 2); under-occupied are 27.6% of the dwellings (number of occupants ≤ number of rooms -2). Table 3.11 shows that cooperative dwellings are more efficiently occupied and more than one third of Mobiliar dwellings are under-occupied.

Table 3.11 – Case study - SHEF Survey - Under/Over occupancy

Number of occupants minus number of rooms	**ABZ**	**SCHL**	**Mobiliar**
-4	0.0%	0.5%	0.4%
-3	1.9%	3.1%	7.4%
-2	16.1%	24.1%	29.1%
-1	51.2%	48.2%	41.4%
0 (number of occupants = number of rooms)	*26.3%*	*20.7%*	*18.0%*
1	4.0%	2.9%	3.7%
2	0.3%	0.5%	0.0%
3 (over-occupancy)	0.2%	0.0%	0.0%

Number of occupants minus number of rooms	**ABZ**	**SCHL**	**Mobiliar**
<1 (under-occupancy)	18%	27.5%	37%
-1, 0, 1 (number of occupants = number of rooms ± 1)	*81.5%*	*72%*	*63%*
>1 (over-occupancy)	0.5%	0.5%	0%

- *Equipment, appliances and other*
  The vast majority of Mobiliar households (98%) have a dishwasher; ABZ (82%) and SCHL (73%). The majority (60%) of Mobiliar households have their own private washing machine, whereas this number is smaller in the cooperatives (14% ABZ and 25% SCHL). Approximately half of the households have a microwave and all dwellings have a fridge, apart from 1.5% of SCHL dwellings. The households of Mobiliar seem to own more cars per household than in the cooperatives. The average temperature in the dwelling during winter is set to 22°C.

3.6 Correlation

Apart from the descriptive statistical analysis of the survey data, we study the correlation among several variables. We analyse the relation between many variables, but our focus is on the dwelling surface as we consider that it is a very important indicator of environmental footprint of housing.

- *Net rent to (1) dwelling surface, (2) age of the building and (3) dwelling floor.*
  Based on the initial building stock data (approximately 11,000 dwellings), a multiple linear regression was conducted to check the correlation of the net rent of the dwelling (CHF) (dependent variable), the dwelling surface, the age of the building and the floor of the dwelling (independent variables). There was no violation of normality and linearity, there was no multicollinearity. All coefficients reported were significant, with at least a 99% confidence, so p-values or significance values are not reported. Still, standard deviation is reported, and it is reasonably small for all coefficients and owners. For all owners some outliers are observed, but most points lie close to the diagonal line,

suggesting approximate normality of the residuals; and the models present reasonable overall fits for all owners. Still, models could be improved by adding additional variables. There is a strong correlation between the net rent and the independent variables. For ABZ dwellings the correlation is strong (R^2 = 0.86), which means that 86% of the variance of the dependent variable is explained by the independent variables. For SCHL the correlation is equally strong (R^2 = 0.84). The R^2 values for ABZ and SCHL are above 0.80, suggesting a good overall fit, whereas for Swiss Mobiliar is substantially lower (R^2 = 0.56). After inspection the diagnostic plots in Figure B.7, in the appendix, we conclude that such small R^2 is due to a high variability of the data, rather than a misspecification of the linear model. We observe how $\hat{\beta}_1 > 0$, $\hat{\beta}_3 > 0$ suggesting that, as one would expect, bigger dwellings and dwellings in higher floors are associated with higher rents. Note that Swiss Mobiliar has the greatest $\hat{\beta}_3$ value, with $\hat{\beta}_3 = 38.4$, meaning that if we keep all other variables fixed and increase the floor of a dwelling by one, the monthly rent would increase, on average, by 38.4 CHF. Regarding the surface cost estimate $\hat{\beta}_1$, the values are similar across owners, ranging from 11 to 14. Moreover, $\hat{\beta}_0 > 0$ for all owners, and it takes similar values for ABZ and SCHL, but it is substantially larger for Swiss Mobiliar. This suggests that keeping the age, floor and surface of the dwelling constant, the baseline rent for dwellings in Swiss Mobiliar is much higher than for dwellings in the cooperatives. Furthermore, $\hat{\beta}_2 < 0$ suggesting that older buildings are associated with lower rents. Swiss Mobiliar has the highest absolute value, with $\hat{\beta}_2 = 5.48$. This can be interpreted as that once the dwelling is built, the rent decreases, on average, by 5.48 CHF every year.

Finally, the assumptions of no collinearity, linearity, normality and homoscedacity are satisfied[14] and we assess the normality of the residuals. The plots on the left side of Figure B.7, in the appendix, show the standardised residual quantiles against a standard

[14] Multiple regression model assumptions check: Recall that linear regression models make several assumptions about the data: (1) No collinearity: Predictors X_j are assumed to be independent (2) Linearity: The relation between the outcome Y and predictors X_j is assumed to be linear (3) Normality: The residual error is assumed to be normally distributed, i.e. $\epsilon \sim N(0, \sigma)$ (4) Homoscedasticity: The variance σ^2 of the residual error ϵ is constant for all y. We first assess the possible multicollinearity between the selected predictors: age, surface and floor. The correlation matrix shows all pairwise correlations are below 0.5, suggesting that the no collinearity assumption (assumption 1) is satisfied. We further compute the Variable Inflation Factors (VIF), which determines the strength of correlations between variables by regressing each independent variable against every other variable. We find all VIF are well below 5, which is the common rule-of-thumb value above which there is suspicion of multicollinearity. Observing the residual vs fitted plots in the following figures it seems that the variance of residuals is smaller for predicted values below 700 CHF/month, but for the rest of the range it appears to be approximately constant. Thus, homoscedasticity (assumption 4) is not fully satisfied, but it might still be a reasonable assumption. The absence of a trend in the residual versus fitted plot of Figure B.7 (left in the appendix) suggests that linearity (assumption 2) is satisfied for the Swiss Mobiliar model. For ABZ and SCHL however, the residuals appear to be a bit higher in the lower and upper range of the predicted values. We further check residual vs surface and residual versus age plots, and we observe high residuals in the low predicted range correspond to the smaller dwellings, and high residuals in the high predicted range correspond to the older dwellings. In conclusion, for ABZ and SCHL the linearity assumption is not fully satisfied, but after trying models with different non-linear terms, the best fit is still obtained with our linear model.

normal distribution. For all owners some outliers are observed, but most points lie close to the diagonal line, suggesting approximate normality of the residuals; and the models present reasonable overall fits for all owners. Still, models could be improved by adding additional variables. However, for the purpose of a rough estimation of the net rent of a purchased dwellings it is accepted. The investment cost is calculated as the purchase price, by sampling from a truncated Gaussian distribution of data from the case study about the average purchase price per square meter (CHF/m^2).

- *Dwelling surface (dependent variable) to (1) household income and (2) household size (independent variables) by market type.*
  Based on the SHEF survey data, a multiple linear regression was conducted to check the correlation of the living surface of the dwelling m^2 (dependent variable), the income of the household and the number of occupants per dwelling (independent variables). There was no violation of normality and linearity, there was no multicollinearity. There is a strong correlation between the number of occupants, the income of the household and the surface of the dwelling. In the free-market dwellings the correlation is strong ($R^2 = 0.445$) which means that 45% of the variance of the dependent variable (surface m^2) is explained by the independent variables (income and number of occupants). In the subsidized dwellings the correlation is even stronger with ($R^2 = 0.640$). The findings are statistically significant as *Sig.* < 0.001 in both free-market and subsidized dwellings. If we check the contribution of each independent variable, "Number of occupants" explains better the dependent variable (Beta: 0.468), and the income of the household less (Beta: 0.350). The picture is similar for the subsidized dwellings, with the variable "Number of occupants" explaining better the dependent variable (Beta: 0.707), and the income of the household less (Beta: 0.334). We notice that in the subsidized dwellings the "Number of occupants" has a very high correlation with the living surface (m^2) as it was expected.

- *Dwelling surface (dependent variable) to (1) household income and (2) household size (independent variables) by owner.*
  To investigate whether the correlation is stronger in some of the owners, we conducted a linear regression for the same variable but grouped by owner. Based on the SHEF survey data, a multiple linear regression was conducted to check the correlation of the living surface of the dwelling (m^2), the income of the household and the number of occupants of the dwellings. There was no violation of normality and linearity, there was no multicollinearity and the findings are statistically significant as *Sig.* < 0.001 for all owners and in both free-market and subsidized dwellings. There is a strong correlation between the number of occupants, the income of the household and the surface of the dwelling.

ABZ: In the free-market dwellings, the correlation is strong (R^2 = 0.504). In the subsidized dwellings the correlation is even stronger with (R^2 = 0.972), and the independent variables explain 97% of the variance of the dependent variable.
SCHL: In the free-market dwellings, the correlation is strong (R^2 = 0.497). In the subsidized dwellings the correlation is even stronger with (R^2 = 0.586).
Mobiliar: In Mobiliar there are only free market dwellings and the correlation is noteworthy (R^2 = 0.274). The correlation here is poorer and a small part of the variance of the dwelling surface can be explained by household's income and size.
We notice that in ABZ the independent variables explain stronger the dependent variable. Especially in the case of subsidized dwellings. In SCHL there is a very strong correlation, in the free market the correlation is the same in both cooperatives. However, in the subsidized dwellings, ABZ shows a huge correlation while SCHL a weaker, but yet very strong. This could be explained by the strict rules and control of Zurich city but also, we don't have many cases, which is a limitation and doesn't allow to come to a conclusion.
If we check the contribution of each independent variable:
ABZ: In the free-market dwellings, both independent variables have a strong correlation with the dependent variable. More specifically, the variable "Number of occupants" explains better the dependent variable (Beta: 0.522), and the "income of the household" less (Beta: 0.342). In the subsidized dwellings the variable "Number of occupants" explains better the dependent variable (Beta: 0.979), and the results for the "income of the household" is not statistically significant.
SCHL: In the free-market dwellings, both independent variables have a strong correlation with the dependent variable. More specifically, the variable "Number of occupants" explains better the dependent variable (Beta: 0.515), and the "income of the household" less (Beta: 0.286). In the subsidized dwellings the variable "Number of occupants" explains better the dependent variable (Beta: 0.768), and the "income of the household" less (Beta: 0.362).
Mobiliar: The independent variables have a noteworthy correlation with the dependent variable. More specifically, the variable "Number of occupants" explains better the dependent variable (Beta: 0.397), and the "income of the household" less (Beta: 0.282). The same picture is in the subsidized dwellings, with the variable Number of occupants explaining better the dependent variable (Beta: 0.707), and the "income of the household" less (Beta: 0.334). We notice that in the subsidized dwellings the the number of occupants are strongly correlated to the dwelling surface.

4 Model Design

4.1 Introduction

Based on the description of the Swiss housing market in chapter 2 and the case study presentation in chapter 3, this chapter lays out the design of the model, and the next chapter presents the results of the model simulation. This chapter outlines (1) the conceptual model that describes the housing market, its main actors, their goals and their principal interactions, (2) the design of the agent-based model that describes the agents, environment, interactions between the agents and the environment and the main functions of the model. For reasons of clarity, the model is divided into three model components: (2a) the Building Stock Model, (2b) the Household Model and (2c) the Matching Model.

4.2 Methodology

To develop the conceptual model of the housing market of the housing system under study and to finally build the agent-based model, we used the following methods:

- *Housing data analysis*
  We conducted a thorough analysis of the available data about the housing market of Switzerland. In addition, we analysed the case study, e.g., building stock attributes, household attributes, owner's and household's decision-making processes. The results of this analysis are used to describe the housing market, to define the agents and their behaviour and to quantify the agent's attributes into the model.

- *Owner Workshops*
  This thesis focuses on the decision-making processes of large-scale property owners of rental dwellings. For that reason, we organised three workshops, one with each owner /

collaboration partner of this project (for more information see chapter 3 and section C in the appendix). During the workshops, we obtained valuable information about the decision-making processes of the owners that contributed to building the model. This information was both qualitative and quantitative, e.g., strategy, funding of construction activity, construction capacity, rental income calculation, occupancy rules, etc.

- *SHEF Survey*
  In 2019, we conducted a tenant survey, with a sample of tenants of the three housing owners. In total 3,000 households were contacted; the final number of participants was 968, which translates in a 32% response rate. This allowed to create a reliable household description and fill the gaps of household data. The survey provided valuable information regarding the housing preferences of households, their satisfaction with their current dwelling, their environmental awareness, the triggers that make them move out of their current dwelling, etc. (for a detailed description of the survey and its results, see chapter 3, section 3.5).

- *Dynamic accounting models*
  The number of dwellings and households don't remain static, they evolve over time. Dynamic accounting-type models of the populations of dwellings and households are developed in order to model the evolution of the building stock and households (see section 4.4).

- *Agent-based model*
  To study the Swiss housing market, an agent-based model (ABM) is developed. The model comprises the agents and the environment of the housing system that we study; agents evolve and make decisions based on their behavioural characteristics. The reason for developing an ABM instead of a traditional model and a description of the characteristics of ABMs can be found in section 4.5.

- *The software environment*
  The ABM is built in Python and Mesa, an agent-based modelling framework in Python. Mesa is a modular framework for building, analysing and visualizing agent-based models and aims to be an alternative software to NetLogo, Repast, Swarm, etc. (Vo et al., 2012). It provides built-in core functionalities such as agent schedulers that allow to quickly create agent-based models, to visualize and analyse their results and using Python's data analysis tools. The model was coded with the help of our student assistant Andreu Arderiu. Data analysis, modelling of the initial stock data and visualisations are performed with SPSS, R and Python libraries Pandas, NumPy and Matplotlib.

4.3 Conceptual Model

Real estate is a tangible asset composed of the land and the building. Housing is characterised by heterogeneity, durability, spatial fixity, high start-up and transaction costs (Favarger and Thalmann, 2007; Fallis, 1985; Gibb, 2003; Tu, 2003; Neto, 2005). In addition, it has long time delays because it takes a long time to finance, find land, design and construct. These attributes are distinctive attributes of the housing commodity and in combination with heterogeneous households, they create a complex housing system (Fallis, 1985; Quigley, 2003). Rental housing market follows the rules of supply and demand (Fallis, 1985; Balchin, 1996; MacLennan, 1982). Supply describes the available dwellings for rent and their specific characteristics, e.g., size, rent, location, centrality, luminosity, etc. Traditionally, supply is set to maximise profits and households to maximise utility, in a way that the different housing actors search for equilibrium outcomes in the market for existing and new dwellings (Gibb, 2003). Developers and investors interested in investing in real estate can be owners of existing dwellings or aspiring future owners that decide about the production of new dwellings. Therefore, they make decisions about the characteristics of the dwellings, e.g., floor plans, number and size of dwellings, location, materials, energy performance, renovations, demolitions, etc.

Real estate investors can origin either from the public or the private sector, and they can be profit or non-profit oriented, e.g., private individuals, housing cooperatives, institutional investors, banks, insurance companies or pension funds. Depending on their origin, they might have different goals. For example, housing cooperatives are non-profit organizations that aim to provide affordable good quality dwellings at a price 20%-40% lower than the rest of the free-market dwellings. Rental income has to cover the costs of investment and maintenance. Additionally, cooperatives try to accommodate households that are diverse in terms of income, social status, nationality, age, and they are attentive to families with children and single parents (Wüest Partner, 2019*e*; Sotomo and FSO, 2017). Most of the rental real estate owners are profit oriented, which translates into perceiving real estate as an investment asset, and are mainly interested in maximizing the returns of their investment. However, investors are not acting always in a rational way, they are limited by bounded rationality and imperfect information (Montezuma, 2006).

Supply depends on a plethora of factors such as land availability and price, land-use regulation, demand, funding opportunities, interest rates, housing prices, construction costs, tax policies, etc. All housing investors have to ensure that they will acquire rental income, which means that they will offer dwellings of a certain quality in order to be attractive to households, to be competitive in the housing market and to minimize vacancies. For that reason, they make investment decisions to grow and/or to maintain their existing building stock (MacLennan, 1982; Malpezzi, 2003; Gibb, 2003). Dwellings should be offered at a price that households would be willing to pay.

Investors can choose either to invest in a new construction or in an existing building. If they decide to construct a new building from scratch, firstly they have to find available land either to buy or to lease; this land has to be buildable, allowing the development of residential buildings according to the actual land zoning that defines which parts are dedicated to housing, agriculture, forestry, etc. The land has to be affordable, which means that the price should allow the future rental income to cover the costs (land, construction, transaction and maintenance costs) and reach the desired returns. In order to accomplish that, they have to develop dwellings that respond to the needs of the demand in terms of location, size, comfort, price, etc.

In addition, real estate owners might choose to invest in existing buildings. If they are already owners of dwellings, they make decisions about the maintenance and management of the stock; they might decide to invest in renovations in order to maintain their dwellings in a good condition or to attract potential renters, and thus, make it more profitable by increasing rental prices and reducing vacancies (Schüssler et al., 2005; Malpezzi, 2003; Fallis, 1985; Tu, 2003). They make decisions about when to renovate, what kind of renovation to undertake (heavy or light renovation, insulation, facade, heating system, floors, kitchen and bathroom), what materials to use, etc. By renovating a building, its life span is prolonged and the quality of the dwellings is improved, which makes it more attractive to potential tenants. In parallel, it allows owners to increase the rent, and thus, to achieve higher rental income.

Owners might also decide to transform an existing building, which means to undertake a heavy renovation, where only the main structure, the skeleton of the building is kept intact and all complementary elements are demolished. Transformation allows choosing materials, changing the floor plans, densifying by creating more dwellings or dwellings that are more suitable to the modern needs of households. The motivation for owners to renovate or transform a building concentrates on improving the dwelling standards, repairing problems, limiting vacancies, increasing rental income, decreasing maintenance cost and energy consumption, etc. In parallel, owners might be hesitant investing in a renovation because of not having access to adequate funding or funding terms are not favourable. Moreover, owners might not proceed to a renovation because they might be afraid to not being able to increase enough the rents after the renovation works or the tenants react negatively, etc. (Schüssler et al., 2005). Investing to existing buildings is expected to increase in the next years in Switzerland because of land scarcity and the ageing stock (Nägeli et al., 2020; Sartori et al., 2008; Stadt Zürich, 2015; Stadt Zürich, 2020; Rey and Brenner, 2016).

Real estate owners and investors might also decide to demolish an existing building and, in its place, reconstruct a new one. Usually they decide to demolish in order to replace an old building that has already been renovated several times and/or has low energy performance, when a potential renovation could be very expensive or even fail to guarantee a higher energy performance. They might even renovate a younger building, to exploit the maximum floor area ratio and build the maximum permissible building surface (Riser et al., 2017), which would allow them to increase the rental surface and thus the rental income.

In general, owners decide whether to build, renovate, transform or demolish a building by evaluating the building's condition, estimating the costs of a possible intervention and studying the local housing market. This evaluation is not a simple procedure, it depends on many factors such as the cost of construction and demolition. Sometimes a demolition and reconstruction of a building is less expensive than a renovation. Additionally, the evaluation depends on the age of the building, its potential life span, the targeted energy performance and possible energy performance improvements. Furthermore, the evaluation depends on the zone and land use regulation, e.g., maximum floor plan area, maximum plot area ratio, etc. Finally, real estate owners and investors might decide to buy or sell an existing building. They usually conduct a research of the local housing market to estimate the current / potential rental income. A particular piece of property will be valued based on its location, improvements, zone, competition, local employment and the availability (or lack of availability) of other, similar properties (Kahr and Thomsett, 2005). Developers and owners analyse data from both perspectives; demand and supply. On the demand side, the population, number of households, demographic characteristics, income, purchase power, employment and migration are taken into consideration. On the supply side, existing land and housing units, vacancy rate, types of tenants and buyers, projects under construction and market rents based on location and quality are taken into consideration (Pagourtzi et al., 2003).

Owners of rental dwellings, apart from deciding about the management of their stock, e.g., renovation, transformation, demolition, they often choose directly or indirectly (through real-estate agencies) their tenants. The result is the allocation of their dwellings to households. Some owners allocate their dwellings based on occupancy rules that define the minimum and maximum number of occupants depending on the number of rooms of a dwelling (room stress). They might also have financial criteria to ensure that the future tenants have adequate income to pay the rent. Additionally, owners select their tenants based on a set of priority criteria. According to these criteria they might promote a certain type of household, e.g., families with minor children, single-parents, etc.

Housing demand is the result of housing decisions made by households in search of a dwelling. Households are heterogeneous entities characterized by several elements, e.g., age, size, nationality, gender, income, lifestyles, etc. Based on their characteristics and preferences they choose a dwelling to live in. The essence of dwelling choice is the trade-off between size, quality, locational considerations and price (Quigley, 2003; Fallis, 1985). However, households are not static, they evolve over time, and thus, their number, characteristics and preferences alter. There are important changes, e.g., household growing (marriage, birth), household shrinking (divorce, death, moving out of children), income change (salary change, marriage, divorce) that influence the housing decisions of households. In different life phases of a household, the

housing preferences and needs may change.
Furthermore, the evolution of the households and their constantly changing needs and preferences trigger households to move out of their current dwelling and find another one to move in (Marsh and Gibb, 2011). A trigger to move could be for example a change in income, household size or finding a new job in another city. Triggers could be imperative events, when it is critical for a household to find a new dwelling or just optional.
Usually, tenants have preferences regarding the dwelling they apply for, based on a plethora of parameters, e.g., rent in relation to their income, size of the household in relation to the dwelling size, balcony, location, centrality, vicinity to work, luminosity, room size, etc. (Wüest Partner, 2020*i*). Households are triggered to move because of these events, but do move when the benefits of moving outweigh its costs (Fallis, 1985; Mulder and Hooimeijer, 1999; Pagani et al., 2021). Although households might be willing to move, there are a lot of constraints that might not allow them to move into their desired dwelling, e.g., high rents, high demand, low vacancy rate, etc. Particularly in Switzerland, rents are high and the vacancy rates are very low, even lower in urban centres. As a result, households cannot easily find affordable dwellings, let alone their desired dwelling.
This research focuses on the rental housing market of Switzerland, which in general follows the rules of housing markets, but also has specific characteristics, has unique traits (the Swiss housing market is described in chapter 2). It is characterized by very low vacancy rates, especially in the urban centres. This generates new construction and at the same time pushes the rental prices higher. Although new construction rate is high and is expected to continue to be high (FSO, 2020*b*), demand is growing very fast and as a result there is scarcity of dwellings and vacancy rates remain low. The population forecast predicts a growing demand in terms of population but also changes in household composition, which translates into a higher demand/need for specific types of dwellings (FSO, 2016*b*). At the same time, land reserves especially for housing are shrinking fast (ARE, 2017). The Confederation and the cantons want to limit urban sprawl and discourage developers building in a way that the urban tissue expands. However, demand is growing and people have to find a dwelling to live in, somehow supply has to respond to the rising demand. Therefore, there is need for more dwellings either by new construction or by densifying the existing building stock. Supply usually responds slowly because there are several constraints such as financial constraints or buildable land availability, high land prices, legal procedures, construction costs, complexity of construction procedure, time needed to build, etc. (Schüssler et al., 2005).
The conceptual model helps build the bridge between the complex housing system and the agent-based model; it helps to define the main actors, their attributes and goals, and thus, to design the model agents, their behaviour and interactions. In the context of this research, supply refers to the supply of rental housing units and is represented by the owner agents and the building stock itself, analysed in three owner entities: (1) settlements, (2) buildings and (3)

dwellings. Supply is defined by the decision-making of rental property owners, analysed in seven owner actions: new construction, renovation (light or heavy), transformation, demolition and reconstruction, purchase and sale (owner actions are described in detail in section 4.6.1 that follows). Demand is represented in the model by rental households agents, which have three main characteristics: size, income and type (household agents are described in section 4.6.2).

To summarize, the aim of this research project is to study the housing rental market and its environmental impact. Owners and households of rental dwellings are considered the main actors. The focus lies on the decision-making processes of large-scale real estate owners and on the environmental impact of these decisions. This thesis concentrates on the supply side, the building stock's evolution and the analysis of the owner's decisions. However, the system of owners and tenants is studied as a whole.

For this purpose, we built an agent-based model (ABM) that represents both the supply and demand of the housing market of a defined system by describing the decision-making processes of property owners of rental dwellings and of their tenants (more details about ABMs can be found in section 4.5 that follows). Developing an ABM allows a bottom-up analysis of the housing system. The input of the model is an initial building stock and the households that occupy these dwellings. The owners, the building stock and the households evolve over time. As a result, housing environmental indicators, e.g., dwelling size, floor area per room, floor area per capita, persons per room, take different values. That allows to better understand the dynamics of the housing market, a system that is characterized by high complexity, and to develop measures that will contribute to decrease the environmental footprint of housing. The output of the model is the updated inventory of dwellings and households and a set of indicators. The indicators related to the occupancy (floor area per capita and persons per room) and the dwelling size are of particular interest. The material and energy footprint is estimated as part of another thesis (thesis of R. Shinde, ESD Laboratory, ETHZ)[1] within the SHEF project. However, we concentrate on assessing the environmental impact of housing through the floor area indicators.

[1]Housing cooperatives offer affordable housing; the rebound effect because of the lower rent that cooperative households pay is as well studied by ESD laboratory in the context of SHEF project. The reduced rent increases the disposable income of tenants and households tend to spend the 'extra' income on housing (e.g. for larger apartments) and travel (Shinde et al., 2022).

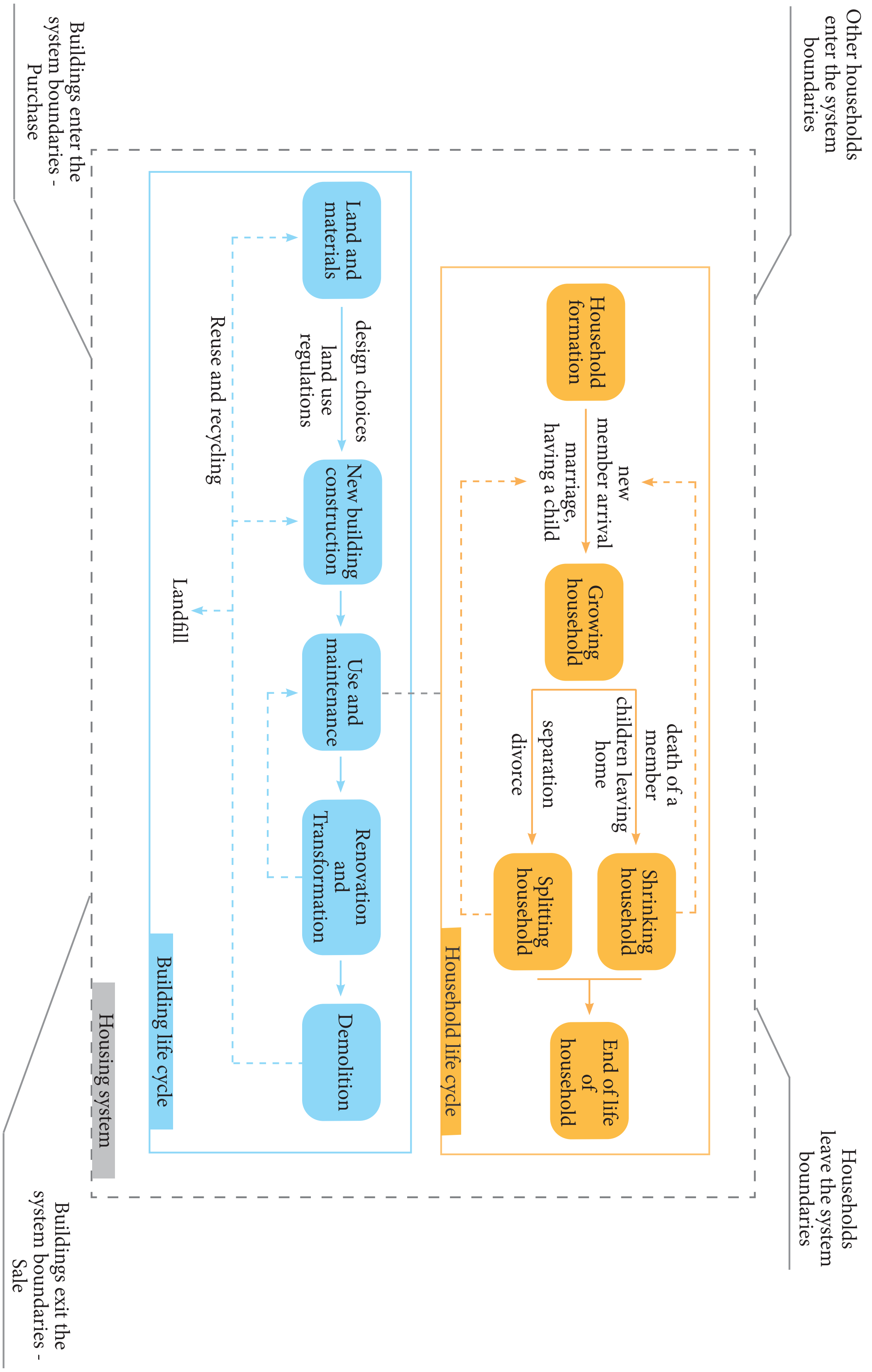


Figure 4.1 – Model design - Life cycle of buildings and households

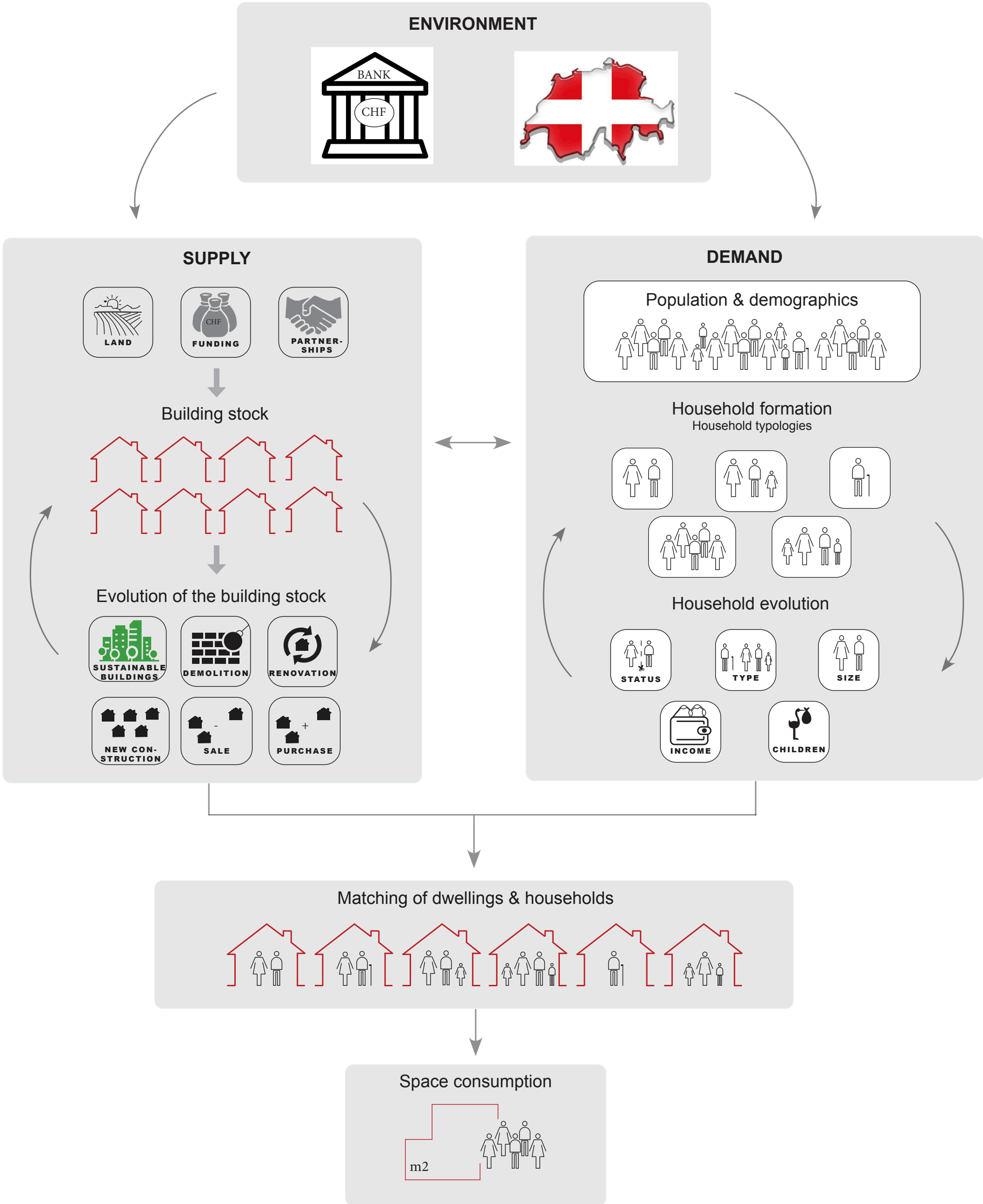


Figure 4.2 – Model design - Conceptual model overview

4.4 Dynamic accounting models

The population's need for housing creates the need for a stock of residential buildings. Associated to the dwelling stock is the activity of construction, demolition, reconstruction, transformation and renovation. The building stock evolves over time in terms of number and size of dwellings, floor area, quality characteristics, e.g., equipment, insulation, materials, etc. In the context of this thesis, the following seven owner actions are identified:

- New construction (NC): New residential units are built.
- Demolition (D): An existing building is demolished, is removed from the available dwelling stock.
- Reconstruction (RE): After a demolition, a new substitution building is built. Usually the substitute building has more dwellings, larger total floor area and different layout.
- Transformation (T): It is a form of heavy renovation; during a transformation, the main structure - skeleton of the building is kept intact, but many building elements are changed, e.g., architectural plans, facade or materials. Usually, the number of dwellings is different afterwards.
- Renovation (R): Owners decide periodically to renovate their buildings; they invest to their existing buildings in order to maintain or improve their state, e.g., façade, insulation, heating system, bathroom, kitchen, etc. Renovations can be heavy or light, depending on the extent of renovation works. Renovation only alters the qualitative characteristics of dwellings.
- Purchase (P): Some owners decide to grow their building stock by purchasing an existing building.
- Sale (S): On rare occasions, large-scale owners decide to sell a building.

The seven owner actions and the building stock (BS) is updated on a yearly basis. The BS at time t is equal to the BS that was already included in the stock of the owner in the previous year t-1, adding dwellings as a result of new construction, reconstruction, purchase and transformation (if any) and subtracting dwellings because of a demolition, sale or transformation (see equation 4.1).

$$BS(t) = BS(t-1) + \sum NC(\Delta t) + \sum P(\Delta t) + \sum RE(\Delta t) - \sum D(\Delta t) - \sum S(\Delta t) \pm \sum T(\Delta t) \quad (4.1)$$

In order to better understand the dynamics of the dwelling stock, dynamic analysis and modelling is proposed. This implies that past activity is taken into consideration and future activity is affected by past activity. New construction and demolition are the most frequent activities. However, according to Sartori, renovation and transformation will become the dominant activities related to the built environment (Sartori et al., 2008). New construction is of decreasing importance, the focus of research on sustainability is shifting to the management of the existing building stock (Kytzia, 2004; Stadt Zürich, 2017*b*; Stadt Zürich, 2015; Swiss Energy Scope, 2019).

Building stock accounting models have various approaches in the way they simulate the evolution of the number of dwellings. In some studies, the building stock has been modelled using assumptions such as fixed rates for demolitions, constructions and renovations (Myhre and Kibert, 2000). Other studies, in order to avoid having a fixed growth rate, they calculate the number of future dwellings based on the forecast of future population (Sartori et al., 2016). Building stock models have been mainly developed based on representative building types or building clusters (Jakob et al., 2012; Heeren, 2017; Ostermeyer et al., 2017). Most of the models concentrate on modelling the energy consumption of buildings and the green-house gas (GHG) emissions but neglect the material-related footprint (Heeren, 2017; Ostermeyer et al., 2017).

In this research project, we are modelling a small part of the housing market; the system's boundaries are defined by the building stock and the tenants of the three collaboration partners. In addition, the model assumes that for the next 30 years, there will always be a growing demand for housing, and as a result, the owners will always be interested to grow their stock. However, they have financial and physical (manpower) constraints, which prohibits to increase their stock indefinitely. The analysis of the collected data (past evolution of the stock) and the owner workshops, allow to estimate the yearly number of dwellings by which each owner grows its building stock. Based on equation 4.1, the building stock growth is the aggregated result of the seven owner actions. More details can be found in the relevant model functions in section 4.6.1.

4.5 Agent-based modelling

An ABM is a computational model for the simulation of actions and interactions of autonomous agents in order to better understand the behaviour of the actors of a system and what governs its outcome (Wooldridge, 2002; Epstein and Axtell, 1996; De Marchi and Page, 2014). They are bottom-up stochastic models where a set of agents is created and their behaviour is programmed. Agents are set to operate in a defined environment, to act and interact with one another in discrete time steps, based on their programmed behaviour (Axelrod, 1997; Wooldridge, 2002; Epstein, 2021).

Agent -based modelling focuses on the individual active components of a system (Behrman, 2001). There are three main ABM components: agents, environment and time. A simulation evolves by a number of time steps that are called ticks. For every tick the agents and/or the environment might be updated. Agents are updated according to their own decisions or due to environment changes that affect them (Billari and Prskawetz, 2003; De Marchi and Page, 2014; Epstein and Axtell, 1996; Epstein, 1999). Depending on the system being modelled, agents can represent a wide variety of entity types in an environment; they can be both individual or larger entities such as organizations or groups[2] (Tesfatsion, 2006). They exist within an environment, they have a goal and their behaviour can be implemented via simple or more complex rules (Axelrod, 1997). The environment is the space where the agents exist, it can be static or dynamic, and it can just be an abstract space that depicts the characteristics of the system we are studying.

The global dynamics of a system emerge from the interactions of the many individual behaviours. Even a simple ABM can show complex behaviour patterns and provide valuable information about the dynamics of the real-world system that it describes (Ligman-Zielinska and Jankowski, 2010; Tesfatsion, 2006; Parker and Filatova, 2008). ABMs represent models at the micro-scale, which attempt to explain the emergence of higher order properties of the overall system (Gilbert and Hamill, 2016; Billari and Prskawetz, 2003; Tesfatsion, 2003; De Marchi and Page, 2014; Wilensky and Rand, 2015). In order to build an ABM, there are specific aspects that need to be analysed: formulate the research question, assemble hypotheses for essential processes and structures, design the agents, design their attributes and behaviours, design the mutual interaction among the agents, design the environment and the way agents interact with it, define the method of model calibration and validation to analyse, test and revise the model (Tesfatsion, 2006; Railsback and Grimm, 2019).

In the context of this thesis, an agent-based model is built in order to study the Swiss housing market. But why did we choose to built an ABM instead of a traditional model? A model, in general, is a purposeful simplification of a system to solve a specific problem. However, many social processes have very high degree of complexity if modelled with a traditional mathematical model. Furthermore, neoclassical economic theory is based on homo economicus that assumes that individuals are rational actors that know their preferences, have perfect information and decide based on the maximization of a utility function. Over time, a fundamental concern among scientists arose: the idea that a rational actor doesn't correspond to a real human (Parker and Filatova, 2008; Tesfatsion, 2006). An individual's construction of reality defines its behaviour. However, cognitive biases might lead to inaccurate judgement, perceptual distortion and irrationality. Bounded rationality could be a result of human processing limitations, time inadequacy, lack of access to information. Therefore humans do not act according to the optimal decision after a cost-benefit analysis (Herbert, 1997; Kahneman, 2011; Thaler, 2015, 2008; Ariely, 2008). Models based on rational actors have limits in complex environments. In the effort to better describe human decision-making processes with bounded rationality, agent-based modelling became increasingly popular (Marks, 2006;

[2] According to Tesfatsion "The term “agent” refers broadly to bundled data and behavioural methods representing an entity constituting part of a computationally constructed world. Examples of possible agents include individuals (e.g., consumers, workers), social groupings (e.g., families, firms, government agencies), institutions (e.g., markets, regulatory systems), biological entities (e.g., crops, livestock, forests), and physical entities (e.g., infrastructure, weather, and geographical regions). Thus, agents can range from active data-gathering decision-makers with sophisticated learning capabilities to passive world features with no cognitive functioning. Moreover, agents can be composed of other agents, thus permitting hierarchical constructions" (Tesfatsion, 2006).

Ligman-Zielinska and Jankowski, 2010; Tesfatsion, 2006). Over the past years, a transition from rational actor models to ABMs, and from top-down macro decision-making to bottom-up micro-simulation is taking place. Since Schelling's research on the racial segregation in cities in the seventies (Schelling, 1978), a new field of research of socio-economic systems has been developed under a multitude of names, e.g., agent-based computational economics (ACE) (Tesfatsion, 2006), artificial societies, individual-based modelling (Railsback and Grimm, 2019; Gilbert and Troitzsch, 2000; Epstein and Axtell, 1996), agent-based computational demographics (ABCD) (Grow and Van Bavel, 2017).

In addition, real-world heterogeneity is concealed in traditional models[3], as a result, individual behaviour and its influence to the system level are not taken into consideration (Hommes, 2006; Tesfatsion, 2006; Kostadinov and Ankenbrand, 2013). ABMs are increasingly used in studying complex[4] adaptive systems (Flake, 1998; Tesfatsion, 2006). Micro-level interactions among heterogeneous agents are very popular in the modelling of problems in social sciences, such as economics, political science, urban geography, sociology and other disciplines such as ecology and environmental sciences (Billari and Prskawetz, 2003; Tesfatsion, 2021). Agent-based modelling provides a powerful way to address certain enduring and especially interdisciplinary questions. A wide range of research questions has been studied with multi-agent models, such as wealth distribution (Epstein and Axtell, 1996), trade networks (Tesfatsion, 2002; Epstein and Axtell, 1996), health and epidemics (Epstein and Axtell, 1996), traffic flows (Nagel and Rasmussen, 1994) and cultural patterns (Axelrod, 1997). Agent-based modelling is very close to the ideas of induction and deduction, "whereas the purpose of induction is to find patterns in data and that of deduction is to find consequences of assumptions, the purpose of agent-based modelling is to aid intuition" (Axelrod, 1997).

Furthermore, technological progress and advance in computing allowed agent-based modelling to be used on a broader scale. Many scientists interested in Artificial Intelligence propose decentralising the decision-making. ABMs are used in order to study a plethora of subjects in economics (Tesfatsion, 2006, 2003; Axelrod, 1997; Arthur, 1991). It is frequently claimed that the most important advantage of agent-based modelling compared to standard modelling approaches is that agent-based tools facilitate the design of agents with relatively more autonomy and that events are driven solely by agent interactions once initial conditions have been specified (Tesfatsion, 2006). ABM researchers argue more pragmatically that agent-based tools facilitate the modelling of cognitive agents with more realistic social and learning capabilities (hence more autonomy) than one finds in traditional homo economicus (Tesfatsion, 2006, 2005). Among the disadvantages of ABM relative to standard modelling approaches is that

[3]Heterogeneity and individual attributes are suppressed either on purpose in macroeconomic models that use representative agents or indirectly in aggregate models that try to describe system processes.

[4]A system is typically defined to be complex if it exhibits the following two properties: (1) it is composed of interacting units, (2) it exhibits emergent properties that arise from the interaction of the units and are not properties of the units.

ABM modelling requires the construction of dynamically complete models (Tesfatsion, 2001*b*). Starting from the initial conditions, the model must permit and fully support the evolution of agent interactions over time without further intervention from the modeller. To create a complete ABM, it requires detailed initial specifications for agent data and methods determining structural attributes, institutional arrangements, and behavioural dispositions. ABMs should be seen as complementary rather than an alternative to such more standard modelling (Tesfatsion, 2001*a*).

Traditional models assume complete rationality and individual homogeneity. But in real world, housing choices are deterministically unpredictable due to bounded rationality and heterogeneous agents. An agent-based framework can naturally capture these features. *"Modelling housing behaviour using complexity is fundamentally different from traditional neoclassical econometric models; in conventional models, all agents are homogeneous and random errors are considered a nuisance. By contrast, the properties of modern agent-based computation models, often used to apply economic principles to complexity, are dependent on stochastic distributions, stressing the heterogeneity between agents"* (Meen, 2003).

4.6 The Agent-based Model

In this thesis, three models are built; the Building Stock Model (BS_ model), which describes the supply of the housing market, and specifically the decisions made by large-scale owners of rental dwellings and the evolution of the building stock (BS); the Household Model (HH_ model) that describes the housing decisions of households and the evolution of households; the Matching_ model that is responsible for matching dwellings to households.

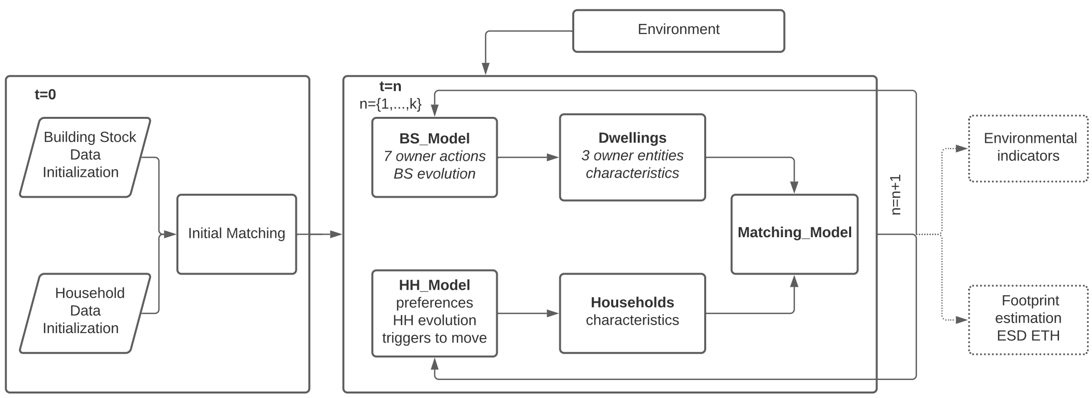


Figure 4.3 – Model design - Model flowchart

The Matching_ model functions like a connector between the first two models. The functions allow the communication between each other in order to allocate dwellings to households. Figure 4.3 illustrates the model flowchart showing the initialisation, input and output of the model as well as the connections between the three models.

At time t = 0, the model is initialised with the initial building stock (settlements, buildings, dwellings of the case study owners) and the initial households. The model also conducts the initial matching between dwellings and households. Once the initialisation is complete, the model starts running, and in every time step both dwellings and households are updated. Some of the households alter their characteristics because of a change, e.g., birth when the size of the household increases, marriage, new job, etc. In parallel, property owners make decisions about the building stock and update the stock and its attributes, for example they decide to renovate, to demolish, to construct a new building, etc. Once both households and building stock are updated, the matching model allocates households to dwellings. As a result, at the beginning of the next time step, both inventories are updated and the model runs all the functions from the beginning. This is repeated for n monthly time steps. At the end of every time step, the model provides an overview of the dwellings and their occupants. Several indicators are calculated such as yearly returns on investment for all owners, yearly settlement financial returns, average floor area per capita, average dwelling surface and room surface, etc. In addition, a full yearly inventory is generated and delivered to the material - energy model built by ESD laboratory at ETHZ that calculates the environmental footprint of housing in terms of CO_2-eq.

The model is a bottom-up model that is built using model assumptions that are derived from data analysis, empirically observed phenomena and the theory of section 4.3. Since we gain insight into the behaviour of individual components of the housing system, we aim to study the system-level behaviour and effects that emerge from their interactions.

For reasons of data availability, we are limiting the system boundaries to a case study that encompasses the rental dwellings and the tenants of the three collaboration partners of the project. As a result, the system boundaries of the model are narrower than the total of the Swiss housing market. In chapter 3, the case study is presented, it includes two housing cooperatives ABZ and SCHL and an institutional investor Mobiliar, altogether owners of approximately 11,000 rental dwellings. The dwellings of the cooperatives are located in the region of Zurich in the case of ABZ (4,931 dwellings) and in the region of Lausanne in the case of SCHL (2,122 dwellings). Mobiliar (4,059 dwellings) owns dwellings all over Switzerland[5] (for more information see chapter 3).

[5] Data collection took place in 2018-2019 and the analysis in 2019, so the description of the building stock represents the building stock as it was during the data collection period in 2018-2019.

4.6.1 Building Stock Model (BS_ model)

The Building Stock model describes the housing supply. It focuses on rental dwelling owners, describes the decision-making processes regarding their building stock and estimates the environmental impact of these decisions. In the context of this research, housing supply is portrayed by the three dwelling owners and their building stock. Supply is also defined by the decision-making processes of rental property owners, grouped and analysed in seven owner actions: New Construction (NC), Demolition (D), Reconstruction (RE), Renovation (light or heavy) (R), Transformation (T), Purchase (P) and Sale (S). For more details, see the conceptual model in section 4.3.
The input of the model is the initial building stock of the case study owners, which is the existing building stock of the three property owners as in 2019 and its characteristics (for a full list of the attributes of the building stock see Table A.21 in the appendix). In each time step, the model decides among the seven owner actions; this way the building stock evolves in terms of quantity, e.g., number of dwellings and quality, like equipment and other characteristics of dwellings. The output of the model is the updated building stock, the financial performance of each owner and settlement and environmental indicators related to the building stock.

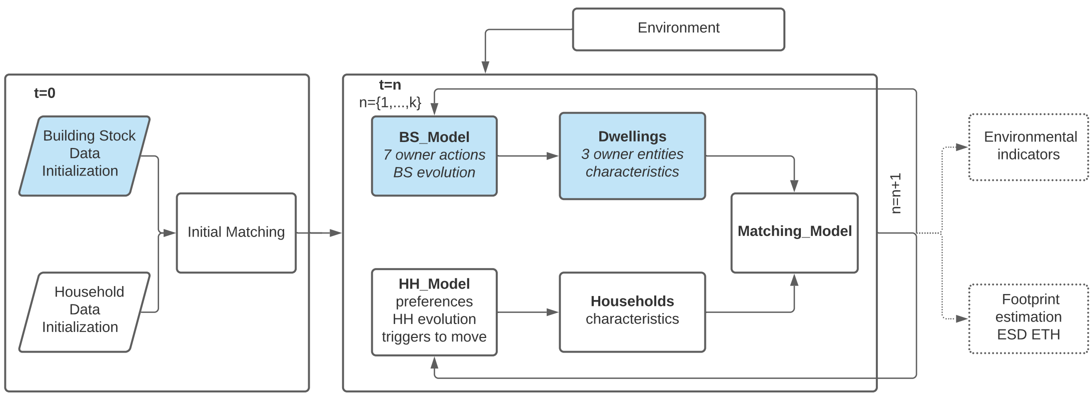


Figure 4.4 – Model design - Building stock model flowchart

4.6.1.1 Design of agents

In the BS_ model the dwelling owners (ABZ, SCHL, Mobiliar) are agents, named "owner" agents that take decisions regarding the building stock and their tenants. ABZ and SCHL are housing cooperatives, and in the model they represent non-profit investors, while Mobiliar represents profit-oriented investors. In addition, the building stock itself is considered a BS_ model agent. The latter has three entity levels or three classes: (1) settlements, (2) buildings and (3) dwellings. Some of the owner decisions are made at the settlement level, while others at the dwelling level. To sum up, there are four classes of the BS_ model: owner class, settlement

class, building class and dwelling class. This choice of classes allows to create classes under which we define various attributes (variables, properties) and methods (functions, actions). These attributes can be static or dynamic over time and they define the behaviour of the agents. The agents and their attributes can be found in detail in Table 4.1.
Settlements, buildings and dwellings (BS agents) are agents that change dynamically, based on the decisions made by the owner agents. When the owner agents decide to proceed with one of the seven owner actions, the BS agents are updated. Creating the BS agents allows the model to directly translate the decisions made by the owner agents into building stock information and update the BS agents. With their turn, BS agents interact with the household agents in the HH_ model and Matching_ model.
For example, let us assume that one of the owners decides to demolish a building of its stock. The model runs the function "Demolition and Reconstruction" as explained in the respective section that follows (section 4.6.1.10.2). The model selects the settlement to be demolished, removes it from the available settlements, buildings and dwellings (update of the BS agents). Then, after a specific number of time steps, it adds the new - reconstructed settlement and updates the BS agents again. In Figure 4.5, the BS agents flowchart is illustrated.

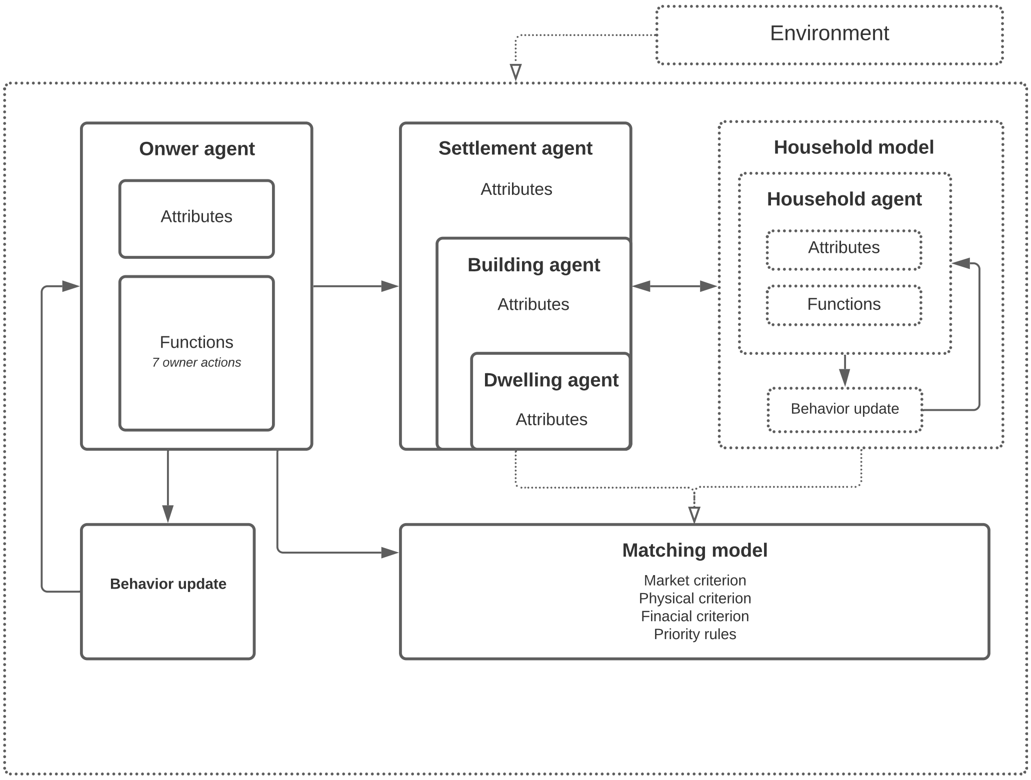


Figure 4.5 – Model design - Building stock model agents flowchart

Table 4.1 – Model design - Building stock model - Agents and attributes

BS_ model agents and attributes		
Agents	**Attribute / characteristic**	**Value & Metrics**
Owner		
	Growth capacity number	Number of dwellings
	Construction rate	%
	Reconstruction rate	%
	Transformation rate	%
	Purchase rate	%
	Renovation capacity number	Number of dwellings
	Additional rent calculator	
	Construction costs	CHF/m^2
	Land price range	CHF
	Land surface range	m^2
	Cap rents	CHF/m^2/year
Settlement		
	Settlement number	
	Settlement id number	
	Owner	{1,2,3}
	Number of buildings per settlement	
	Number of dwellings per settlement	
	Settlement address	
	City	
	Canton	
	Postcode	
	Municipality typology	{11,12,13,21,22,23}
	Heritage protected settlement	{YES,NO}
	Construction year	year
	Acquisition year	year
	Reference year	year
	Demolition year (if applicable)	year
	Reconstruction year (if applicable)	year
	Renovation year 1 (if at least one renovation)	year
	Renovation year 2 (if at least two renovation)	year
	Renovation year 3 (if at least three renovation)	year
	Renovation year 4 (if at least four renovation)	year
	Transformation year (if applicable)	year
	Land property	{Own, Leasing}
	Land surface (Land_m^2)	Square meters (m^2)
	Land price	CHF
	Settlement surface (HNF m^2)	Square meters (m^2)
	Market type	{Free, Subsidized, Mixed}
	Geo-coordinates	
	Investment Cost	CHF
	Insurance Value	CHF
	Rental Income yearly	CHF
Building (additional to the settlement characteristics)		
	EGID Unique building number	
	Number of dwellings	
	Number of floors	
	Height	Meters (m)
	Heating source	{Oil, Gas, Pellet, District heating}

Dwelling (additional to the settlement and the building characteristics)		
	Dwelling number	
	Dwelling id number	
	EWID Unique dwelling number	
	Size living surface	Square meters (m^2)
	Size number of rooms	{1-1.5room,2-2.5room, 3-3.5room, 4-4.5room,5+room,}
	Volume	Cubic meters (m^3)
	Floor	
	Net rent	CHF
	Net rent per living surface	CHF/ m^2
	Additional cost (heating & hot water)	CHF
	Gross rent	CHF
	Gross rent per living surface	CHF/ m^2
	Vacant	{YES, NO}
	Empty	{YES, NO}
Source: Margarita Agriantoni		

4.6.1.2 Design of the environment

The environment of the BS_ model consists of factors that influence the housing market and more specifically the housing supply, the production of dwellings and in general the decisions made by real estate investors. In the context of this thesis, the environment represents various levels of the state and financial institutions, e.g., the confederation, cantons, municipalities, banks, the Swiss National Bank, Federal Offices and Agencies, like the Federal Office for Housing. They are responsible for the development of housing policies and regulations, for calculating the reference mortgage rate, for the supply of money to the market in the form of mortgage loans, etc.

The environment of this model is rather simple. It comprises banks that offer mortgage loans at a mortgage rate, which at the initialisation is set to 1.5% (bank rate = 0.015), and the mortgage reference rate calculated quarterly by the Swiss National Bank, initialized at 1.25% (ref.rate = 0.0125)[6]. The latter is dynamic over time, and it randomly fluctuates between 1.25% and 1.75% every three months, with a step of ±0.25 to ±0.5% (for the evolution of the reference rate in the past, see chapter 2 "Housing in Switzerland"). The confederation, cantons and communes are developing housing policies and regulations. In this model, we are taking into consideration zoning and land use regulations that define the land reserves and the future land use. Specifically, it defines the allowed land use (housing, commerce, mixed, forests, agriculture); the floor area ratio (FAR) that determines the maximum permissible floor area that one can build on a particular plot/piece of land; the plot area ratio (PAR) that determines the maximum ratio of the permissible building surface to the permissible land area[7]; and the maximum permissible building height. In the model, the zoning and land use regulation might change: (1) the land reserves for housing will increase because it was decided

[6] Actual reference rate in September 2021,
Source: https://www.bwo.admin.ch/bwo/de/home/mietrecht/referenzzinssatz.html

[7] All surface rates and final surfaces are calculated according to SIA 416 (SIA, 2003*b*).

to introduce more land for residential use. The model assumes that there is zero probability to introduce more land. This means that land reserves will progressively decrease, which implies an increase of land prices[8]; (2) the floor and plot area ratio might change if the state decides to increase or decrease the density of a specific zone. The model assumes that there is a 5% yearly probability for the FAR to increase or decrease. Once a change occurs, no other change can occur for the next ten years.
In addition, the model's environment includes regulating mechanisms of the state to control the rents by adjusting the rent based on the current reference mortgage rate; to regulate the dwelling occupancy (occupancy rules) by defining the maximum allowed number of rooms depending on the household size. The latter doesn't change autonomously in the model, it is set as a model parameter. The rent adjustment depends on the fluctuation of the reference rate as described above (for more details, see the rent update function in section 4.6.1.9.
Furthermore, the environment can promote the environmental awareness of households by organising environmental awareness campaigns, introducing an environmental tax or giving incentives to move to a smaller dwelling, etc. Since this model focuses on the owners, there is a simple rule in the form of a switch ("on"/"off"); the switch is on when the environment promotes actively the environmental awareness and off when it doesn't. The initial state of the switch is "off", which means that the environmental awareness level of households remains static over time. When the switch turns to "on", the environmental awareness level of households goes one level higher every twelve ticks.

4.6.1.3 Agent - agent and environment interaction

Based on the description of the environment, several attributes of the owners and the building stock are potentially affected and updated at each time step:

- If the reference rate changes in a specific time step, then (1) the reference rate based on which owners calculate the rental income of their settlements is updated and (2) the rents of the cooperative dwellings adjust to new updated rents as shown in the rent adjustment function that follows. For Mobilar households, only a random 20% of their dwellings adjust the rent after a reference rate change.
- The land reserves decrease, which might lead to a land price increase. Since the land price depends strongly on the location, the model assumes that there is 50% probability for owners to buy a land with a price increase of 10%-30% (the exact increase is randomly chosen) compared to the land prices in Table 4.5.
- If there is a change in FAR, then FAR changes by ±10%, depending whether an increase

[8] Land price depends significantly on the location. However, the more scarce is land, the higher the price; the land supply will be limited while demand will continue to be high (ZKB, 2008; Ligman-Zielinska and Jankowski, 2010)

or decrease was decided and all the relevant tables change accordingly (see Table 4.6).

- The occupancy rules are set as a model parameter. The baseline scenario runs with the initial occupancy rules. However, if the occupancy rules change, the Matching model allocates households to dwellings using the new updated set of occupancy rules.
- The owners agents of the BS_ model influence the dwelling agents by deciding about the future of their building stock, e.g., renovating, demolishing, etc. The BS_ model agents interact with the household agents of the HH_ model through the matching model and the allocation of dwellings to households.

4.6.1.4 Time steps function

The time step (step function) of the overall merged model, also called tick, and also corresponds to a real month. However, the decisions that owners make about the building stock are taking place on a yearly basis (every 12 ticks). This also corresponds to reality as dwelling owners usually perform yearly building diagnostics[9] in order to evaluate the condition of their building stock. This helps them to decide whether to proceed to one of the seven owner actions.

4.6.1.5 Capacity control function

This model assumes that owners have access to adequate funding and are always willing to grow their building stock. However, due to constraints they cannot grow limitless, and the model considers that there is a yearly growth capacity limit. On a yearly basis, the model does a capacity control to verify whether each owner can proceed and undertake more owner actions. There is a yearly renovation capacity number per owner that corresponds to the number of dwellings that they can renovate every year and a yearly growth capacity number that corresponds to the number of dwellings they can add to their building stock (see section 4.6.1.5, Table 4.2). This number is stable and is the result of thorough statistical analysis of the past construction activity of the owners. This has been verified by the owners during the owner workshops. The building stock can grow through a combination of owner actions (NC, P, T, D and RE). However, most new dwelling additions is a result of new construction (Schüssler et al., 2005). For example, ABZ can grow by 50 dwellings per year: 65% of the ABZ capacity number, which is 32 dwellings, will be the result of a new construction, 3 dwellings per year due to purchase, 3 dwellings due to transformation, 12 dwellings as a result of demolition

[9] Building diagnostics is the process of evaluating a building, detecting the problems and proposing solutions to problems of the buildings. It is a holistic approach that includes techniques regarding the inspection and analysis of an existing building. Sometimes it includes future prediction of defects in the condition of the structure, facade, equipment of building. It can be carried out using naked eye or aided by advanced tools. The result of building diagnostics is a description of the building's condition, a prediction of the causes of problems in a building and suggestion of appropriate building solutions (interventions).

and reconstruction. Let us assume that in a specific time step, ABZ decides to start a new construction of a settlement with 160 dwellings; this implies that the total of 160 dwellings will be added in the BS in that time step; however, for the next 160 / 32 = 5 years, ABZ will not have the capacity to start another new construction. The same applies for the capacity control of all owner actions.

Table 4.2 – Model design - Building stock model - Capacity control

Capacity control						
Owner action	Owner					
	ABZ		SCHL		Mobiliar	
Capacity number growth (yearly)	**50 dwellings**		**20 dwellings**		**75 dwellings**	
New construction	65%	32 dwellings	75%	15 dwellings	75%	56 dwellings
Purchase	5%	3 dwellings	5%	1 dwelling	10%	7 dwellings
Reconstruction	25%	12 dwellings	15%	3 dwellings	10%	7 dwellings
Transformation	5%	3 dwellings	5%	1 dwelling	5%	5 dwellings
Capacity number for renovation (yearly)	**80 dwellings**		**32 dwellings**		**65 dwellings**	
Source: own analysis						

4.6.1.6 Eligibility test function

This is a function used in the cases of renovation (R), transformation (T) and demolition (D). Eligibility test is a combination of pass/fail criteria and a scoring system that determines which settlements are eligible and finally chosen for each owner action. As mentioned above, every year owners decide about proceeding to one of the seven actions; if the capacity control allows them to proceed, then the eligibility test will choose the settlement.

For example, an owner is capable (pass capacity control) to start demolition; all settlements of this owner are potentially eligible for demolition, so a list with all settlements is created; each settlement of this list will go through the eligibility test. The first criterion to check is whether the settlement is heritage protected, if so, then the specific settlement is not eligible for demolition and thus excluded from the list[10] (Wüest Partner, 2019*d*). Subsequently, following criteria are checked: type and year of last intervention, number of past interventions, age of the settlement, profitability of the settlement by comparing the average net rent per square meter of the settlement to the respective owner average. Some of the criteria are pass or fail criteria, while other introduce scores for each settlement. Respectively, according to the above order, a higher score in the point system is achieved: the older the settlement, the higher the

[10] In Switzerland in the 1970s, buildings started being recognised for the cultural heritage value (architectural or historic value, faced, artistic elements , etc. and they were considered important to be protected. For that reason there are two categories of buildings the ones that are recognised as protected buildings, approximately 5% of the building stock (90,000 buildings). The second category includes the buildings that exhibit cultural interest but are not yet included in the final inventory of protection (10-15% of the building stock). Buildings that belong to both categories are protected and there are many constraints in the case of a renovation or transformation. These buildings are protected and cannot be demolished, as a result, this is an obstacle in may cantons that wish to stop urban sprawl and exploit by densifying the existing building stock (Wüest Partner, 2019*c*).

number of past interventions, the more the settlement underperforms in terms of net rent (CHF/m^2). The higher the score, the more probable it is for the settlement to be chosen to be demolished. For each owner action, the threshold is different for each criterion (see respective owner action and thresholds in detail in the following sections).

Table 4.3 – Model design - Building stock model - Eligibility test

Eligibility test criteria		
Criteria	**Description**	**Type of criteria**
Heritage protected	Is it allowed to proceed with the action?	Pass/fail
Number of past actions	How many times has been a settlement renovated for example	Point system
Type of last action	Was the last action a renovation or a transformation?	Pass/fail
Years since last action	How many years have passed since the last action?	Pass/fail
Age of the settlement	How old is the settlement	Point system
Average net rent per living surface	What is the average net rent per square meter of a settlement in comparison to the average net rent per surface of the owner?	Point system
Source: own analysis		

4.6.1.7 Decision steps function

We are analysing the decision-making processes of owners using decision steps. The model defines four steps of decision-making: (1) Planning, (2) Deciding, (3) Starting and (4) Finishing, as shown in Table 4.4. These steps are not the same as the time steps of the model (ticks), this is why we are calling them decision time steps. Investors and developers need time to proceed to an owner action. Depending on the owner action, decision time steps might differ in terms of duration (months=ticks). Planning step describes the willingness of the owner to proceed to an owner action. However, there might be constraints that don't allow to proceed, such as bureaucracy, funding or manpower issues.

For example, assume that a housing cooperative fulfils the capacity criteria of transforming an existing settlement; according to the eligibility criteria, the settlement to be transformed is chosen and the planning starts. However, in the case of the cooperatives, it is essential to find substitute dwellings that could accommodate the tenants of the settlement to be transformed during the renovation time. For that reason, they have to assure having enough empty dwellings to accommodate the households. The model, for the next twelve months after the planning phase, collects and keeps empty the necessary dwellings. In 12 ticks after planning, a check is done to verify if the necessary empty dwellings are found, if so, the deciding phase can start. If not, more empty dwellings will be gathered till the number is sufficient for the households that are forced to move. In the deciding phase, all tenants are informed that renovation works will start in three months, and all the decisions about the owner action are taken, e.g., number and size of dwellings, future rent, etc. After checking that all tenants moved out, the starting phase is activated, which means that all households have successfully moved out, left the settlement and construction works can start. Transformation lasts 18 months, which means that 18 months after the starting phase, the transformation will finish and the transformed settlement and dwellings will be available in the housing market again. One or more of the phases could coincide with each other. For more details, see Table 4.4 and the functions section that follows.

Table 4.4 – Model design - Building stock model - Decision steps

Owner decision steps						
Owner action	Decision steps					
	PLANNING	DECIDING	ANNOUNCING to the tenants *	STARTING	REMOVING dwellings from the market	FINISHING and adding dwellings to the market
New construction	t = n	t = n	no	t = n	no	t = n+18
Demolition and Reconstruction	t = n	t = n + 12 months	t = n + 12 months *that they have to leave & propose other apartment to the tenants of the cooperatives	t = n + 15 months	t = n + 15 months	t = n + 33 months
Renovation light	t = n	t = n	t = n *that the rent will be higher	t = n	no	no *change of rent in t = n+3 months
Renovation heavy	t = n	t = n + 12 months	t = n + 12 months *that they have to leave & propose other apartment to the tenants of the cooperatives	t = n + 15 months	t = n + 15 months	t = n + 24 months
Transformation	t = n	t = n + 12 months	t = n + 12 months *that they have to leave & propose other apartment to the tenants of the cooperatives	t = n + 15 months	t = n + 15 months	t = n + 33 months
Purchase	t = n	t = n	no	t = n	no	t = n
Source: own analysis						

4.6.1.8 Empty dwelling list function

The empty dwelling list function is responsible for creating a list with empty dwellings. In the context of this thesis, empty dwellings are considered to be kept empty intentionally for a specific reason such as accommodating households that have to move in from another dwelling because of a renovation or demolition; we distinguish the notion of empty dwelling from the notion of vacant dwelling, which corresponds to a dwelling that is available in the market but not occupied / rented yet. This function is activated only for the housing cooperatives because only in that case the owner is responsible to offer a substitute dwelling to the household during the time of construction works, specifically, in three owner actions of housing cooperatives, demolition, renovation and transformation. During these owner actions, the households are informed that an intervention will take place to the building and that they have three months to free their dwelling. At that point, they offer to the households alternative housing for the duration of the works. That means that the owner has to organise and anticipate the need for substitute dwellings. It takes place between the decision phases 1, 2 and 3. In decision step 1, the model plans which settlement will be transformed, for example, recognises the number and the characteristics of the dwellings to be transformed and starts keeping vacant dwellings and adding them to the empty list. After 12 ticks, the model checks if the empty dwellings are sufficient to accommodate the moving households; if the latter is satisfied, the transformation can be decided and start. In the case of Mobiliar, this function is not needed as the tenants are informed, usually with a three month notice that renovation works are about to start and that they have to move out within the next three months.

4.6.1.9 Rent update function

Rent adjustments must be examined separately; this function is activated to alter the net rent of dwellings. In the context of this model, the rent adjusts in the following cases:

- In the case of investments to a settlement that result in a significant increase in value (added value), e.g., transformation, renovation heavy, renovation light. The new / updated net rent is calculated based on the method Fracheboud, for a detailed calculation see the respective sections for each owner action (see equations 4.16c, 4.21b).
- In the case of a change of the reference mortgage rate, the net rent might get updated (Le Conseil Fédéral Suisse, 1990; Lachat, 1996). The mortgage reference rate is calculated quarterly by the Swiss National Bank. In the case of a decrease of the rate, tenants have the right to ask for a rent adjustment. The adjustment of the net rent is calculated based on article 13 of OBLF[11] (Le Conseil Fédéral Suisse, 1990). If the reference mortgage rate increases by 0.25% it allows a maximum rent increase of:
  - RA = 2% when the reference mortgage rates are higher than 6%;
  - RA = 2.5% when the reference mortgage rates are between 5% and 6%;
  - RA = 3% when the reference mortgage rates are lower than 5%

  The maximum rent increase (MRI) is calculated as in equation 4.2, with rent adjustment (RA) as described above depending on the reference mortgage rate range and ΔM the increase of the rate.

  $$MRI = RA \times \frac{|\Delta M|}{0.25\%} \tag{4.2}$$

  For example, based on equation 4.2, if the mortgage rate increases from 5.5% to 6% the maximum allowed increase is: $MRI = 2.5\% \times |6\% - 5.5\%|/0.25\% \approx 5\%$.

[11] Ordonnance sur le bail à loyer et le bail à ferme d'habitations et des locaux commerciaux (OBLF)

In the case of a decrease of the mortgage rate, the net rent is reduced proportionally. The rental decrease (RD) is calculated in equation 4.3, with rent adjustment (RA) as described above and ΔM the increase of the rate.

$$RD = \frac{RA \times \frac{|\Delta M|}{0.25\%}}{100\% + RA \times \frac{|\Delta M|}{0.25\%}} \tag{4.3}$$

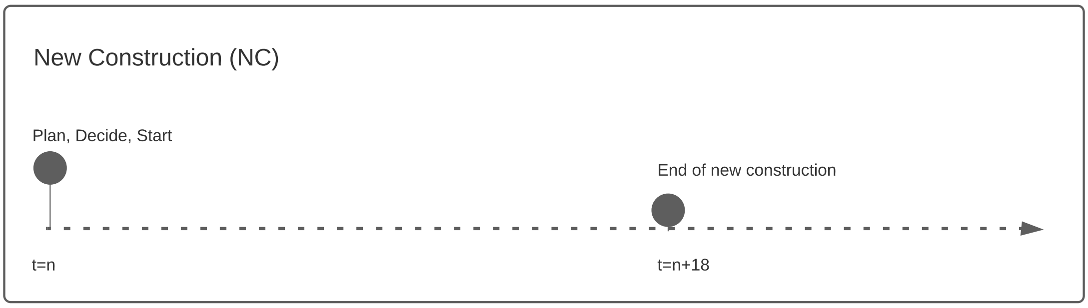
For example, if the mortgage rate decreases from 5% to 4.5% the rental decrease is calculated based on equation 4.3: $RD = (3\% \times (|4.5\% - 5\%|)/0.25\%)/(100\% + (3\% \times (|4.5\% - 5\%|)/0.25\%)) = 6/106 \approx 5.66\%$.
The housing cooperatives automatically update the net rent in case of a change of the reference mortgage rate higher than 0.5% (Δmortgage rate$\geq$ 0.5%). Mobiliar doesn't update the rent automatically; the model assumes that only 20% of the dwellings (randomly chosen) are affected by a decrease of the mortgage rate[12].

4.6.1.10 Owner actions function

In the context of this model, we define seven owner actions: New Construction (NC), Demolition and Reconstruction (D and RE), Renovation (R), Transformation (T), Purchase (P), Sale (S). Dwelling owners make decisions about their existing BS (five owner actions: D, RE, R, T, S) and future BS (two owner actions: NC, S). On a yearly basis, they evaluate their existing BS and decide about potential actions for maintenance, e.g., renovations, transformations, demolitions. They decide whether to grow their BS and add more dwellings, either by starting a new construction or purchasing an existing building. The model assumes that every decision taken by the owners applies for the whole settlement, not just for a building or dwelling. All this improves the understanding of the building stock evolution and allows predictions of the future evolution.

[12]Housing cooperatives are always adjusting the net rent in case of a mortgage rate change higher than 0.5%, so the model automatically updates the rent of all cooperative dwellings. The tenants of Mobiliar are entitled to a decrease of their net rent if the reference mortgage rate decreases; tenants have to ask for this rent decrease on their own; however, often tenants don't apply for, thus, the model assumes that only 20% of Mobiliar dwellings decrease their rent.

4.6.1.10.1 New Construction



The new construction function describes the decision-making processes of owners to construct a new settlement. The model controls if the owner has the capacity to start a new construction project (NC). If a project can start, the model finds a plot and decides about the characteristics of the new settlement to be built; the model calculates the total investment cost and the rental income; after 18 months it introduces the new dwellings in the market of the model's system.
As noticed above, the decisions of planning, deciding and starting happen simultaneously, at the same time step. The main reason for this is the assumption that owners always want to grow and that they have started searching for a land beforehand, thus, finding the land doesn't influence the rest of the functions. Therefore, after the capacity control affirms that the owner is able to build, the construction can start immediately. In total, it takes one and a half years (18 ticks) to complete the construction and add the new dwellings into the market.
The model describes the decisions taken by the developers (profit and non-profit) from the beginning of the building project; checks whether they can proceed with the project, designs and constructs the building, estimates the costs, introduces the dwellings to the market and through the Matching_model allocates the dwellings to households in search for housing. The main steps are:

Step 1: *Check the capacity for each owner*
Firstly, the model controls whether the owner has the capacity, as defined above (see section 4.6.1.5, Table 4.2), to start a new construction. At time step t = 0, all owners are set to pass the capacity control, so they can start building. Every year (every 12 ticks), a capacity control takes place for each owner. The model checks if previous construction has finished and the owner can start a new project. For example, at time t = 0, SCHL is able to build a settlement. Let us assume that the new settlement has 60 dwellings; the yearly capacity of SCHL amounts to 15 dwellings; that means that SCHL cannot start a new project for the next 4 (= 60 / 15) years.

Step 2: *Find the land*

Land is scarce in Switzerland. However, the model assumes that land is available; if the owners are able to start a new construction (passed step 1), they find a buildable land. The model selects the land surface within a range of land surface values. This range is the result of a thorough analysis of their existing building stock as in year 2019[13]. Similarly, the model selects the land price per square meter (CHF/m^2) within a range of land price per square meter values. This range is the result of analysis of their existing stock and the price they have bought land in the past. We assume the future land price is within a price range defined by the property owners (data analysis and workshops). Additionally, the future land price is verified by the land price estimations by Wüest Partner[14].

The model chooses the land surface (m^2) and price (CHF/m^2) by sampling from a truncated Gaussian distribution with given minimum, maximum, mean, and standard deviation values (see Table 4.5). This allows the model to calculate the cost of land as in equation 4.4. After finishing this step, the model has defined the following:

- Land surface
- Land price per square meter (CHF/m^2)
- Land cost (CHF)

$$Land\_cost = Land\_surface \times Land\_price\_per\_surface \tag{4.4}$$

Table 4.5 – Model design - Building stock model - Land surface and land price

Owner	Land surface (m^2)			Land price / m^2 (CHF/m^2)		
	min	max	mean	min	max	mean
ABZ	500	30,000	5,508	700	1,400	1,000
SCHL	500	30,000	3,360	500	900	700
Mobiliar	500	15,000	1,300	500	3,000	1,000

Step 3: *The location of the new project*

As described in previous chapters, the two housing cooperatives are operating in specific locations: ABZ in the agglomeration of Zurich and SCHL in the area of Lausanne. Mobiliar owns buildings scattered all over Switzerland. We assume that the new construction project will be developed in a location (postcode) where the specific owner already has a property. The

[13]Because there is a lack of reliable information regarding the size of the remaining buildable land, the model assumes that the remaining land reserves for housing have a size among the land size range of the initial building stock for each owner. In Table 4.5, the minimum, maximum and average value of the initial stock land size are illustrated. The model assumes that it follows a normal distribution and randomly chooses the value of the new land size.

[14]Based on Wüest Partner, land prices exhibit high variability depending on the location (Wüest Partner, 2021*h*). For more details regarding land prices in Switzerland, see chapter 2, section 2.4 and city of Zurich (Stadt Zürich, 2017*b*,*c*).

model selects a postcode among the postcodes of the existing building stock for each owner; the choice of the postcode for the new project is done with a random sampling, weighted with the frequency of the postcode in the existing building stock. For a detailed list of all postcodes for each owner, refer to Table A.20 in the appendix. The more frequent the postcode, the likelier for the model to build there. After defining the postcode of the new settlement, the city, canton and typology of the municipality can be defined based on the categorization of the Federal Statistical Office of all the municipalities in Switzerland (FSO, 2017) into 9 categories[15]. In this step, the model has defined the following:

- Canton
- City
- Postcode
- Municipality typology (9 categories)
- Urban or rural

Step 4: *Settlement surfaces*
After the land has been bought, the next step is to design the settlement. In the context of this model, we are not developing detailed architectural plans. The model selects the main features of the building(s), e.g., dwelling size, number of dwellings per building, number of floors, etc. The model assumes that the purchased land is characterized either as residential (W) or as central (Z) building zone; this means the land is buildable and appropriate for residential use. The residential zone is a residential area that mainly allows the development of residential buildings and offers lower densities; the central zone is a mixed land use zone, which allows a mix of land use and offers higher densities, thus higher floor area ratios. The zone categories choice is based on the zoning plans of the city of Zurich (Stadt Zürich, 2014).The settlement zone is chosen based on fixed probabilities based on the land reserves of Switzerland. Residential land reserves represent 15% and central zones 10% of the total available land reserves. Based on that, the model attributes a 60% probability of having a land in a residential area and a 40% probability of finding land in a central area.
Regarding the choice of the exact zone the land belongs to, the model chooses among nine different housing zones, namely W2, W3, W4, W5, W6, W7, and Z5, Z6, Z7[16] with a random sampling, weighted by the percentage of land reserves of each category (UVEK, 2018; ARE, 2017; FSO, 2015*a*). For more details, refer to Table 4.6 and chapter 2, section 2.4. The model assumes that all postcodes have similar housing land reserves, first, due to lack of data and

[15]Urban municipality in a big agglomeration, urban municipality in a middle-sized agglomeration, urban municipality in a small agglomeration, peri-urban municipality of high density, peri-urban municipality of medium density, peri-urban municipality of low density, rural central municipality, rural near-center municipality, rural peri-urban municipality

[16]There are many zones in the zoning system of Zurich. However, in the context of this model, only the residential and mixed zones are selected for reasons of simplification. For example, W2 corresponds to the housing building zone where up to two-floor buildings are allowed, W3 allows a maximum of three floors, etc.

second, because our research does not focus on modelling land and land availability.

Table 4.6 – Model design - Building stock model - Zones and land reserves

Housing zones W				
Zone	**Residential Zone Reserves**	**% of the total W**	**Residential Zone Reserves**	**% of the total W**
W2	126	4%	410	5%
W3	597	17%	1594	20%
W4	1655	48%	3512	44%
W5	769	22%	1463	18%
W6	133	4%	322	4%
Other	172	5%	622	8%
TOTAL Housing	3452	100%	7923	100%
Central zones Z				
Zone	**Residential Zone Reserves**		**Residential Zone Reserves**	**% of the total**
Z5	139		455	36%
Z6	6		505	40%
Z7	-53		288	23%
TOTAL Housing	92		1248	100%
Source: City of Zurich				

Based on the zone where the land is located, the maximum allowed building characteristics, like maximum number of floors, building height and floor area ratio are defined (see Table 4.7). For simplification reasons, the model uses the regulations of the city of Zurich (Stadt Zürich, 2019). The model assumes that developers use the maximum building permissible dimensions (maximum number of floors, height, floor area ratio (FAR)) and a plot area ratio between 20 - 30%. Knowing the plot surface and the floor area ratio, the model calculates the total gross surface (TGS)[17] and the total effective surface (TES)[18] (SIA, 2003*b*).

Table 4.7 – Model design - Building stock model - Zone category and maximum building characteristics

Characteristics defined	**Zone categories**							
	W2	W3	W4	W5	W6	Z5	Z6	Z7
Max. Floors	2	3	4	5	6	5	6	7
Max. Building Height	9m	9.5m	12.5m	15.5m	18.5m	19m	22m	25m
Max. Floor area ratio FAR	60%	90%	120%	165%	205 %	200%	230%	260%
Source: City of Zurich								

The total gross surface (TGS) is calculated by multiplying the floor area ratio (FAR), which corresponds to the zone category (see Table 4.6), with the land surface (LS) (equation 4.5). The total effective surface (TES) is not a fixed proportion of the total building surface; on the

[17]According to SIA 416: "TGS refers to the sum of the surfaces corresponding to all sides. The floor area includes the construction area. The surface of the empty spaces located below the last accessible basement is not considered as TGS floor area. TGS surface is subdivided into: (a) Net floor area and (b) Building area (ger.) GF: Geschossfläche, (fr). SP: Surface de plancher".

[18]According to SIA 416: "TES refers to the main surface as part of the effective surface that is dedicated to the functions corresponding to the purpose and functionality, in the strict sense, of the building. (ger.) HNF: Hauptnutzfläche, (fr). SUP: Surface utile principale".

contrary, it depends on the size and shape of the building. By analysing the case study data, the average value of TES/TGS is 0.78 with values ranging between 0.62 and 0.86.

$$TGS = FAR \times LS \tag{4.5}$$

TES plays a determinant role in the calculation of cost; construction and renovation costs depends on many factors, e.g., size of the building (m^2), shape of the building (defines the facade surface), structural design, construction logic (simple or complex), floor plan flexibility, repetitions (parts of the building that repeat), material quality, finishing works, ground quality, gradient of slope, location, tax and legal framework, etc. (Perret et al., 2020; Pointet and Guillod, 2012). In this model for simplicity reasons, the cost depends on the effective surface. In this model, the total effective surface (TES) is calculated by multiplying TGS with a TES ratio ranging between 0.6 and 0.8 (TES.rate = 0.6-0.8) (equation 4.6).

$$TES = TES.rate \times TGS \tag{4.6}$$

The building footprint (BF) is calculated by dividing the total gross surface (TGS) by the number of floors of the building. For the sake of simplicity, we assume that all floors have the same surface (equation 4.7).

$$BF = \frac{TGS}{Number\_of\_floors} \tag{4.7}$$

For example, let us assume that one of the owners finds an affordable land of 3,000 m^2 (at a price of 1,100 CHF/m^2) in the Zurich area, where the zone category is W4. Based on Table 4.7, the maximum number of floors that can be built is four, with a maximum building height of 12.5 meters and a maximum floor area ratio of 120%; the latter translates into a maximum gross building surface of 1.2 x 3,000 m^2 = 3,600 m^2. We assume that the owner is going to exploit the maximum of the permissible floor area ratio FAR = 1.2% and as a result TGS = 3,600 m^2. However, the surface that we are interested in and that the model uses for most of its calculations, is the total effective area (TES). If TES. rate is 0.8 (randomly chosen from a uniform distribution from a range of values between 0.6 and 0.8), the total effective area is 80% of the gross building surface, which translates into TES = 0.8 x 3,600 m^2 = 2,880 m^2.
The total effective surface is a critical surface; it is very close to the total of the surface of all the dwellings in a building or settlement; the owners use it as a reference surface for many of their calculations, for example in their financial analysis, energy consumption, occupancy, etc. In this step, the model has defined the following:

- Number of floors of the building (from 2 to 7 floors)
- Height of the building: Height = (number of floors + 1) x 3 meters
- Floor area ratio, based on W2, W3, W4, W5, W6, W7, Z5, Z6, Z7 (from 60% to 260%)

- Plot area ratio (20-30%)
- Total gross surface (TGS)
- Total effective surface (TES)

Step 5: *Number and size of dwellings*
In this step, the model defines the characteristics of the settlement. Firstly, the model defines the number of dwellings of the whole settlement; the number of dwellings is defined, for each size category of dwelling (1-room, 2-room, etc.). The proportion of dwelling sizes is based on Stat1990, a statistical analysis of the existing building stock of the owners of the case study after 1990, e.g., number of dwellings, dwelling room size, dwelling surface (see Table 4.8). Stat1990 serves as a reference scenario of future development of the building stock and it is based on the past activity of owners between the period 1990-2020. For more detail refer to Table A.20 in the appendix. The model uses the results of Stat1990 for each owner in order to create the new settlements, buildings and dwellings, assuming that the owners will continue building in the near future (next 30 years) following their construction patterns of the last 30 years.
The model generates new dwellings with many combinations of sizes but following the statistics Stat1990 in a specific order. For each dwelling size category, the number of dwellings is generated (number of 1-room, 2-room, etc.); the surface of each dwelling (m^2) is defined by sampling a Gaussian distribution with a specific mean, standard deviation, minimum and maximum for each dwelling size category. The model continues generating new dwellings until the sum of their surfaces exceeds the total effective surface of the settlement. For the last dwelling, the surface is set accordingly to fit the total effective surface. In this step, the following quantities are defined:

- Number of dwellings according to size (number of rooms)
- Living surface of each dwelling (m^2)

Step 6: *Number of buildings*
We assume that the geometry of the plot allows the architects to freely position the buildings in the plot while respecting border distances and any other parcel constraints. Based on the data analysis of the existing building stock of the collaboration partners, we estimated the range and the average of the floor area of a building. The model also assumes that all floors have the same floor area. The model assigns the number of buildings within the settlement based on the statistical analysis of the existing building stock after 1990 (Stat1990). Once the number of buildings is chosen, the model distributes the dwellings to the buildings; this allows to calculate the total effective surface of the buildings. In this step, the model has defined the number of buildings of the settlement and the number of dwellings per building.

Table 4.8 – Model design - Building stock data 1990-2020 (Stat1990) - Key figures

Stat1990					
Key figures					
Owner	**Variable/Characteristic**	**Minimum**	**Maximum**	**Mean**	**Std. Dev.**
ABZ	Number of dwellings = 1291				
	Number of dwellings per settlement	16.0	277.0	175.3	74.2910
	Number of dwellings per building	2.0	27.0	13.4	4.5990
	Number of buildings per settlement	1.0	20.0	13.9	4.8990
	Dwelling floor	0.0	6.0	3.2	1.4290
	Dwelling surface (m^2)	30.5	149.8	93.2	23.5279
	Square meters per room (m^2/room)	16.5	36.3	24.0	2.28129
	Number of rooms	1.0	6.5	3.9	1.1196
	Net rent (CHF)	348.0	2181.0	1324.5	289.0341
	Net rent per square meter (CHF/m^2)	10.4	20.9	14.5	1.7102
	Gross rent (CHF)	406.0	2338.5	1447.3	298.8014
SCHL	Number of dwellings = 701				
	Number of dwellings per settlement	8.0	233.0	117.1	85.4220
	Number of dwellings per building	4.0	79.0	29.7	20.3150
	Number of buildings per settlement	1.0	10.0	5.0	3.7670
	Dwelling floor	-1.0	5.0	2.0	1.4860
	Dwelling surface (m^2)	35.4	163.1	87.7	18.7462
	Square meters per room (m^2/room)	17.9	45.7	25.9	3.01059
	Number of rooms	1.0	5.0	3.4	0.8140
	Net rent (CHF)	428.0	2859.0	1400.8	311.5824
	Net rent per square meter (CHF/m^2)	9.7	21.0	16.0	1.5000
	Gross rent (CHF)	593.0	3109.0	1538.6	334.4272
Mobiliar	Number of dwellings = 2968				
	Number of dwellings per settlement	6.0	225.0	65.3	53.1720
	Number of dwellings per building	1.0	57.0	16.2	10.7990
	Number of buildings per settlement	1.0	13.0	4.9	3.1850
	Dwelling floor	0.0	9.0	2.1	1.6440
	Dwelling surface (m^2)	16.0	189.0	90.7	25.2817
	Square meters per room (m^2/room)	15.7	98	25.1	4.15853
	Number of rooms	1.0	6.5	3.6	0.9720
	Net rent (CHF)	360.0	4540.0	1654.7	446.7683
	Net rent per square meter (CHF/m^2)	8.4	33.1	18.9	4.4796
	Gross rent (CHF)	400.0	4840.0	1882.0	486.2547

Dwelling size							
Owner	**Number of rooms**	**Frequency**	**Percent**	**Min m^2**	**Max m^2**	**Mean m^2**	**Std. Dev.**
ABZ	1-1.5 room	38	2.9%	31	55	41	5.8
	2-2.5 room	240	18.6%	38	76	61	6.7
	3-3.5 room	353	27.3%	58	102	86	7.0
	4-4.5 room	465	36%	90	130	106	6.5
	5+ room	195	15.1%	115	150	126	8.4
	Total	*1291*	*100%*				
SCHL	1-1.5 room	1	0.1%	35	35	35	
	2-2.5 room	94	13.4%	50	91	57	7.0
	3-3.5 room	272	38.8%	54	128	80	9.8
	4-4.5 room	290	41.4%	88	125	99	6.2
	5+ room	44	6.3%	113	163	125	7.9
	Total	*701*	*100%*				
Mobiliar	1-1.5 room	125	4.2%	16	98	35	16.2
	2-2.5 room	550	18.5%	32	114	62	11.7
	3-3.5 room	1129	38%	47	147	89	9.9
	4-4.5 room	1015	34.2%	79	158	109	10.7
	5+ room	149	5%	95	189	135	19.7
	Total	*2968*	*100%*				

Source: Own analysis based on the partner's data

Table 4.9 – Model design - Building stock data 1990-2020 (Stat1990) - Number of buildings per settlement

Stat1990 - Number of buildings					
Owner	**Frequencies**	**Min**	**Max**	**Mean**	**Std. Dev.**
ABZ	13	1	20	13.93	4.899
Mobiliar	70	1	13	4.86	3.185
SCHL	15	1	10	5.04	3.767
Source: Own analysis based on the partner's data					

Step 7: *Additional characteristics*

The model has to assign some important characteristics to the settlement, buildings and dwellings. All new buildings are not heritage protected. The construction year is assigned as the year when the new construction owner action is completed and the dwellings are available to the market; this means 18 ticks after the beginning of the project. The reference year is identical to the construction year, unless the settlement was demolished and a new settlement was constructed in its place. In this case, the reference year is considered to be the construction year of the reconstructed settlement. Moreover, a new construction has never undergone a renovation (R), transformation (T) or demolition (D). In this step, the following is defined:

- Heritage protected settlement: Decision whether the settlement is heritage protected; in the case of new construction, there is zero probability having a settlement that is heritage protected.
- Construction year = The year, at time step, when the dwellings enter the housing market.
- Reference year = Construction year
- Renovation, Transformation and Demolition years = R1, R2, R3, R4, T, D = empty

Step 8: *Investment Cost*

The construction cost is calculated based on a fixed construction cost per square meter of total effective surface (equation 4.8a). Based on the data analysis of the case study and the workshops, an average construction cost per TES and owner has been defined (see Table 4.10). The investment cost is calculated as the sum of the land cost and construction cost (equation 4.8b). In addition, the model calculates the insurance value of the settlement; it is set at that time step equal to the construction cost (equation 4.8c).

$$Construction\_cost = Construction\_cost\_per\_surface \times TES \tag{4.8a}$$

$$Investment\_cost = Land\_cost + Construction\_cost \tag{4.8b}$$

$$Insurance\_value = Construction\_cost \tag{4.8c}$$

Table 4.10 – Model design - Building stock model - Construction cost by owner

New construction cost per square meter of TES (CHF/m^2)	
Owner	**Construction cost (CHF/m^2)**
ABZ	3,600
SCHL	4,000
Mobiliar	4,500
Source: Own analysis based on partner's data	

Continuing with the example mentioned in step 4, let us assume that the owner is ABZ. The land is 3,000 m^2 and was sold at a price of 1,100 CHF/m^2, which translates into 3.3 million CHF; the new settlement has a total effective surface of 2,880 m^2. For ABZ, based on Table 4.10, new construction cost per TES is 3,600 CHF/m^2; the total construction cost is 10,368,000 CHF (= 3,600 CHF/m^2 x 2,880 m^2), the total investment cost is 13,668,000 CHF and the insurance value is 10,368,000 CHF. In this step, the model has defined the following:

- Construction cost
- Investment cost
- Insurance value

Step 9: *Rent pricing*

Housing cooperatives are non-profit oriented owners; the rental income is calculated to cover the costs (Sotomo and FSO, 2017; Wüest Partner, 2019*e*; Kemeny, 1995). Some cantons and municipalities are setting specific rules for the rent calculation of housing cooperatives and demand that the rental income should cover land, construction and maintenance costs allowing a small margin for profit. For example, the city of Zurich gives detailed instructions of what costs should be included in the calculation of the cost-covering rent and when it is accepted to adjust the rents (Stadt Zürich, 2009). For more details regarding the rent adjustment, refer to the rent update function in section 4.6.1.9. The rent is calculated yearly on the basis of the total investment costs of all apartments of a settlement. These regulations shall apply to all apartments of non-profit housing construction. Each owner follows a different way of funding its projects.

- ABZ acquires every year a rental income from renting its dwellings; however, there might be vacant or empty dwellings. Actual rental income (ARI) of each settlement is the sum of the yearly rents from all occupied dwellings of the settlement (equation 4.9).

$$\sum_{s=1}^{S} ARI_s = \sum_{s=1}^{S} Net\_rent\_yearly_s \tag{4.9}$$

  ABZ is financing new construction projects with own capital. The needed rental income (NRI) of a new settlement has to cover the total cost (TC) of the new construction; NRI might be different than the ARI.

$$\sum_{s=1}^{S} NRI_s = Ref.rate \times \sum_{s=1}^{S} Investment\_cost_s + 3.75\% \times \sum_{s=1}^{S} Insurance\_value_s$$
$$= \sum_{s=1}^{S} TC_s \quad (4.10a)$$

$$NRI_{new} = \sum_{s=1}^{S+1} TC_s - \sum_{s=1}^{S} ARI_s \quad (4.10b)$$

ABZ in order to calculate the net rent of the newly constructed settlement calculates the needed rental income (NRI) (see equation 4.10a) based on all settlements (s=S) and not for each individual settlement. The factors taken into consideration are the investment cost, the insurance value of all settlements and the reference rate (FOH, 2021*b*). The formula for calculating the needed rental income of the new settlement is described in equation 4.10b.

- SCHL is financing a new construction project with a mortgage loan (1^{st} rank mortgage from a bank and 2^{nd} rank mortgage, usually CCL[19]) and the rest is covered by equity capital. Mortgage loans cover 80% of the total investment cost, the remainder 20% is covered by equity capital. SCHL calculates the rental income for a newly constructed settlement at the basis of the settlement; the needed rental income (NRI) has to cover the total investment cost (equation 4.11). The factors taken into consideration are the interest mortgage rate, interest on equity, depreciation and general expenses for maintenance and renovations. In the following formula the needed rental income (NRI) for SCHL is calculated, with "a" representing a percentage of the investment cost, which includes the above-mentioned factors. The full formula cannot be disclosed.

$$NRI = a \times Investment\_cost \quad (4.11)$$

- Mobiliar is a profit-oriented investor looking for profitable investments. It is a large-scale investor with a diversified portfolio[20] and has a strong knowledge of the housing

[19]The CCL was founded in 1990 by the umbrella organizations of public housing, with the support of the Federal Housing Office. The purpose of CCL is to acquire funds for the financing of housing. It does this by continuously recording the capital needs of its members and periodically issuing loans. The loans are in the form of normal mortgages at a fixed rate for a specified period. In fact, the CCL functions like a bank, since it can offer loans at particularly advantageous rates for the reason that the loans are guaranteed by the Confederation within the framework of the Housing Act. Since its creation, the CCL has issued 82 bonds with a total volume of almost 6.48 billion CHF. Currently, the volume of outstanding loans amounts to approximately 3.1 billion CHF. The current number of financed housing units is approximately 33'000. The financing is carried out according to the normal sequence of ranks; first is the first-ranking mortgage; this is followed by the CCL loan share. The remainder is covered by equity. In order to be eligible for a CCL loan, a series of criteria has to be met; borrowers have to be companies of public utility; equity capital has to be at least 20% of the investment cost, etc. Source: http://www.egw-ccl.ch

[20]Mobiliar is an example of an institutional investor, who after 2000 and especially after the financial crisis in

market. Mobiliar aspires to maximize the yearly returns of its settlements. However, average returns are tolerated as well[21]; the minimal target return is 3%, average returns range from 5% to 7%, and many of its settlements achieve returns even higher than 8% and 10%. For targeted and desired returns for owners in Switzerland, see the FSO report (Schüssler et al., 2005). To calculate the rental income of Mobiliar, the model uses a financial plan (RI as calculated in Table 4.11). The main sources used for the financial plan are: (De Best, 2021; Favarger and Thalmann, 2007; Riser et al., 2017). The funding of a new construction project is 100% from equity capital; the total investment cost is covered by own capital. The yearly cost of the new settlement is estimated and it is calculated based on several factors, e.g., renovation funds, insurance, property taxes, opportunity cost of equity capital, administration, operation and maintenance. Below is an example of a financial plan of Mobiliar (Table 4.11); an new construction project example is presented, starting with the choice of land, designing the settlement's main characteristics, estimating the yearly costs and calculating the rental income, net rent per square meter and yearly return of the settlement.
Once the yearly rental income for the new settlement is calculated, the model calculates the yearly net rent for each dwelling. Firstly, it calculates the yearly net rent per square meter of the settlement (equation 4.12a), afterwards, it calculates the yearly net rent of every dwelling by multiplying it with the floor area of the dwelling (equation 4.12b).

Yearly net rent calculation:

$$Net\_rent\_per\_surface = \frac{NRI}{TES} \tag{4.12a}$$

$$Net\_rent = Net\_rent\_per\_surface \times Dw\_surface \tag{4.12b}$$

The monthly net rent is calculated for each dwellings; the gross rent is the sum total of the net rent and the additional cost that covers the expenses for heating and hot water of each dwelling (equation 4.13c). The additional cost is estimated after analysing the case study data. The model is using the average value of additional cost per square meter based on the available data of the existing building stock per partner[22]. For ABZ, the value of the additional cost per dwelling surface is 15.6 CHF/m^2, for SCHL it is 21.6 CHF/m^2, for Mobiliar 30 CHF/m^2. The gross rent of Mobiliar dwellings can be higher than this calculation if the local housing market allows it. The final rent is set by the market, it is a result of supply and demand and

2007 and the introduction of negative interest rates by the Swiss National Bank, started being more interested in investing in real estate assets (Wüest Partner, 2021*e*).

[21]Although Mobiliar is targeting for a minimum return between 2% and 3%, it can also accept lower returns especially for settlements that are located in spots with high potential of increase in the rents over the next years.

[22]The additional cost in this model is a yearly fixed cost per living surface, different for each owner. This is a simplification for the model. The additional cost of dwellings is not identical to all settlements; it varies depending on the age, location, heating system, age of the heating system of the settlement.

it depends on the rental prices of similar residential units in the area. This model does not conduct valuation of a real estate asset depending on its location, and thus, accepts the rent as calculated in equation 4.13c.

Monthly net rent calculation:

$$Net\_rent = \frac{Net\_rent\_yearly}{12months} \tag{4.13a}$$

$$Additional\_cost = Add\_cost\_per\_surface \times Dw\_surface \tag{4.13b}$$

$$Gross\_rent = Net\_rent + Add\_cost \tag{4.13c}$$

In the case of the housing cooperatives, as mentioned above the rent should cover the costs. It could be that for a specific project, the total investment cost for a new settlement is high (usually because the land was expensive). Since the rent is calculated to cover the cost, the rent would have to be high as well. However, housing cooperatives aim to offer affordable dwellings to the market (Sotomo and FSO, 2017; ABZ, 2021; SCHL, 2021). To prevent rents being high, cooperatives introduce a cap net rent, this way they make sure to keep the rent affordable. In the case the rent calculated to cover the costs is high, they use equalisation funds[23] in order to keep the rent low.
In this model, SCHL uses a cap net rent of 220 CHF/m^2/year or a cap of 18.3 CHF/m^2/month; ABZ uses a cap of 200 CHF/m^2/year or a cap of 16.7 CHF/m^2/month. The rent cannot exceed the cap value of each owner; if the calculated rent is higher than this value, the rent is set equal to the cap value and the remaining amount is covered by the equalisation funds. Mobiliar doesn't have a cap value for the calculation of the rent.
The model set up the net and gross rent for the newly constructed settlement. Once the dwellings are available in the housing market, households apply to rent them. Although the demand is very high in Switzerland, there are some dwellings that remain vacant. As described in chapter 2, housing cooperatives have very low vacancy rate. However, some dwellings might remain vacant or intentionally kept empty in order to accommodate households for a future renovation, demolition, transformation, etc. This results into a decrease of the rental income. The yearly actual rental income (ARI) expresses the sum total of all occupied (not vacant, not empty) dwellings and it is calculated in equation 4.14a.

Yearly return calculation:

$$ARI = \sum_{d=1}^{D} Net\_rent\_yearly_d - vacancies \tag{4.14a}$$

$$Return(\%) = \frac{ARI}{Investment\_cost} \tag{4.14b}$$

[23]Equalisation funds refers to the french fonds de péréquation.

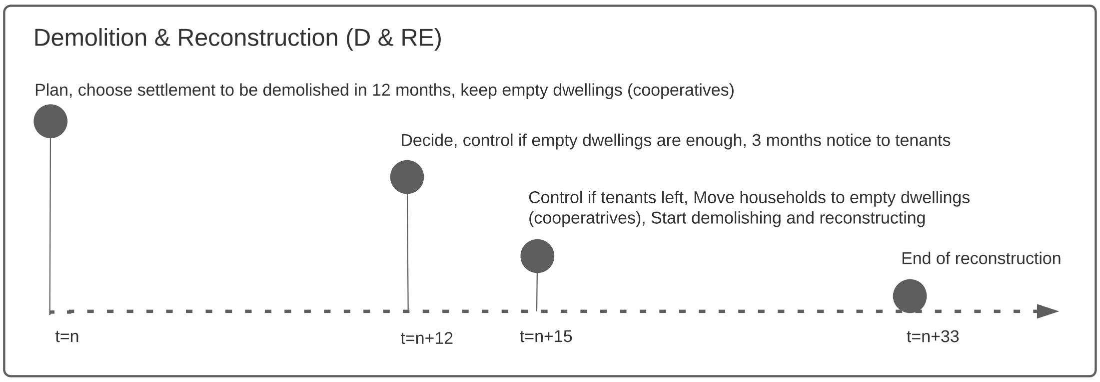
In this step the model has defined the following:

- Rental income of the settlement (CHF)
- Net rent for each dwelling (CHF) and (CHF/m^2)
- Gross rent for each dwelling (CHF) and (CHF/m^2)
- Yearly return of each settlement

Table 4.11 – Model design - Building stock model - Financial plan of profit-oriented investor

Financial plan of Mobiliar			
Variable	**Value**	**Range of values**	**Calculation**
Settlement characteristics			
Land surface (LS) (m^2)	5,000	500 – 15,000	Random choice of land surface within range
Land price (CHF/m^2)	3,000	500 – 4,000	Random choice of land price/m^2 within range
Land cost (CHF)	15,000,000		=LS x land price per m^2=5,000 x 3,000
Zone choice (Floor area ratio FAR)			Choice of Zone and as a result FAR
FAR W2		60%	
FAR W3		90%	
FAR W4		120%	
FAR W5		165%	
FAR W6		205%	
FAR Z5		200%	
FAR Z6		230%	
FAR Z7		260%	
Choice of FAR (based on zone)	120%		Assumption W4 -> FAR=120%
Total gross surface (TGS) (m^2)	6,000		=LS x 120%=5,000 x 120%
Total effective surface (TES) (m^2)	4,800		= 0.8 x TGS = 0.8 x 6,000
Cost calculation			
Construction cost/m2 (CHF/m^2)	4,500	4,500	Fixed cost for each owner
Construction cost (CC) (CHF)	21,600,000		= CC/m2 x TES = 4,500 x 4,800
Total cost (land & construction) (CHF)	36,600,000		= 15,000,000 + 21,600,000
Funding (CHF)	36,600,000	100% equity	
Yearly expenditure / cost (CHF)			
Renovation funds (% of CC)	216,000	1.00%	= 216,000 x 0.01
Insurance (% of CC)	108,000	0.50%	= 216,000 x 0.005
Property tax (% of IC)	54,900	0.15%	= 36,600,000 x 0.015
Opportunity cost of equity capital (% of IC)	732,000	2.00%	= 36,600,000 x 0.02
Calculate Income	1,110,900		
Administration (% of Income)	44,436	4.0%	= 1,110,900 x 0.04
Operation (% of Income)	22,218	2.0%	= 1,110,900 x 0.02
Maintenance (% of Income)	111,090	10.0%	= 1,110,900 x 0.10
Vacancies 4% (% of Income)	44,436	4.0%	= 1,110,900 x 0.04
	222,180		
Rental Income (RI) (CHF)	1,333,080		= 222,180 + 1,110,900
Net rent/m2 (CHF/m^2) yearly	277.7		= 1,333,080 / 4,800
Net rent/m2 (CHF/m^2) monthly	23.1		= 277.7 / 12
Yearly return	3.6%		= 1,333,080 / 36,600,000
Source: Own work			

4.6.1.10.2 Demolition and Reconstruction



In most cases, the demolition of a settlement is decided when the settlement is very old, it has been renovated several times, its condition is deteriorating or if it was built according to zoning regulations of the time, and it could be under-exploiting the current floor area ratio (FAR). Usually in old settlements there is the potential to increase the total building surface by demolishing and reconstructing, which allows to build according to the updated land zone regulations (higher FAR). The latter implies that there is a smaller or larger densification potential as well. If the total floor area could increase significantly, more people could be accommodated. As a result, density would increase in terms of number of people per land surface (Stadt Zürich, 2015, 2019). Some rare cases exist for profit-oriented investors that decide to demolish a young building to build a new one that will allow them to increase the financial return; this case is not taken into consideration in this model.

The demolition function describes the decision-making processes of owners to demolish an existing settlement and construct in its place a new settlement. The action of demolition is directly connected to the action of reconstruction; when an owner decides to demolish, the model automatically activates the action of reconstruction as well. According to the demolition data from the case study owners, the demolition rate is relatively low. However, because of their ageing building stock, land scarcity and the promotion of densification of the existing stock (Stadt Zürich, 2015; Stadt Zürich, 2020), we expect it to increase in the near future.

First, the model controls if the owner has the capacity to start a demolition / reconstruction project (D and RE). If a project can start, the model starts running the eligibility test to find the eligible settlements for demolition and finally chooses the settlement to be demolished. For the demolition to start, all households have to move out and the dwellings have to be empty. In the case of housing cooperatives, the households forced to move because of the demolition will be accommodated to a substitute dwelling of the same owner, and thus, the owner has to ensure having enough available dwellings before the demolition starts. In the model, responsible for that is the empty dwelling list function (section 4.6.1.8). This function is then activated, and for the next 12 ticks, is gathering enough dwellings to cover the needs of the households that have to move during construction works. A list is created that comprises of a sufficient number of dwellings at least equal to the number of demolished dwellings (only for housing cooperatives). In the next step, the decision for the demolition is taken. The tenants are informed that they have to move out in three months. Three ticks later, the model controls if the settlement has been evacuated, moves the households to their substitute dwelling and removes the dwellings from the housing market. Subsequently, the demolition and reconstruction can start; 1.5 years later, the reconstruction is finished and the new dwellings are entering the housing market of the model's system.

Step 1: *Capacity check*
First the model checks whether the owner has the capacity to reconstruct and to demolish (see section 4.6.1.5, Table 4.2). If the result of the capacity control is positive, the owner can start planning the demolition; if not, the owner has to wait. At time t = 0, all owners can start a demolition project.

Step 2: *Choice of settlement*
The model has to select the settlement to be demolished. All the settlements of the owner go through the eligibility test with a set of pass/fail criteria and the result is a list of eligible settlements. The winner settlement is chosen based on a scoring system. Factors like the building's state and the age are decisive in being chosen for demolition (Wüest Partner, 2020*k*; Sartori et al., 2008; Elliott, 2008).
The criteria are the following:

- Cultural heritage protection: If the settlement is protected, then it cannot be demolished.
- Type of the last intervention and years that have passed since: If the last owner action performed to the building was transformation, at least 45 years (20 years for Mobiliar) have to pass for the settlement to be eligible for demolition; if the last owner action was renovation, at least 30 years (20 years for Mobiliar) have to pass for the settlement to be eligible for demolition (Sartori et al., 2008; Gerheuser, 2004; Volland et al., 2020; Riser et al., 2017; CRB, 2012)(FSO and case study analysis, see chapter 2).
- Age of the building: If the age is less than 50 years (30 years for Mobiliar), the building is not eligible for demolition. Based on data from the partners, the average age for a demolition is 80 years (Gerheuser, 2004; Volland et al., 2020).

The settlements that are eligible compete based on a scoring system. The one with the highest score gets demolished. If there is a tie, the settlement with the lowest net rent per square meter is chosen.

- Age of the building: For cooperative settlements, if 50 < age < 70 years then points = 1, if age ≥ 70 years then points = 2, and for Mobiliar if 30 years < age < 60 years then points = 1, if age ≥ 60 years then points = 2.

- Number of past interventions: The more interventions performed to the building in the past (number), the more probable it is for the building to be selected. If number < 2 then points = 0, if number = 2 the points = 1, if number > 2 interventions then points = 2.
- Net rent per living surface: For cooperative settlements, if rent < 10 CHF/m^2 then points = 2.5, if 10 ≤ rent ≤ 15 CHF/m^2 then points = 1.5, if rent > 15 CHF/m^2 then points = 0. For Mobiliar if rent < 10 CHF/m^2 then points = 2.5, if 10 ≤ rent ≤ 18 CHF/m^2 then points = 1.5, if rent > 18 CHF/m^2 then points = 0.

Step 3: *Planning decision step*

After step 2, the settlement to be demolished is chosen, the planning phase can start but the demolition cannot start yet, as the cooperatives have to assure that they can offer a substitute dwelling to their tenants. Mobiliar does not provide its tenants with an alternative dwelling, it just gives a three month notice to the tenants and proceeds with the demolition (see empty dwelling list function, section 4.6.1.8). For coding simplicity reasons, all three owners follow the same time steps. At this stage, the empty dwelling list function is activated that creates the necessary empty dwellings. The model runs for twelve time steps and checks if there are enough empty dwellings for the cooperative households in need for a substitute dwelling. If not, the model keeps gathering empty dwellings until there are enough; if the number of empty dwellings is sufficient, the decision phase can start.

Step 4: *Decision phase*

In the decision phase, owners announce to tenants that the settlement will be demolished and proposes the empty substitute dwellings to the tenants (cooperative dwellings). The model assumes that all households accept the relocation offer and that they will not move back to the old dwellings after the completion of the reconstruction. The households move out in three time steps, whereupon the demolition starts. The demolition decision step coincides with the planning, deciding and starting phase of the reconstruction.
In the previous steps, the model has decided:

- Whether the owner is able to demolish.
- The settlement to be demolished.
- When to start the demolition and the reconstruction (set timer).

Step 5: *Reconstruction settlement*

The reconstruction is completed 18 months after the beginning of the works, counting from the time all households moved out and the dwellings are empty. The model decides about the characteristics of the new settlement. As described above, demolition takes place mainly in order to rejuvenate and densify the building stock; the model assumes that after a demolition, the reconstructed settlement has more dwellings than before (Stadt Zürich, 2015; Riser et al., 2017; Stadt Zürich, 2020). Based on past demolition and reconstruction activity of the owners, we estimated that on average the number of dwellings of the reconstructed settlement is 55% higher than the before[24]. The statistical analysis of past reconstructions allows the model to calculate the number of dwellings sampled from a truncated Gaussian distribution with fixed mean, standard deviation, min and max values (*mean: 155*, *SD*: 20, *min*: 120, *max*: 250). This is also verified by other sources such as (Stadt Zürich, 2015; Riser et al., 2017). The number of rooms and floors of the dwelling are randomly sampled according to their distribution in the initial stock. Given the dwelling size, its surface is sampled from a truncated normal distribution using the statistics of the initial stock (Stat1990), as described in step 5 of new construction. In this step the model has defined the following:

- The empty dwellings have been gathered.
- The settlement to be demolished has been removed from the market.
- The characteristics of the reconstructed settlement have been selected, e.g., number of dwellings, size of dwellings, floors, etc.

Step 6: *Rent pricing*

In the case of a demolition and reconstruction there are fixed demolition-reconstruction costs per owner and the calculation follows the same path as in the previous section "New Construction". Housing cooperatives calculate the needed rental income (NRI) to cover the total cost, allowing a small margin of profit. First, the model calculates the total cost of the demolition and reconstruction, based on the fixed cost per reconstructed effective surface (CHF/m^2), provided by the property owners (see Table 4.12). Knowing the total effective surface (defined in the previous step 5), the model calculates the demolition-reconstruction cost (equation 4.15a). Next, it estimates the residual value of the real estate asset (pre-existing land and building) in equation 4.15b. The model assumes a 1% yearly depreciation rate since its construction.

$$Reconstruction\_cost = TES \times Reconstruction\_cost\_per\_surface \tag{4.15a}$$

$$Residual\_value = Initial\_investment\_cost \times 0.99^{settlement\_age} \tag{4.15b}$$

$$Investment\_cost = Reconstruction\_cost + Residual\_value \tag{4.15c}$$

[24]We based this calculation on the number of dwellings instead of the total floor area of the settlement because of lack of data about the old building. In general, data regarding demolitions on a national level are quite limited. Usually, there is information about the number of yearly demolitions in terms of number of dwellings but no reliable information about the age of the demolished building at the time of the demolition. Therefore, we use the results of the case study demolition history.

Table 4.12 – Model design - Building stock model - Demolition cost by owner

Reconstruction costs per square meter of TES (CHF/m^2)	
Owner	**Cost (CHF/m^2)**
ABZ	3,800
SCHL	4,700
Mobiliar	4,500
Source: Own work based on project partners	

The model calculates the yearly needed rental income (NRI); the calculation of NRI is done according to the respective formula of each owner, as described in detail in the previous section (new construction function, section 4.6.1.10.1). In the case of housing cooperatives, NRI has to cover the total demolition-reconstruction cost. Once the needed rental income is calculated, the yearly net rent of the dwellings is calculated (equations 4.16a, 4.16b). Next follows the calculation of the monthly net and gross rent (equations 4.16c, 4.16e).

Yearly net rent calculation:

$$Net\_rent\_per\_surface = \frac{NRI}{TES} \tag{4.16a}$$

$$Net\_rent = Net\_rent\_per\_surface \times Dw\_surface \tag{4.16b}$$

Monthly net rent calculation:

$$Net\_rent = \frac{Net\_rent\_yearly}{12 months} \tag{4.16c}$$

$$Add\_cost = Add\_cost\_per\_surface \times Dw\_surface \tag{4.16d}$$

$$Gross\_rent = Net\_rent + Add\_cost \tag{4.16e}$$

The rent calculated above is the rent the dwelling is offered at the market. However, to calculate the actual rental income (ARI) of property owners we have to take into consideration potential vacancies, dwellings kept empty, etc. (equation 4.17a). The rental income depends on the occupied dwellings and their rental price (see equation 4.17b).

Yearly return calculation:

$$ARI = \sum_{d=1}^{D} Net\_rent\_yearly_d - vacancies \tag{4.17a}$$

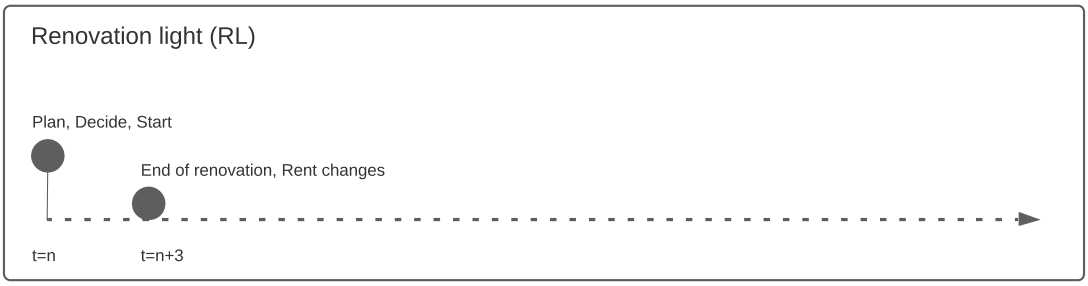
$$Return(\%) = \frac{ARI}{Investment\_cost} \tag{4.17b}$$

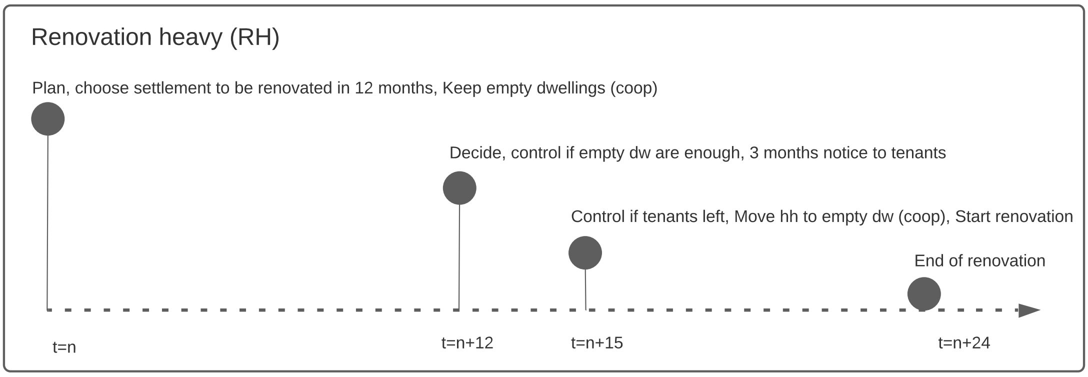
In this step, the model defines the following:

- The rental income of the reconstructed settlement
- The net rent of the reconstructed dwellings

- The gross rent of the reconstructed dwellings
- The yearly return of the reconstructed settlement

4.6.1.10.3 Renovation





The renovation function describes the decision-making processes of owners to renovate an existing settlement. According to SIA, *a renovation describes the essential changes of components of building elements or the whole building, in order to adapt them to the modern requirements. The aim is to ensure the development of the building.* (SIA, 2003*a*). This function is divided into two categories: (1) light renovation and (2) heavy renovation.

Light renovation refers to a small-scale renovation, e.g., windows replacement, mini bathroom makeover, cosmetic kitchen renovation, change of pipes. In the model, its duration is set to three months and the tenants can stay in their dwelling while the renovation works take place. After a light renovation is over, the qualitative characteristics of the dwellings change and the net rent increases.

Heavy renovation refers to a large-scale renovation, e.g., floor surface change, kitchen-bathroom full renovation, insulation improvement and the combination of the above. In this case, tenants have to move out of their dwellings until renovation works are completed. The cooperatives offer their tenants substitute dwellings, Mobiliar announces to the tenants that they would have to move out after three months. Once the renovation works are completed, the qualitative characteristics of the dwellings change, and the net rent increases as calculated in the step 5 "Rent pricing". The duration of heavy renovation works is 9 months; during this time, the model removes the dwellings from the market.

Step 1: *Capacity check*

The model checks if the owner has the capacity to proceed with a renovation project; this depends on the yearly renovation capacity number(see section 4.6.1.5, Table 4.2). If the renovation project can start, the next step is to choose which settlement will be renovated.

Step 2: *Eligibility test*

In this step, the settlement to be renovated is chosen; there are two factors that influence the result: (1) the type of the last intervention (renovation, transformation, none) and (2) the years that have passed since the last intervention. Based on Table 4.13, first the model chooses the type of the next renovation and then the years that have to have passed since then. If the last intervention was none, or transformation, then the next renovation will be a renovation R1[25], and at least 40 years must have passed since; if the last intervention was R1, the next renovation will be R2 and at least 20 years must have passed since. The same applies for the second renovation R2 of a settlement and so on;for all possible combinations of past and future renovations refer to Table 4.13. Every year, the model checks all settlements for each owner and creates a list with the settlements that are eligible for renovation. The eligible settlements have to fulfil the two criteria mentioned above. In this step, the model creates a list per owner with all the eligible settlements for renovation.

Table 4.13 – Model design - Building stock model - Frequency of renovations

Renovation frequency depending on the last renovation type				
	Last intervention type			
	Today - Construction year (1st renovation R1 - Construction year) *	Today - R2 (2nd renovation R2 - 1st renovation R1)	Today - R2 (3rd renovation R3 - 2nd renovation R2)	Today - R3 (4th renovation R4 - 3rd renovation R3)
Years between renovations	40 years	20 years	20 years	20 years
Future renovation	R1, 1st renovation	R2, 2nd renovation	R3, 3rd renovation	R4, 4th renovation
** this applies for the transformations as well: Today - Transformation year (1st renovation - Transformation year)* *Source: own work*				

Step 3: *Renovation type*

The renovation status of each settlement has information about the type of past renovations and transformations (if any) and the year they took place. Depending on the past renovation,

[25] R1 refers to the first renovation that was performed to the building chronologically, R2 to the second, R3 to the third, etc. A settlement that was renovated only once in the past, has only R1 value; another settlement that has been renovated three times already, has R1, R2 and R3 values.

the model decides about the type of the future renovation (see Table 4.14). If the last renovation was a heavy renovation or transformation, the next one will be light. If the previous renovation was a light renovation, the model checks all previous renovations of the settlement. If the last two renovations were light, the next one will be heavy; if only the last renovation is light, then there is a 60% probability the next renovation to be light and 40% probability to be heavy. This is based on a thorough data analysis of past renovation activity of the owners of the case study. In this step, the model chooses the renovation type among heavy and light renovation.

Renovation type definition	
Previous renovation type	**Next possible renovation type**
Heavy renovation	100% light renovation
Transformation	100% light renovation
Light renovation	60% light renovation and 40% heavy renovation
Light renovation 2nd in a row	Heavy renovation
Source: own work	

Table 4.14 – Model design - Building stock model - Renovation type choice

Step 4: *Choice of settlement*

The model selects the settlement to be renovated among the eligible settlements from the list that was created in step 2. The winner settlement is chosen based on a scoring system: There are two criteria: (1) the average net rent per floor area of all dwellings of the settlement and (2) the years that have passed since the last intervention. More specifically it is chosen based on:

- Net rent per floor area: For the cooperative buildings: if rent < 10 CHF/m^2 then points = 2.5, if 10 ≤ rent ≤ 15 CHF/m^2 then points = 1.5, if rent > 15 CHF/m^2 then points = 0. For Mobiliar, if rent < 10 CHF/m^2 then points = 2.5, if 10 ≤ rent ≤ 18 CHF/m^2 then points = 1.5, if rent > 18 CHF/m^2 then points = 0.
- The years that have passed since the last intervention: If 15 < years passed < 30, then points = 0; if years passed ≥ 30, then points = 1 .

Step 5: *Rent pricing*

For each owner and renovation type, there is a fixed renovation cost per floor area. According to Table 4.15, the model calculates the total renovation cost. The renovation cost is calculated by multiplying the fixed cost per square meter depending on the renovation type with the floor area (TES) (equation 4.18).

$$Renovation\_cost = TES \times Renovation\_cost\_per\_surface \tag{4.18}$$

Table 4.15 – Model design - Building stock model - Renovation cost by owner

Renovation cost per square meter of TES (CHF/m^2)		
Owner	**Light renovation cost (CHF/m^2)**	**Heavy renovation cost (CHF/m^2)**
ABZ	600	2,300
SCHL	600	2,500
Mobiliar	700	2,700
Source: Own work and project partners		

In order to calculate the new net rent of the renovated settlement for the cooperatives (Simonot, 2020), the model uses Fracheboud method[26]. Based on that, the costs caused by renovations are considered, at a rate of 50-70%, as added value. The model calulates the added value as a result of a renovation as 60% of the renovation cost (equation 4.19).

$$Added\_value = 0.6 \times Renovation\_cost \tag{4.19}$$

The Swiss Federal Law on Real Estate provides that the owner, after an investment for renovation works to a building, may charge to the rent: (1) amortisation cost, (2) the interest on invested capital cost and (3) new maintenance costs. Specifically, the model estimates the updated rent with: (1) amortisation cost depends on the life cycle of the renovation works (see equation 4.20b, we assume 30 years); (2) the interest on the capital cost corresponds to the cost of the works with added value, multiplied by the current reference mortgage rate at the time (tick) of the increase increased by half a point (0.5%) (see equation 4.20a); (3) the future maintenance of the new installations corresponds to 10% of the total of the depreciation and interest on capital cost (equation 4.20c). The yearly rent increase for the whole settlement is calculated in equation 4.20d.

Yearly rent increase calculation, according to Fracheboud method:

$$Capital\_cost = Added\_value \times (Ref.rate + 0.5)/2 \tag{4.20a}$$

$$Amort\_cost = \frac{Added\_value}{30 years} \tag{4.20b}$$

$$Maint\_cost = 0.1 \times (Capital\_cost + Amort\_cost) \tag{4.20c}$$

$$Rent\_increase = Capital\_cost + Amort\_cost + Maint\_cost \tag{4.20d}$$

After calculating the yearly rent increase for the whole settlement (with D number of dwellings), the model calculates the rent increase for each dwelling based on its surface (equation 4.21a). At the time the renovation is complete, the new increased rent is calculated (equation 4.21b), and the dwellings enter the market and are available for rent.

[26]ALSOCA, source: https://www.asloca.ch/calculateur-de-loyer/?q=node/157

Monthly net rent calulation:

$$Rent\_increase\_per\_surface = \frac{Rent\_increase}{TES} / 12 months \tag{4.21a}$$

$$Net\_rent = Rent\_increase\_per\_surface \times Dwelling\_surface + Old\_net\_rent \tag{4.21b}$$

This is how the model calculates the rent for all cooperative dwellings; Mobiliar updates the dwelling rent by choosing the maximum value between two values: (1) the net rent calculation as calculated for the cooperatives and (2) the maximum net rent/m^2 of a settlement in the same location (based on the postcode). The model assumes that Mobiliar aims to reach the market price and assumes that it will be the maximum value of all settlements in the same region[27]. If there is no other settlement in the region, the updated rent is chosen as follows: in the case of a light renovation, the new rent is defined as the maximum value between the above calculation (equation 4.21b) and 1.3 times the old rent (before the renovation); in the case of a heavy renovation, the updated rent is defined as the maximum value between the above calculation (equation 4.21b) and 1.7 times the old rent (before the renovation). This is based on the statistical analysis of the owners of the case study where on average a 30% increase in rent was observed after a light renovation and a 70% increase after a heavy renovation. In this step, the new updated, after the renovation, net rent is calculated for each dwelling. Once the renovation works are over, the dwellings are available for rent in the market. Most of them get occupied soon as the demand is high, however, there might be some vacant or empty. As a result, there is a loss of rental income, and the actual rental income (ARI) is calculated as in equation 4.22a. The yearly financial return is estimated based on the actual yearly rental income (equation 4.22c).

Yearly rental income and return calulation:

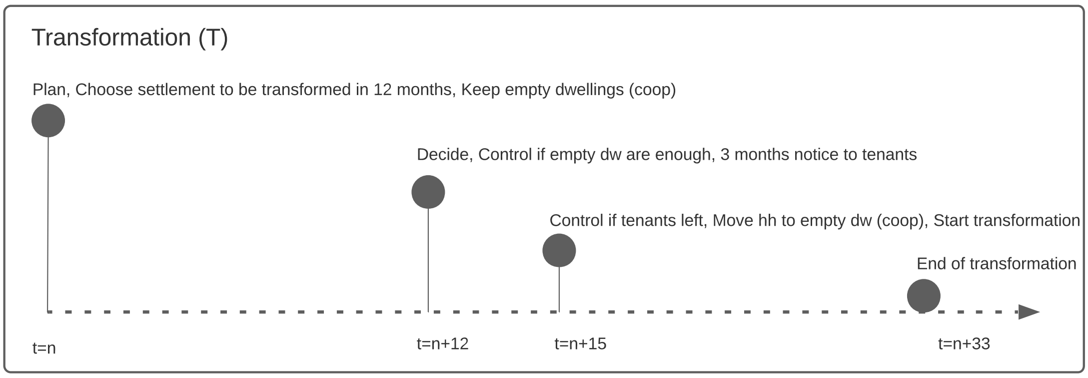
$$ARI = \sum_{d=1}^{D} Net\_rent\_yearly_d - vacancies \tag{4.22a}$$

$$Investment\_cost_t = Investment\_cost_{t-1} + Added\_value \tag{4.22b}$$

$$Return(\%) = \frac{ARI}{Investment\_cost} \tag{4.22c}$$

[27]There are many valuation methods for real estate assets (Pagourtzi et al., 2003; Kahr and Thomsett, 2005). The target was to compare the rents of the dwellings with equivalent rental units (centrality, size, view, age, etc.) located in the same place (postcode). However, after analysing data from WüstPartner it was very difficult to acquire the necessary information that would allowed to relate the postcodes of all Switzerland and the qualitative characteristics of dwellings. As a result, this is done only by using the data for the existing dwellings of Mobiliar. In the future, this could be enriched.

4.6.1.10.4 Transformation



The transformation function describes the decision-making processes of owners to transform an existing settlement. In reality, this owner action describes a form of heavy renovation where the main structure of the building is kept intact but most of the construction elements and dwelling floor plans are changed. Transformation is similar to a total renovation. According to SIA: *Total renovation of a building implies essential building modifications, in a way that after the transformation works, the building corresponds in its whole to a new building.* (SIA, 2003*a*). Based on the transformation data of the case study owners, the transformation rate is very low. Because of the ageing building stock and the densification trend (see demolition function, section 4.6.1.10.2 and chapter 2), we expect an increase of transformations in the near future.

Step 1: *Capacity check*
First, the model controls if the owner has the capacity (capacity control function) to start a transformation project (see section 4.6.1.5, Table 4.2).

Step 2: *Eligibility control*
If a transformation project can start, the model starts running the eligibility test to find the eligible settlements for transformation. The criteria to populate a list of all eligible settlements for transformation are the following:

- The age of the settlement has to be at least 50 years (age ≥ 50 years).
- The settlement has been renovated at least once in the past.
- The settlement has never been transformed in the past.
- More than 20 years must have passed since the last renovation (years since last renovation ≥ 20).
- The settlement has to have more than 20 dwellings.

Step 3: *Settlement choice*

Once the list with eligible settlements is created, the model decides which settlement to transform based on two criteria: (1) the average net rent per square meter of the settlement (CHF/m^2) and (2) the average room surface of the settlement (m^2/room). For both criteria, the model computes the top and bottom 10% from the set of all eligible settlements. It creates three groups for each criterion (below 10%, between 10% and 90%, and above 90%), which we represent as (0,1,2). For each eligible settlement, the model assigns a number among 0, 1 and 2, depending on which group it belongs. As a result, there are nine groups corresponding to all the pairwise combinations for the three groups of net rent per square meter and room surface (0,0),(0,1),(0,2),(1,0),(1,1),(1,2),(2,0),(2,1) and (2,2). The settlement with the lowest first index (net rent per square meter) and the highest second index (room surface) is chosen. In case of a tie, the settlement is chosen randomly.

Step 4: *Dwelling size*

In the case of a transformation, the main structure of the building/s stays intact. The model assumes that the total floor area of all the building (TES) does not change. The action of transformation is chosen for older buildings, for buildings that have low rental income and relatively big rooms. For that reason, the model has the tendency to decrease the size of the dwellings and to create more dwellings. Therefore, TES remains the same, and the model creates the new dwellings according to Stat1990.

Step 5: *Rent pricing*

The model assumes that when property owners transform a settlement, they invest money, and as a result, they add value to the existing settlement. Each owner works with a fixed cost per effective dwelling surface for the transformation works (Table 4.16). According to the transformation cost per square meter, the model calculates the total transformation cost (equation 4.23). Transformation cost per surface is slightly higher than the cost or a heavy renovation; however, the difference is small. The main difference between a heavy renovation and a transformation is that the latter entails a change of floor plan, number of dwellings, dwelling size, etc.

$$Transformation\_cost = TES \times Transformation\_cost\_per\_surface \tag{4.23}$$

Table 4.16 – Model design - Building stock model - Transformation cost by owner

Transformation cost per square meter of TES (CHF/m^2)	
Owner	**Construction cost (CHF/m^2)**
ABZ	2,700
SCHL	2,900
Mobiliar	3,000
Source: Own work and project partners	

In order to calculate the updated net rent of the transformed settlement for the cooperatives, the model uses Fracheboud method as described in the renovation section above (see section 4.6.1.10.3). This method assumes that, the costs caused by the transformation are considered, at a rate of 60%, as added value (equation 4.24).

$$Added\_value = 0.6 \times Transformation\_cost \tag{4.24}$$

The Swiss Federal Law on Real Estate provides that the owner may charge to the rent: (1) amortisation cost, (2) interest on invested capital cost and (3) new maintenance cost.(1) The amortisation cost depends on the life cycle of the transformation works (see equation 4.25b, we assume for 30 years); (2) the interest on the capital cost corresponds to the added value; the added value multiplied by the reference mortgage rate at that time (specific time step of the model) of the increase, increased by half a point (0.5%) (see equation 4.25a); (3) the future maintenance of the new installations corresponds to 10% of the sum of the depreciation and interest on capital cost (equation 4.25c). The yearly rent increase for the whole settlement is calculated in equation 4.25d.

Yearly rent increase calulation, according to Fracheboud method:

$$Capital\_cost = Added\_value \times (ref.rate + 0.5)/2 \tag{4.25a}$$

$$Amort\_cost = \frac{Added\_value}{30 years} \tag{4.25b}$$

$$Maint\_cost = 0.1 \times (Capital\_cost + Amort\_cost) \tag{4.25c}$$

$$Rent\_increase = Capital\_cost + Amort\_cost + Maint\_cost \tag{4.25d}$$

The total rent increase has been calculated, but it corresponds to the whole settlement (with D number of dwellings of the settlement). This amount should be distributed to all the dwellings of the settlement. When the transformation is complete, the updated rent is calculated (equation 4.26b), and the dwellings are available to the market for rent.

Monthly net rent calulation:

$$Rent\_increase\_per\_surface = \frac{Rent\_increase}{TES} / 12 months \tag{4.26a}$$

$$Net\_rent = Rent\_increase\_per\_surface \times Dw.\_surface + Old\_net\_rent \tag{4.26b}$$

This is how the model calculates the rent for all cooperative dwellings; the dwellings of Mobiliar adjust their rent by choosing the maximum value between two values: (1) the net rent calculation as calculated for the cooperatives and (2) the maximum net rent/m^2 of a settlement in the same location (based on the postcode). The model assumes that Mobiliar aims to reach the market price and assumes that it will be the maximum value of all settlements in the same region. If there is no other settlement in the region, the updated rent is defined as the maximum value between the above calculation (equation 4.21b) and 1.8 times the old rent (before the transformation). This is based on the statistical analysis of the owners of the case study where on average a 80% increase in rent was observed after a transformation. Once the dwellings are available at the market they get progressively occupied by households. However, some dwellings remain vacant or empty. Therefore there is a loss of rental income; the actual rental income (ARI) is calculated based on the rented dwellings (equation 4.27a). This allows to estimate the yearly returns for the settlement (equation 4.27c).

Yearly rental income and return calculation:

$$ARI = \sum_{d=1}^{D} Net\_rent\_yearly_d - vacancies \tag{4.27a}$$

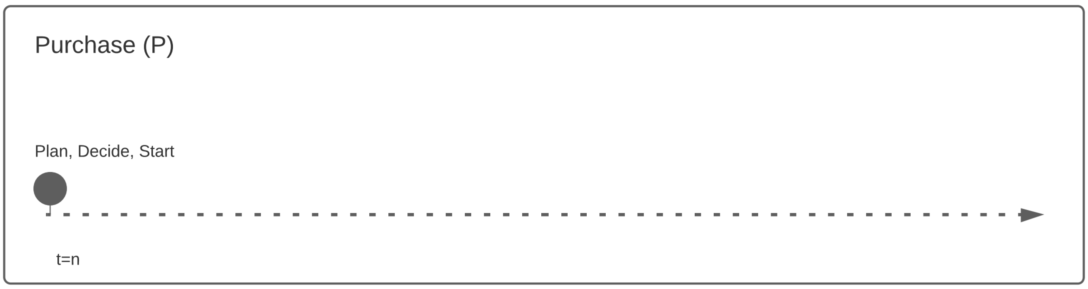
$$Investment\_cost_t = Investment\_cost_{t-1} + Added\_value \tag{4.27b}$$

$$Return(\%) = \frac{ARI}{Investment\_cost} \tag{4.27c}$$

In this step, the following are calculated:

- The net and gross rent of the transformed dwellings
- The investment cost of the settlement is updated
- The yearly return

4.6.1.10.5 Purchase



The purchase function describes the decision-making processes of owners to purchase an existing building / settlement[28]. The analysis of the case study owners revealed that they prefer constructing new dwellings than purchasing existing ones. However occasionally, they

[28]This model assumes that owners can buy an existing settlement out of the system boundaries. This means that in each purchase a new settlement enters the system boundaries.

buy a building or group of buildings. The low yearly purchase rates can be: (1) a result of an elaborated investment strategy, like in the case of Mobiliar or (2) because in Switzerland it is difficult to find a large enough settlement for sale at a good price. In addition, the specific owners are large scale property owners, with experience in constructing; they have construction departments and they also collaborate with external construction companies. Hence, it might be more convenient for them to buy / lease a plot and construct than to buy an existing settlement. In the future, the purchase rate might increase due to the limited availability of buildable land for housing, the promotion of the densification of the existing building stock and the augmenting interest for demolition transformation (ZKB, 2008; Stadt Zürich, 2020, 2017*c*).
All decision steps happen simultaneously at the same tick. The model controls if the owner has the capacity to add purchased dwellings into its BS based on the purchase capacity number. The new purchased settlement and its characteristics are defined, and it enters the housing market at the same time step. Purchase decision is taken every 12 ticks, and it follows the steps:

Step 1: *Capacity control*
The model checks whether the owners have the capacity to purchase. If not, they have to wait; otherwise they can proceed with planning, deciding and making the purchase at the same time step.

Step 2: *Purchased settlement*
In this step, the characteristics of the purchased settlement are defined. The location is chosen as in steps 3 and 7 of the new construction function (section 4.6.1.10.1). The number of dwellings of the settlement, the size of the dwellings and their surface are based on the statistics of the initial building stock of the case study owners after 1990. The data is generated by sampling the number of dwellings from a truncated normal distribution using Stat1990, as it was thoroughly described in section 4.6.1.10.1.

Step 3: *History of the settlement*
If the purchase is done in time step t = k, the construction year is randomly sampled from a truncated normal distribution (*mean*: k - 20 years, *SD*: 15 years, *min*: t - 60 years, *max*: t – 1 years). Additionally, past renovations are generated, depending on the construction year as Table 4.17 shows.

Table 4.17 – Model design - Building stock model - Purchases - Renovation history

Renovation history of purchased settlement	
Years passed since construction	**Renovation type**
Construction year +25 years	R1, light renovation
Construction year + 50 years	R2 (70% probability light renovation & 30% probability heavy renovation)
Construction year +80 years	R3 • if in the past there was one heavy renovation performed, then there is 100% probability to do light renovation • if in the past there were only light renovations performed, then 100% probability to do heavy renovation
Source: Own work	

Step 4: *Rent pricing*

The monthly net rent is computed with a linear multivariate regression model (equation 4.28a) using three dependent variables as predictors: the surface of the dwelling (m^2), the age of the building and the floor of the dwelling. The net rent (Y) is the dependent variable, x = $(x_1,...,x_n)$ are the predictors or independent variables used to estimate Y, whereas ϵ is a random variable corresponding to the error term. Therefore, by estimating the parameters β_j, we can predict the rent y (equation 4.28b). The predictors are the surface of the dwelling (m^2) (x_1), the age of the building (x_2), and the floor of the dwelling (x_3). The net rent regression model is expressed in equation 4.28c.

$$Y = \beta_0 + \sum_{j=1}^{m} \beta_j \times x_j + \epsilon \tag{4.28a}$$

$$\hat{y}_i = \hat{\beta}_0 + \sum_{j=1}^{m} \hat{\beta}_j \times x_{ji} \tag{4.28b}$$

$$Net\_rent = \hat{\beta}_0 + (\hat{\beta}_1 \times Dw.surface) + (\hat{\beta}_2 \times Dw.age) + (\hat{\beta}_3 \times Dw.floor) \tag{4.28c}$$

Table 4.18 shows the estimated β coefficients with standard deviation as well as the R^2 score for each owner. Each owner calculates separately the net rent, see equation 4.28c. For more details about the regression model, refer to chapter 3, section 3.6.

Table 4.18 – Model design - Building stock model - Regression model coefficients

Owner	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\beta}_3$	R^2
ABZ	154(10)	11.74(0.09)	-2.60(0.07)	24.0(1.2)	0.86
SCHL	160(21)	13.99(0.21)	-4.99(0.15)	14.3(2.2)	0.84
SM	507(20)	12.26(0.19)	-5.48(0.24)	38.4(3.0)	0.56

This allows calculating the monthly net rent for each dwelling (equation 4.28c). The monthly gross rent is calculated as in equation 4.29b by adding the additional monthly costs for heating and hot water (more detail about the additional cost in section "new construction").

Monthly gross rent:

$$Add\_cost = Add\_cost\_per\_surface \times Dw\_surface \tag{4.29a}$$

$$Gross\_rent = Net\_rent + Add\_cost \tag{4.29b}$$

Yearly net rent:

$$Net\_rent = Net\_rent \times 12 months \tag{4.29c}$$

Once the rent is set and the dwelling is available for rent in the market, households apply to rent the vacant dwellings. However, not all dwellings of the purchased settlement (with D number of dwellings in the settlement) are absorbed. This translates into rental income loss; the actual rental income (ARI) corresponds to the rental income from the occupied dwellings (equation 4.30). Potential vacant or empty dwellings are not included.

$$ARI = \sum_{d=1}^{D} Net\_rent_d - vacancies \tag{4.30}$$

4.6.1.10.6 Sale

As described in chapter 3, the owners of the case study rarely sell their settlements. The model does not take the owner action Sale into account due to lack of reliable data. Thus, we assume that the sale is negligible for the overall housing dynamics of this model system.

4.6.1.11 BS_ model Initialisation

The building stock model is initialized with data gathered from the SHEF project property owners. The initial building stock is the effective settlements and dwellings and their characteristics, e.g., size, rent, location, construction year, past renovations of the three property owners in 2019. The initial building stock, at time t = 0, consists of the 11,112 dwellings of the property owners.

Table 4.19 – Model design - Building stock model - Initialisation - Number of dwellings

Number of settlements, buildings & dwellings - Initialization		
Owner	**Number of settlements**	**Number of dwellings**
ABZ	58	4,931 (4,770 free-market, 161 subsidized)
SCHL	41	2,122 (1,792 free-market, 330 subsidized)
Mobiliar	125	4,059
Total	*224*	*11,112*
Source: Own analysis based on the partner's data		

The following table present key figures describing the initial building stock. A detailed description of the initial building stock can be found in chapter 3, and a detailed list of all the initialisation values can be found in Table A.23 in the appendix.

Table 4.20 – Model design - Building stock model - Initialisation - Key figures

Key figures of the building stock - Initialization					
Variable	**ABZ Free-market**	**SCHL Free-market**	**Mobiliar**	**ABZ Subsidized**	**SCHL Subsidized**
Number of dwellings	4770	1792	4059	161	330
	Average values				
Number of dwellings per settlement	160	100	55	128	61
Number of dwellings per building	12	43	16	13	38
Number of buildings per settlement	17	3	4	11	2
Dwelling floor	2.8	2.3	2.1	2.2	1.8
Number of rooms	3.5	3.1	3.6	4.2	3.0
Dwelling surface (m2)	78	75	88	98	76
Square meters per room	22.5	24.8	24.7	23.8	25.3
Net rent (CHF)	1006	1030	1556	1023	904
Net rent per square meter	12.9	13.4	18.3	10.7	11.8
Additional costs (CHF)	99	132	226	87	168
Additional costs per m2	1.3	1.8	2.6	0.9	2.2
Gross rent (CHF)	1146	1157	1782	1104	1018
Gross rent per m2 (CHF/m2)	14.8	15.1	20.9	11.7	13.1
Reference year	1970	1976	2000	2007	1967
Source: Own analysis based on the partner's data					

4.6.1.12 BS_ model Validation

For the validation and calibration of the BS_ model, we are using two sources: (1) the existing building stock data provided by the property owners, and (2) the construction activity and housing market characteristics from FSO. The simulations were initialised with a subset of the building stock data including all dwellings constructed until the year 2000; all dwellings constructed later are deleted from the dataset. The model runs for 20 years, until the year 2020. We run the model for 50 repetitions, and the the model simulations offer a full evolution of the building stock between 200 and 2020, as well as a set of indicators. To validate the model, we compare the results of the model simulations with the effective building stock data provided by the property owners. Using both sources as reference, several indicators, e.g, number of dwellings (overall and per partner), average dwelling surface (m^2), room surface (m^2/room) and proportion of dwelling sizes were validated. For more detail see Table 4.21.
The discrepancy in the results for the private property owner Mobiliar is expected because the owner had a very high construction activity between 2000 and 2020 as shown in Table 3.14 in chapter 3. This intensive dwelling increase was a result of a change of strategy of Mobiliar, who turned more to real estate asset investments after 2000. However, the model assumes that this activity will be moderated in the future. Therefore, the model is expected to underestimate the

construction activity and the increase of the number of dwellings of this owner.

Table 4.21 – Model design - Building stock model - Model validation

	Effective building stock in 2000	Building stock predicted from the model in 2020	Effective building stock in 2020
All owners			
Number of dwellings	6.581	9.891*	11.112
Dwelling surface (average m^2)	76.2	80.7	81.4
Room surface (m^2/room)	23	23.9	23.8
Proportion of dwelling sizes			
1-1.5room	4 %	3.5 %	3.8 %
2-2.5room	19.7 %	18.9 %	19 %
3-3.5room	42.2 %	39.7 %	40 %
4-4.5room	28.1 %	31.1 %	30.7 %
5+room	6 %	6.8 %	6.5 %
ABZ			
Number of dwellings	3.722	4.872	4.931
Dwelling surface (average m^2)	73.7	77.8	78.6
Room surface (m^2/room)	22.1	22.4	22.5
Proportion of dwelling sizes			
1-1.5room	3.60%	3.20%	3.4 %
2-2.5room	17.10%	17.40%	17.3 %
3-3.5room	43.90%	40.20%	40.5 %
4-4.5room	29.10%	31.00%	30.9 %
5+room	6.30%	8.20%	7.9 %
SCHL			
Number of dwellings	1.556	2,016	2.122
Dwelling surface (average m^2)	71	74.8	75.4
Room surface (m^2/room)	24.4	25	24.9
Proportion of dwelling sizes			
1-1.5room	3.4 %	2.50%	2.5 %
2-2.5room	26.6 %	22.70%	22.8 %
3-3.5room	43.9 %	42.90%	43.7 %
4-4.5room	23.2 %	28.00%	27.6 %
5+room	2.9 %	3.90%	3.4 %
Mobiliar			
Number of dwellings	1.303	3.003*	4.059
Dwelling surface (average m^2)	82.7	87.5	87.9
Room surface (m^2/room)	23.8	24.9	24.7
Proportion of dwelling sizes			
1-1.5room	6.00%	5.90%	5 %
2-2.5room	18.80%	18.80%	19.2 %
3-3.5room	35.40%	35.30%	37.5 %
4-4.5room	30.90%	33.50%	32.1 %
5+room	8.90%	6.50%	6.2 %

Source : Own work based on date from project partners
** The number of dwellings of Mobiliar is underestimated because the model assumes that the growth rate of this owner will decrease in the future, after a period of sudden increase of number of dwellings.*

4.6.1.13 BS_ model Assumptions and Limitations

The model makes several assumptions:

- The decisions of the owners whether to proceed with one of the seven actions apply for a whole settlement and not at the level of a single building or single dwelling.
- Only one of the seven actions can take place per settlement every time step.
- Owners demolish in order to reconstruct; the two functions handling demolition and reconstruction are connected and reconstruction automatically starts after a specific period after the demolition.
- At time t = 0, we assume that all owner actions can happen and that the owners can plan an action for all settlements; there are no constraints based on previous actions of the owners.
- The model assumes that all owners want to grow their building stock and have access to adequate funding. However, there are constraints that are represented by the capacity of each owner.
- The model assumes that demand for dwellings is very high and will keep increasing.
- We assume that owners are constantly willing to renovate or transform; in reality, there are constraints that prohibit to renovate their building stock faster. The model assumes the capacity constraints of each owner. However, in the future their capacity limit might change allowing the to renovate and transform more dwellings per year.
- The model features a hierarchy in terms of the order of owner actions. In each time step, the model runs the owner action function in the following order: new construction function, demolition-reconstruction function, renovation function, transformation function, purchase function. For example, before owners can decide whether to renovate, they decide about demolitions. This doesn't affect the capacity numbers for each owner action. However, a settlement might be chosen for demolition before being controlled for a renovation.
- The capacity number and the owner actions are set based on limited data for renovation, transformation and demolition. Therefore, in the baseline scenario, the model assumes a very low transformation rate.
- The model assumes that selling a property is very rare, and thus, the sale of a settlement is not included.
- Land availability is not studied and the assumption is that although land reserves decrease, land will be available for new construction.
- In the case of a new construction, the land is situated close either to central or residential areas (as they are characterised); no other land use is taken into consideration. Additionally, developers exploit the maximal permissible FAR and building height.

The limitations of the model can be summarised in the following points:

- This model is based on the three property owners and their building stock, which constitute a subset of the Swiss housing market. The model rests on assumptions derived from the analysis of the data gathered from the property owners. They are context-dependent and cannot be generalised for the whole Swiss housing market.
- Land availability and price are not modelled. In a future model, land scarcity, the location of land and the competition of potential buyers could be studied to capture the effects of the residential land market.
- Taxes, state subsidies and land leasing is not included. In the future, a broader model including these parameters would better describe the housing market and allow investigating the effect of these policy measures on the construction activity and environmental assessment of housing.
- In the case of renovations and transformations, building energy performance improvements are not studied separately, although they entail advantages for the owners, the tenants and the environment (Wüest Partner, 2020*b*).
- Location plays an important role and affects most of the parameters of the model, e.g., construction cost, land availability and price, rental income, vacancies, etc. (Pointet and Guillod, 2012; Ligman-Zielinska and Jankowski, 2010; Parker and Filatova, 2008). The model is not very sensitive to location change. A future model could be more detailed including the spatial diversity of the parameters.

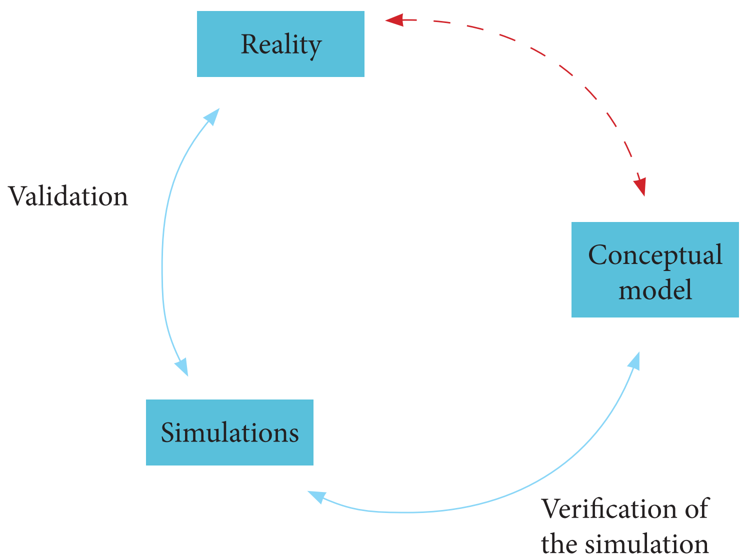


Figure 4.6 – Model design - Validation process

4.6.2 Household Model (HH_ model)

The household model describes the households' housing preferences and decisions. Households have specific characteristics, e.g., type, size, income that evolve over time; the model describes their static and dynamic attributes. The input of the HH_ model is the total of the households living in the dwellings of the initial building stock. However, since households evolve over time (see section 4.6.2.5 and 4.6.2.9), they change and update their attributes; the changing attributes of certain households are considered as possible triggers, pushing them to move to a new dwelling. Based on a set of preferences, households find a set of desired dwellings and apply in order to find a new dwelling. The output of the HH_ model is the updated household agents and a list of desired dwellings, for the households wanting to move.

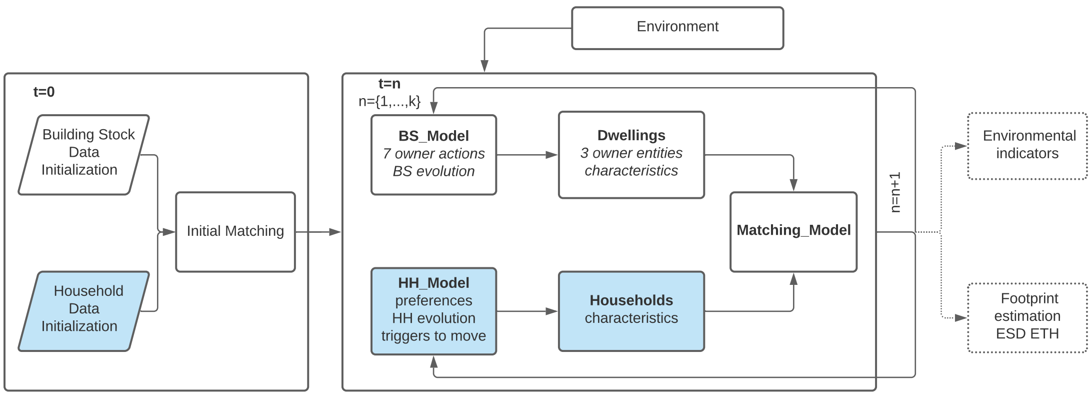


Figure 4.7 – Model design - Household model flowchart

4.6.2.1 Design of agents

In the HH_ model, the agents are households. They are initialized with certain attributes, as seen in Table 4.22; they are divided in seven household typologies based on the household synthesis and age; sorted in five size groups, depending on the number of occupants per household and in five income groups, depending on the total income of the household. In addition, they are characterized as free or subsidized, depending on whether they live in a free-market or subsidized apartment; they are also characterised by the owner of their current dwelling. Seniority refers to the number of days the main tenant of the household has been a member of the specific cooperative, and it is exclusively used for the cooperative households. Each household is also characterized by a level of satisfaction with its current dwelling (low, medium, high) and a level of environmental awareness (low, medium, high) that defines many of its housing choices and preferences. In the context of this research, environmental awareness is defined by two factors: (1) the willingness of the household to move to a smaller dwelling if its size shrinks and (2) the significance of building energy labels when choosing a dwelling (see Table 4.31 and Table 4.30). Furthermore, each household agent has a set of attributes related to the trigger to move to another dwelling. For example, the reason to move out is an attribute that is updated in every time step and can be the renovation or demolition of their current dwelling, the loss of the right to a subsidy, the arrival of a new member into the family, etc. (for more detail, see section 4.6.2.7). In addition, the type of reason indicates whether the moving is an imperative event that forces the household to move as quickly as possible or an opportunity to move to a dwelling that gives a higher level of satisfaction to the tenants.

Table 4.22 – Model design - Household model - Agents and attributes

HH_model agents and attributes		
Household	**Attribute**	**Value & metrics**
	Typology	{One-person household < 65 years old, One-person household >= 65 years old, Couples without children < 65 years old, Couples without children >= 65 years old, Single parents with at least one child, Couples with at least one child, Other multi-person households}
	Size	{1,2,3,4,5+}, number of occupants
	Income group	{<=60 000 CHF/year, 60 001 – 88 000 CHF/year, 88 001 – 120 000 CHF/year, 120 001 – 164 999 CHF/year, >= 165 000 CHF/year}
	Income	CHF
	Market	{Free, Sub}
	Dwelling owner	{ABZ, SCHL, Mobiliar}
	Seniority	days
	Environmental awareness level	{1: low, 2: medium, 3: high}
	Satisfaction level	{1: low, 2: medium, 3: high}
	Status (trigger class)	{on, off}
	Reason (trigger class)	{Demolition or Renovation, Stop of subsidy, Birth, Death, Divorce, Typology is couple with children or single parent with children, Cooperative member}
	Type of reason (trigger class)	{Opportunity change, Imperative change}
	Timer (trigger class)	Months waiting
Source: Own work		

4.6.2.2 Design of the environment

Both models, HH_ model and BS_ model, have a common environment (see section 4.6.1.2).

4.6.2.3 Agent - agent and environment interaction

The BS_ model is directly affected by the environment. Household agents interact with the BS_ model through the Matching model. When dwellings become vacant and available for rent in the market, households might express their interest. The building stock evolves over time; new construction, demolition and reconstruction, renovation, transformation update the building stock. New dwellings or existing dwellings with updated characteristics, e.g., surface, rent, quality, etc., enter the market. Households have housing needs and compete with other households that wish to rent and apply for the same dwelling. Households are indirectly affected by the environment, i.e. a change in the reference rate might imply a change in their monthly rent (see rent update function in the BS_ model section). Furthermore, the environment influences the households of the HH_ model directly. Changes of the environment might send signals that lead to an increase of the environmental awareness level of households. This could be a result of an environmental housing tax, incentives to move to move to smaller dwelling, an environmental campaign, etc. A household agent interacts with the environment and updates its environmental awareness level. At the initialisation, all agents have an attribute called environmental awareness, which can take three possible values (low, medium, high). This household characteristic gets updated every time step, depending on whether there is a trigger from the environment. For more detail see section 4.6.1.2.

4.6.2.4 Time steps function

The time step of the HH_ model is one month (1 tick = 1 month). Every month, households are subject to changes and as a result their characteristics change, which may also trigger the household to change a dwelling.

4.6.2.5 Household evolution function

Households are initialized at time t = 0, but they don't remain static, they evolve over time. In the model, we assume that households are subject to the following three changes: (1) size, (2) income and (3) typology change, which is a result of one of the six events that are: (a) marriage, (b) divorce, (c) death of a household member, (d) birth of a new household member, (e) income change and (f) child leaving home. Based on the official Swiss population data published by FSO (FSO, 2015*b*), Table 4.23 illustrates the yearly birth, death, marriage and divorce rates in 2019.

Table 4.23 – Model design - Household model - Swiss demographics

In a total population of 8,600,000 the yearly changes are:		
Reason	**Number**	**Percentage yearly**
Births	86,000	1.00%
Deaths	67,700	0.79%
Divorces	17,000	0.20%
Marriages	39,500	0.46%
Source: FSO		

The model assumes that the population of the tenants follows an evolution similar to the evolution of the Swiss population. In each time step (every month), a small percentage of the households experiences a change, not all households. The model assumes that only one event per household can happen in every time step, e.g., if in a household a marriage (event a) happens at t = n, there cannot be any other event (b, c, d) at the same time step t = n. Only income change and child leaving home (events e and f) can happen simultaneously with one of the other events (a,b,c,d).

Step 1: *Events happen - choice of households that change*
In each time step, certain households are randomly chosen to change. Based on pre-defined probabilities, events happen to certain households. There is a small probability for each of the six events to happen in every time step. For example, since there is a 0.46% probability of having a marriage on a yearly basis, we divide 0.46% by twelve months to find the probability of a marriage event on a monthly basis. In each step, households are randomly chosen based on the monthly probability of one of the six events to happen. Not all events can happen to all types of households. Table 4.24) shows in the first column which household typologies might change depending on the event. All typologies get affected by at least one event, except for type "Other multi-family households". This typology remains stable in the model because the percentage of this typology is very small. For example, in the case of a one-person household older than 65 years old, marriage, death or income change events might occur, but a birth event is excluded.

Step 2: *Change of typology - new typology of households after the event*
In the same table (Table 4.24), the possible new typologies after an event (before and after the event typologies) are presented. For example, if the type "one person's household < 65 years old" household is randomly chosen for a marriage event, it will change its typology either to "couples without children < 65 years old" or to "couples without children ≥ 65 years old" (with 90% probability for the first outcome and 10% probability for the second outcome). In the table, all the possible outcomes for the different household types are presented. All these reasons for change, result in a change of size, type or income of the households.

Step 3: *Change of size and income group after an event*
Depending on the event that happens, changes in the size and income of the household are implied:

- Marriage: A new person joins the household; the household size increases by one and the household typology changes accordingly. We assume that the new person enters the existing household system from outside. The household's income increases by one category because we assume that after a marriage the common income of the household will be higher.

- Divorce: The household splits into two different households; only "couple with children" and "couples without a child" typologies can have a divorce. In the next time step, two households are created; the income group decreases by one category.
- Birth: One more person (child) is added to the household and the household typology changes accordingly.
- Death: The household's size decreases by one. If the household reaches size zero, it is deleted from the model's system.
- Income change: In this case, there is neither a change in the type nor in the size of the household; only the income of the household changes. There is an equal probability (1/3) that the income increases by one level, or decreases by one level or remains the same. For the subsidized dwellings, if the income increases to the third category(≥ 88,000 CHF/year), the household stops being entitled to a subsidy in the next step.
- Child leaving home: At every step, households with typology "couples with at least one child" have a 1% chance to trigger the event "child leaving home". For more detail, see function "Children leaving home".

4.6.2.6 Children leaving home function

This function describes the event of a child leaving the parental house. Children grow up and leave their house for several reasons, e.g., studies, job, creating their own family, etc. At every time step, households that belong to the category "couples with at least one child" have 1% probability, to trigger the event "child leaving home" (FSO, 2021*q*).

When such an event happens, the household's size reduces by one and its typology changes into one of the following four categories with equal probability: "couples without children < 65 years old"; "couples without children ≥ 65 years old"; "couples with at least one child < 65 years old"; "couples with at least one child ≥ 65 years old". The last two categories imply that the household has more children that keep living in the house.

The member of the household (child) that left from the parental house creates a new household with the following attributes: The typology of the new household will be either "single person" or "couples without children" with equal probability; the size will be one or two persons; the income group will be group one or two (if typology is "single person") and group two or three (if typology is "couples without children"). The rest of the household attributes are randomly generated.

Table 4.24 – Model design - Household model - Evolution of the households / typologies

Evolution of households			
Typology of household	**Changes because of:**		
One-person household < 65 years old	Marriage, Death, Birth, Income		
One-person household > 65 years old	Marriage, Death, Income		
Couples without children < 65 years old	Death, Birth, Divorce, Income		
Couples without children > 65 years old	Divorce, Death, Income		
Single parents with at least one child	Marriage, Death, Birth, Income		
Couples with at least one child	Divorce, Death, Birth, Income		
Other multi-person households	Keeps stable		
Typology before	**Typology after**	**%**	% of row
Marriage 0.46% => hh: size +1			
One-person household < 65 years old	Couples without children < 65 years old	1/3	90%
	Couples without children > 65 years old		10%
One-person household > 65 years old	Couples without children > 65 years old	1/3	100%
Single parents with at least one child	Couples with at least one child	1/3	100%
Divorce 0.20% => hh: size -1 and new hh			
Couples without children < 65 years old	One-person household < 65 years old	1/3	100%
Couples without children > 65 years old	One-person household > 65 years old	1/3	100%
Couples with at least one child	Single parents with at least one child	1/3	100%
Births 1.00% => hh: size +1			
One-person household < 65 years old	Single parents with at least one child	10%	100%
Couples without children < 65 years old	Couples with at least one child	20%	100%
Single parents with at least one child	Single parents with at least one child	30%	100%
Couples with at least one child	Couples with at least one child	40%	100%
Deaths 0.79% => hh: size -1 or hh stop existing			
One-person household > 65 years old	Stops existing	10%	100%
Couples without children < 65 years old	One-person household < 65 years old	40%	100%
Couples without children > 65 years old	One-person household > 65 years old	40%	100%
Couples with at least one child	Single parents with at least one child	10%	100%
Income change => income change			
All typologies	Income stable	1/3	100%
	Income falls one category	1/3	100%
	Income goes one category up	1/3	100%
Source: own work			

4.6.2.7 Trigger to move function

The above-mentioned changes might trigger households wanting to move out from their current dwelling and find another dwelling, in other words they may generate residential mobility. Life events alter housing needs and preferences of households significantly (Van Ham, 2012), which might make them feel less satisfied with their current dwelling. This might result in triggering households to move out of their current dwellings and wanting to find another dwelling, which will be closer to their needs and preferences (Homegate, 2020; La

Poste, 2020; Marsh and Gibb, 2011).
These events might have a mild or radical impact on households; some changes might not be enough to trigger the need to move out, while others might constitute an imperative event for immediate change of dwelling. Research has shown that the desire to change dwelling depends to the level of satisfaction with the current dwelling (Pagani et al., 2021). Triggers to move might be radical events that force households to change dwelling; or they might be an opportunity to enhance living conditions, and thus, to increase the level of satisfaction of households. For example, if a household has a child, the number of tenants grows by one. This might be a trigger to move to a bigger apartment. The change itself doesn't mean that the household will definitely want to move out and as a result apply for another dwelling. For this reason, a class is created in the model named "trigger to move", which is responsible for managing the triggers that push households to move. A trigger has four attributes:

- State: This attribute can have two values ("on"/"off"). "On" describes the households that want to move while "off" stands for households without intention to change dwellings.
- Reason: It describes the reasons for which the household decides or is forced to look for a new dwelling. Possible reasons are (1) due to renovation, transformation or demolition, (2) stop of subsidy, when a household is not entitled to a subsidy anymore, (3) birth, the size of the household grows by one, (4) death of a household member, the size decreases by one and the income might change, (5) divorce, a household member leaves from the dwelling.
- Type of reason: If the above-mentioned "State" is "on", the model provides the information whether the reason for wanting to move is an opportunity to enhance living conditions (opportunity change) or an imperative event (imperative change) that forces the household to search for a new dwelling.
- Timer: If "State" is "on", a timer keeps track of the waiting months the household has been in search of a new dwelling. The model uses this timer to determine whether the household can continue looking for a dwelling or leaves out of the boundaries of the model's system and starts looking for a dwelling somewhere else.

There are two categories of triggers:

- Opportunity change:
  This refers to a trigger that is an opportunity to enhance the characteristics of their dwelling. In this case, the household sees an opportunity to change dwelling and move to a dwelling that fits better to its needs and preferences. This is not triggered by any change of the household's attributes; it depends on the environmental awareness of the household and the level of satisfaction of the household with its current dwelling.

The model assumes that if the satisfaction level is low or medium, then the household is willing to search for another dwelling among the available dwellings within the system boundaries. If the satisfaction level is high, the household is satisfied with its current dwelling, and there is no reason to start looking for another dwelling. The final decision to move depends on two factors: (1) the dwelling size compared to the household size and (2) the gross rent of the current dwelling compared to the income of the household (see Table 4.25, section 1.a and 1.b). For example, if there is a 3-person household with low environmental awareness and is currently living in a 3-room dwelling, the household will start looking for a bigger dwelling (based on Table 4.25).

- Imperative change:
  An imperative - radical event, forces the household to search for a new dwelling. The model includes four radical events that push the households to move out:

  – Income decrease:
    The household's income decreases radically and the new income is low in comparison to the gross rent of the dwelling. The household has a trigger to move out if the income is:
    HH Income ≤ 2 * current dwelling gross rent
  – Income increase:
    This does not correspond to an opportunity to enhance the dwelling's quality or to improve the satisfaction level (opportunity change). This case refers to a dwelling that was entitled to a subsidy and the household has been living to a subsidized dwelling. But the household's income increases, and the household is not entitled to a subsidy anymore.[29]
  – Increase of household size:
    The size of the household increases and the current dwelling is too small to accommodate all the household members:
    If dwelling size ≤ (HH size + 1)/2, then the household wants to move out. This is considered a radical event that pushes the household to look for a larger dwelling.
  – Owner actions:
    If a heavy renovation, transformation or demolition has been announced to the household. This means that the household has three months to find a new apartment. The cooperative households are offered another substitute dwelling within the same cooperative building stock.
  – Divorce:
    The model assumes that when a household has a divorce, there are two new

[29] This is based on the list of subsidies of the city of Lausanne in 2019. According to this list, the rent subsidy can be calculated based on the yearly income of the household, the size of the household and the number of children (under 18 years old) or young adults that study (under 25 years old).

households created; the first stays in the initial dwelling and the second household starts looking for a new dwelling. This is considered an imperative event and the second household has to find a new dwelling as soon as possible.

Table 4.25 – Model design - Household model - Triggers to move

Triggers for households to want to move and apply for a new dwelling			
1. Opportunity change			
	a. Satisfaction level and current dwelling size		
	1 Low	2 Medium	3 High
Environmental awareness level			
1 Low	Current dw. size < HH_size+1 OR Current dw. size > HH_size+3		Do not wish to move
2 Medium	Current dw. size < HH_size OR Current dw. size > HH_size+2		Do not wish to move
3 High	Current dw. size < HH_size-1 OR Current dw. size > HH_size+1		Do not wish to move
	b. Satisfaction level and current dwelling gross rent		
1 Low	HH Income >= 10*gross rent of current dw.		Do not wish to move
2 Medium			Do not wish to move
3 High			Do not wish to move
2. Imperative event change			
Reason for trigger	a. Income control	Move out if: Income group changed (decreased) AND gross rent >= 0.5 HH Income	
	b. Size control	Move out if: HH size changed (increased) AND Dw. size <= (HH size+1)/2	
	c. Dwelling imperative (R, T, D)	Cooperative empty lists and Mobiliar households must move out	
	d. Lose subsidy	Move out	
	e. Second hh due to divorce	Move out	
Source: Own work			

4.6.2.8 Apply for a new dwelling function

In this function, the model gathers all the households in search for a new dwelling; it creates a list with all the households wishing to move out (HHsearch). First, households decide that they want to move to another dwelling before they choose the dwelling(s) they apply for (Mulder and Hooimeijer, 1999). Each household wanting to move selects three preferred / desired dwellings; the model assigns three desired dwellings (specific dwelling IDs) to each household of the list. These dwellings are chosen based on dwelling characteristics, e.g., location, rent, dwelling and household size and household characteristics, e.g., income, size and environmental awareness. The desired dwellings are the dwellings that each household chooses and applies for; these dwellings have to satisfy the following criteria:

- Location: The new dwelling is usually close to the current dwelling. In 60% of the cases, households move in another dwelling in the same municipality; in 20% of the cases they move to another municipality within the same canton, and in 20% of the cases they move to another canton (FSO, 2001).
- Income: Economic variables such as rental price of the dwelling and income of the household play an important role when choosing a dwelling to rent (OECD, 2008). The desired dwelling has to be affordable. Over the past 100 years, the majority of the Swiss population spends less that 20% for their rent (FSO, 2016*a*; Wüest Partner, 2019*f*). The model assumes that the gross rent of the new dwelling has to be:
  $1/7$ Household's Income $\leq$ Gross rent of new dw. $\leq 1/3$ Household's Income ((FSO, 2020*k*)).
- Size: Depending on the environmental awareness of the household, the household searches for a dwelling that is more or less spacious. The model assumes that apart from the economic variables of price and income, behavioural aspects of households define their preferences. Individuals and households with high environmental awareness are comfortable in less spacious dwellings, while households with low environmental awareness tend to prefer larger dwellings and consume more square meters per capita (OECD, 2008). Dwelling size is measured in terms of number of rooms and household size in terms of number of occupants. The size of the desired dwelling depends on the environmental awareness of the household. Households with high environmental awareness choose a dwelling based on equation 4.31a. For example, a three person household with high environmental awareness will apply for a dwelling that has two to four rooms. Accordingly, the desired dwelling size for households with medium environmental awareness is defined by equation 4.31b and with low by equation 4.31c.

$$HH\_size - 1 \leq Desired\_dwelling\_size \leq HH\_size + 1 \tag{4.31a}$$

$$HH\_size \leq Desired\_dwelling\_size \leq HH\_size + 2 \tag{4.31b}$$

$$HH\_size + 1 \leq Desired\_dwelling\_size \leq HH\_size + 3 \tag{4.31c}$$

4.6.2.9 Update of attributes function

Household attributes get updated because of several reasons as a result of a combination of the above mentioned functions.

- *Typology and age*
  The typology of a household might be updated in several cases, in any of the five events (birth, death, marriage, divorce, child leaves home). For further detail, see the respective section 4.6.2.5. In this model, the typology of the household is combined with the age of

the main tenant. Another reason to change typology is the ageing of the main tenant; when she/he becomes 65 years old, the household changes typology from young to old. In 2020, approximately 1% of the population was 64 years old; 64 years old was also 1,8% of the adults that belong in the age group 18-64 year (FSO, 2021*q*). The model increases yearly by one year the age of 2% of the households from the categories "one person households < 65 years old" and "couples without children < 65 years old" and changes their typology to "one person households ≥ 65 years old" and "couples without children ≥ 65 years old".

- *Income*
  The income group of households might change in each time step according to the household evolution function (see section 4.6.2.5).

- *Size*
  The household size might change as a result of the events of marriage, divorce, birth, death or child leaving home (see section 4.6.2.5). Depending on the event, the size changes accordingly.

- *Owner and market*
  The owner of the dwelling that the household occupies might change when the household changes apartment. If the new dwelling belongs to a different owner than before, the model automatically updates the owner attribute.

- *Seniority*
  Seniority refers to the number of days that a cooperative household is tenant of the same (housing cooperative) owner. It is updated using a seniority counter, which calculates the days that pass.

- *Satisfaction level*
  The satisfaction level of households is updated based on whether they applied for a new dwelling.
  - When households apply for a set of desired dwellings and move into one, then we assume that they will be more satisfied with the new dwelling. The model increases the satisfaction level of the household and increases to the next level (if possible).
  - When households apply for a dwelling but they fail to get one of their desired dwellings, they might degrade satisfaction level. If they wait for more than three months without finding a new dwelling, the satisfaction level decreases one category (if possible).

- *Environmental awareness level*
  In the initialisation, the environmental awareness of households is assumed static. The environment has an environmental switch that influences the households (see section 4.6.1.2. The initial state of the switch is "off", which means that the environmental awareness level of households remains static over time. If the switch turns to "on", the environmental awareness level of households goes one level higher every twelve ticks.

4.6.2.10 Incoming households function

The model has specific system boundaries; at time t = 0, the system boundaries include the initial building stock of the case study (11,112 dwellings) and 10,940 households, for more details see chapter 3 and Table A.23 in the appendix. However, over time the building stock evolves; some dwellings are demolished and new dwellings enter the system boundaries. Additionally, at every time step, new households enter the system boundaries to ensure that there is always sufficient demand. At time t = 0, the cooperative dwellings are always fully occupied (zero vacancy rate), while Mobiliar has approximately 4% vacancy rate[30].

The typology of new households that enter the system is chosen such that the original percentage of typologies is maintained[31]. Once the typologies of new households are chosen, the size, income, environmental awareness and satisfaction level are set similarly as in the initialisation, from the initial household stock and the SHEF survey data. Furthermore, when a new household enters the system, the owner attribute is set to none; the seniority attribute is set to none as well. These change when the new households are assigned to a dwelling in the matching model.

The model is not analysing the subsidized building stock because the specific owners stopped adding subsidized dwellings in their stock (for more details, see BS_ model section). Since the subsidized dwellings are included in the initial building stock, there are also households occupying them, who are entitled to a subsidy. The building stock evolves but the number of subsidized dwellings cannot increase, but it could decrease because of a demolition. In addition, households entitled to a subsidy evolve. For example, they might lose the subsidy; in this case, the subsidized dwelling gets vacant. The model ensures that there are always enough households to occupy the subsidized dwellings.

[30] The vacancy rate of the case study owners is based on the data collected and analysed.

[31] The proportion of each typology and size is defined based on the SHEF survey 3.5 and the Households Budget Survey (FSO, 2016*a*).

4.6.2.11 Leaving the system function

The households that want to move out and are in search of a new dwelling apply for a new dwelling during several time steps. However, if they don't manage to find a dwelling after a specific number of time steps (months), they will leave the system of this model and go look for a dwelling outside of the system boundaries. Depending on the reason to move (opportunity or radical event), households wait for different time steps before leaving the system. Specifically, a household will leave the system if:

- The owner of the current dwelling is a cooperative:
  - If the reason is an imperative event, the household keeps looking for a dwelling of the same owner for six time steps; if it doesn't find a dwelling within the first six months, it starts looking in dwellings belonging to all three owners for three months; if it still doesn't find a dwelling, it leaves the system.
  - If the reason is an opportunity change, the household keeps looking for twelve time steps for dwellings of the same owner. If it doesn't find a dwelling, it looks for another six months in all three owners. After that, if it still hasn't found a dwelling, it leaves the system.
- The owner of the current dwelling is Mobiliar:
  - If the reason is an imperative event, the household looks for six time steps in all three owners. If it doesn't find a dwelling, it leaves the system.
  - If the reason is opportunity change, the household looks for twelve time steps in all three owners. If it doesn't find a dwelling, it leaves the system.

4.6.2.12 HH_model Initialisation

The initialisation of the households allows to populate the initial building stock of the property owners with households. The HH_ model is initialized based on the data gathered from four sources: (1) general statistics of the Swiss population (FSO), (2) the Households Budget Survey 2015-2017 (HBS) from FSO (FSO, 2016*a*), (3) the SHEF survey and (4) the inventories of the building stock of the partners. Initially, there are 11,112 dwellings (4,931 ABZ, 2,122 SCHL, 4,059 Mobiliar) and 10,940 households (4,931 ABZ, 2,122 SCHL, 3,887 Mobiliar) in the model's system. Assuming that at t = 0, both housing cooperatives have zero vacancy rate (0%) and Mobiliar 4.2%, N number of households (N = 10,940) are generated. This means that at t = 0, the number of households equals the number of dwellings minus the vacant dwellings of Mobiliar (see Table 4.26).

Table 4.26 – Model design - Household model - Initialisation - Number of households

Number of households - Initialisation	
Owner	**Number of households**
ABZ	4,931 (4,770 free-market, 161 subsidized)
SCHL	2,122 (1,792 free-market, 330 subsidized)
Mobiliar	3,887
total	*10,940*
Source: Own analysis based on FSO and SHEF survey	

Firstly, based on the SHEF Survey and FSO data, seven typologies of households are developed (One person's household < 65 years old, One person's household ≥ 65 years old, Couples without children < 65 years old, Couples without children ≥ 65 years old, Single parents with at least one child, Couples with at least one child, Other multi-person households). The proportion of each typology is defined based on the results of the SHEF Survey (for more details, see 3.5). All the details of the initialisation can be found in Table A.23 in the appendix. The cooperatives have more families and "single parent" households, in comparison to Mobiliar that has many households that are "couples with at least one child" or "couples without children. In general, as seen in the following table, the typology with the highest percentage is "couple with at least one child", representing 35% of the total number of households. "One-person" households correspond to approximately 30% of the households and "single parent with at least one child" households reach 11.5% (see Table 4.27).

Table 4.27 – Model design - Household model - Initialisation - Typologies

Typologies of households per owner - Initialisation				
Typology	**ABZ**	**SCHL**	**Mobiliar**	**All owners**
Couple >=65 no children	3.2%	4.2%	7.6%	5.0%
Couple <65 no children	9.6%	12.8%	22.8%	14.9%
Couple with children	41.2%	30.6%	29.2%	34.9%
One person >=65	8.2%	10.6%	7.9%	8.5%
One person <65	19.0%	24.6%	18.6%	19.9%
Other multi-person	5.1%	3.6%	6.5%	5.3%
Single parent	13.7%	13.7%	7.4%	11.5%
total	*100%*	*100%*	*100%*	100.0%
Source: Own analysis based on FSO and SHEF survey				

Next, the SHEF survey provides information about the size of the households per owner, the number of children (see Table 4.28) and the income of households based on the typology and size of the household. The size of households is grouped into five categories (1 person, 2 persons, 3 persons, 4 persons, 5 plus persons). As can been found in the following table, only 5% of the total number of households consists of five or more occupants; 28.5% of the households have only one occupant (size 1); more than half of the households (54.5%) are small consisting of one or two persons.

In addition, the households' gross income is grouped into five categories (Group 1: ≤ 60,000 CHF/year, Group 2: 60,001 – 88,000 CHF/year, Group 3: 88,001 – 120,000 CHF/year, Group 4: 120,001 – 164,999 CHF/year, Group 5: ≥ 165,000 CHF/year). The income group of the household is randomly assigned according to the income distributions (see Table A.23 in the appendix), stratified by owner and household typology, obtained from the income data from the SHEF survey and the HBS. Afterwards, the model attributes a specific income amount (CHF) representing the household's income, which is randomly distributed within the range of each income group. By combining the available data about the typologies, size of the households, number of children (see Table 4.29) and income groups, the households and their main attributes are initialised.

Table 4.28 – Model design - Household model - Initialisation - Size and number of children

Distribution of household's size according to owner type					
Size of household	**Number of occupants**	**ABZ**	**SCHL**	**Mobiliar**	**all**
Size1	1	27.2%	35.2%	26.5%	28.5%
Size2	2	19.9%	23.7%	35.1%	26.0%
Size3	3	24.8%	19.8%	17.2%	21.1%
Size4	4	20.7%	16.2%	15.3%	17.9%
Size5	5+	7.5%	5.1%	5.9%	6.5%
Source: Own analysis based on FSO and SHEF survey					

Number of children per household (SHEF Survey)			
Number of children per household	**ABZ**	**SCHL**	**Mobiliar**
1	27%	29%	40%
2	52%	57%	44%
3	17%	10%	14%
4	3%	3%	1%
Total	100%	100%	100%
Source: Own analysis based on SHEF survey			

The model initialises the characteristic seniority to each household of the housing cooperatives. This household attribute refers only to cooperative households and describes the number of years (counted in days) that the household is a member of the specific cooperative. Seniority might range between 1 and 60 years and is randomly distributed to the households based on the age of the household's main occupant. This number is important for the matching of dwellings and households, the allocation of dwellings to households by the owners, because households with higher seniority are given priority. Mobiliar has no seniority number. Specifically, the model assigns a random number between 1 and 40 years if the age of the main tenants is below 65 years, and between 1 and 60 years if the main tenant is older than 65. For Mobiliar households, there is no seniority attribute, thus, it gets initialised to none.

Table 4.29 – Model design - Household model - Initialisation - Combination of typologies and size

Household's size combinations per household typology	
Typologies of households	**Potential size of household**
One-person household < 65 years old	1
One-person household >= 65 years old	1
Couples without children < 65 years old	2
Couples without children >= 65 years old	2
Single parents with children	2,3,4,5+
Couples with at least one child	3,4,5+
Other multi-person households	2,3,4,5+
Source: Own analysis based on FSO and SHEF survey	

In order to initialise the agent's attributes "environmental awareness" and "household's satisfaction", we use data from the SHEF Survey. Specifically, for the satisfaction of the household with its current dwelling we are based on the answers to the survey question: "Overall, how satisfied are you with your current dwelling?". This allows to initialize the satisfaction of households with their dwelling (see Table 4.30 and section 4.6.2.1). The environmental awareness is perceived as the combination of two factors: (a) the willingness of households to move to a smaller dwelling if the household size decreases, and (b) the importance of the existence of energy performance labels when choosing a dwelling. This is based on two SHEF survey questions: (1) "How willing would you be to move to a smaller dwelling if your household size decreased?", (2) "Minergie Standard, LEED Standard, Minergie P: Were these features a factor in your choice of dwelling?" (see Table 4.31). This allows the initialisation of the environmental awareness of each household.

Table 4.30 – Model design - Household model - Satisfaction of households with current dwelling

Household satisfaction	
Question: Are you satisfied with your current dwelling?	
Level of satisfaction	% of households
Low ("No")	14.3
Medium ("neither-neither")	5.7
High ("Yes")	80
Source: Own work and SHEF Survey	

Table 4.31 – Model design - Household model - Environmental awareness of households

Environmental awareness	
Question: "Was the Minergie or any other label important for your dwelling decision?	
Environmental awareness level	% of households
Low ("No")	56.5
Medium ("Partly")	31.2
High ("Yes")	12.3
Question: "Would you be willing to move to a smaller dwelling if your household became smaller?	
Low ("No")	38.7
Medium ("Maybe")	37.6
High ("Yes")	23.7
Source: Own work based on SHEF Survey	

4.6.2.13 HH_model Validation

The Household Model is validated and calibrated with data from FSO and Wüest Partner. There are several reports predicting the evolution of the population and the households ((FSO, 2016*b*, 2021*r*,*f*, 2015*b*)). After initialisation, the model runs for 30 years (360 time steps), and we compare the evolution of the households in the model to the predictions from these sources (see Table A.23 in the appendix for the initialisation values of the parameters, and chapter 2 for the reference values that were used for validating and calibrating the model). Specifically, we look at the evolution of the typologies and the size of households.
According to the predictions (FSO, 2016*b*), we expect a decrease of the household typology "couples with children", mainly because of the fact that the children of baby bloomers grow up and tend to live alone. Although women are expected to give birth at the same rate, there will be less households with "couples" typology. However, "couples with children" will continue to be the dominant typology (FSO, 2015*b*). In addition, the typology "couples without children" will increase significantly (FSO, 2016*b*).
Based on the FSO forecast, small sized households (1-2 persons) are expected to increase (FSO, 2020*b*). In detail, in 2020, 1 person, 2 person and 3+ person households are representing 35%, 33% and 32% of the total households in Switzerland respectively; in 2045, the respective percentages are estimated to be 37.5%, 33.5% and 29%. In 2020, according to the baseline scenario, the average number of persons per dwelling is 2.24; by 2045 we expect it to decrease to 2.16 (FSO, 2016*b*).
Because of the COVID-19 pandemic and the augmenting teleworking,the size of the dwelling is expected to grow further as more people will work from home and spend more hours in the house. Although the number of small sized households will increase, the demand for small dwellings is not expected to grow as much. The trend of having more small dwellings is expected to slow down. During the pandemic, the search for medium-large dwellings increased (Wüest Partner, 2021*i*).
Furthermore, we foresee an augmentation of the average floor area per capita (46 m^2/capita), not only due to the growth of dwelling size but mainly because of the shrinking size of households (Wüest Partner, 2021*i*). Life expectancy is increasing and a great number of old people need housing. Based on the statistical analysis of housing data, the elderly have the highest floor area per capita. Furthermore, regarding the residential mobility (see chapter 2, section 2.8), changing dwellings is becoming more frequent, the relocation rate was 10%-15% in 2017 and is expected to increase over the next years (Wüest Partner, 2020*g*). Based on these trends, the HH_ model has been validated.

4.6.2.14 HH_model Assumptions and Limitations

The HH_ model makes several assumptions:

- The evolution of the household population follows the predictions of the Swiss population in terms of number of persons, size and typology of households.
- The demand is high, and there are always enough households entering the system boundaries looking for a dwelling to rent.
- The initial state of the households and the initial matching of dwellings and households are based on the SHEF survey and HBS. No detailed data about the households that occupy the dwellings of the case study owners was available.
- All dwellings of the cooperatives are considered occupied at t = 0 (vacancy rate = 0% for the cooperatives).
- Households evolve over time; the attributes of households might change because of certain events, e.g., marriages, divorces, births or deaths. The events are represented by yearly probabilities. However, the model has monthly time steps. For this reason, each yearly rate is translated into a monthly rate and applied to households on a monthly basis.
- Only one event per household can happen in each time step. For example, it is not possible for households to experience marriage and child birth in the same time step. Only income change and child leaving home functions can happen simultaneously.
- In the context of this thesis, when we refer to a marriage event, we refer to any kind of official way of two persons forming a couple.
- In the case of a marriage, the model assumes that the main tenant of an existing household gets married and forms a couple with one person coming out of the system boundaries.
- In the case of a divorce, two separate households are created in the next step. The model assumes that both stay within the system boundaries.
- The model assumes the typology "Other multi-family household" is not susceptible to any event change, because the number of such households is very small and we assume it doesn't affect the overall dynamics.
- In the case of a death event, the model assumes that this event cannot happen to the household typology "single parents households".
- In the case of household events, not all possible household typology combinations are studied. Specifically in Table 4.24, all model combinations of household typologies before and after the event are outlined. However, not all combinations are covered.
- The environmental awareness level of households is assumed to remain static over time. In the future, another model could introduce a dynamic character of that attribute. The behaviour of households and the attitude of tenants towards the environment changes

over time and is influenced by several factors such as environmental campaigns, the behaviour of other people, etc.

The limitations of the model can be summarised in the following points:

- The age of the household members is not studied in depth. The focus of this research lies on the owners and the evolution of the building stock. The HH_ model generates households and groups them based on size, income and other characteristics of the household. However, it doesn't follow in detail the age of the occupants; it just differentiates between younger and older households based on the age of the main tenant (older or younger than 65 years old). In the future, a more detailed model could focus on the tenants and model the ageing of all household members. This would improve the description of the households' housing preferences and consumption.
- The initialisation of the model is based on the SHEF survey. The information regarding the income of the households and the households living in subsidised dwellings has been limited.
- The system boundaries of the model include the dwellings and households of the three property owners. This system represents a very small part of the Swiss housing market and has special characteristics such as a high percentage of cooperative dwellings.
- The satisfaction of the households with their current dwellings is only based on a general satisfaction level (based on the results of the SHEF Survey). Household satisfaction is a complex notion and has been studied thoroughly in the literature. However, since this model focuses on owners, it describes the level of satisfaction in a simple way, neglecting elements of its complexity. A future model could describe in depth the satisfaction of the tenants, which could be based on more dwelling characteristics, e.g., location, rent, centrality, vicinity to public transportation, size, view, luminosity, equipment, etc.
- The six events of household change have impact to specific household typologies. The typologies that are affected by each event can be extended to all household typologies. Furthermore, in an improved model, household events could happen simultaneously, allowing several events to occur to each household in each time step.
- Immigration and emigration is not taken into consideration. The evolution of households depends on the yearly birth, death, marriage and divorce rates of Switzerland.
- The income of the households could be studied in more detail; the determinant household income could be taken into consideration. In addition, in the case of a marriage, divorce and death, the model changes income only by one income category. A thorough household model, having more income groups that would describe income changes in more detail, would closer depict reality.

4.6.3 Matching Model (Matching_ model)

The Matching model is responsible to connect the BS_ model and the HH_ model. Its purpose is to allocate the dwellings to the households that have been looking and applying for a new dwelling. It runs on a monthly time step, after the BS_ model and HH_ model have been updated. Its input is a list of all the vacant dwellings (VacDW) at that time step and a list of all the households that search a new dwelling (HHsearch). Each in search household has applied to three desired dwellings (specific dwelling IDs). The output of the model is the matching between dwellings and households, in other words the allocation of the dwellings to the households.

In detail, at a arbitrary time step t = n, there are x number of vacant dwellings on the market. First, the model checks for each vacant dwelling all the possible / interested households; once the household is chosen and the dwelling is rented, it moves to the next vacant dwelling. In addition, there are y number of households (either among the existing households in the system or new households entering the system) wishing to find a new dwelling; each of these households applies to three specific dwellings with specific dwellings IDs. The Matching model, through a set of rules and priority criteria[32], proposes the dwelling to a specific household (ABZ, 2015; SCHL, 2018*b*). Once the household is chosen by the owner, the model assumes that the household will accept the proposed dwelling and move in, in the next time step t = n+1. The households that were not chosen keep applying for a new selection of desired dwellings for some time steps (see section 4.6.2.11 "Leaving the system function"). After that period, if they still haven't found a new dwelling, they leave the model's system. The matching model is based on empirical data and detailed rules of dwelling allocation that were provided by the property owners. The matching model flow chart is explained step by step in the following paragraphs and is illustrated in Figure 4.9. For more details, please refer to Figure B.11, Figure B.8, Figure B.9, Figure B.10 in the appendix.

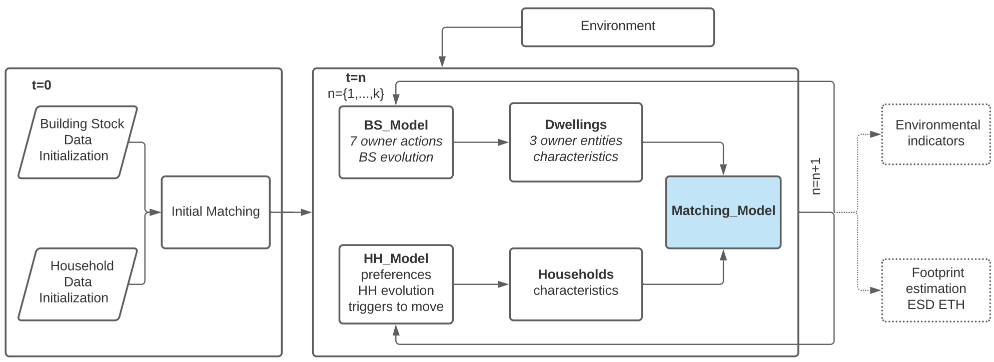


Figure 4.8 – Model design - Matching model flowchart

[32]The occupancy rules and priority criteria are defined by the occupancy rules regulation, which are set by the property owners and were verified during the owner workshops.

4.6.3.1 Initial matching

After initializing the dwellings and the households, the model performs the matching between the initial dwellings and households. The initial matching that describes the housing situation at t = 0 is done as follows:

Step 1: The number of initial households is defined, based on the number of initial dwellings (11,112 dwellings). The model assumes that at t = 0 all cooperative dwellings are occupied, while Mobiliar dwellings have 4% vacancy rate.

Step 2: Based on the results of SHEF survey and the Household Budget Survey (FSO, 2016*a*) the initial households and their attributes (type, size, number of children, environmental awareness level and satisfaction with current dwelling) are generated.

Step 3: The Matching model runs for the initial dwellings and households. The result of it is the initial matching. However, this first matching is close to a perfect match, based on the occupancy rules of the owners. We know that in reality, there is a mismatch between dwellings and households. In order to achieve this, we run the model for five years.

Step 4: The model runs for five years (60 time steps), keeping static both the building stock (no evolution of dwellings) and the households (no evolution of households). The model only allows the movement of the initial households to the initial dwellings. This is done in order to create a mismatch of dwellings and household that is closer to the reality. After that, the timer is set to zero again and this matching of dwellings and household is considered as the initial matching at t = 0 of the model. The initial matching is the same for every time the model runs.

4.6.3.2 Market control function

Once the model starts running, at every time step there are households wanting to move to another dwelling and new households entering the system searching for a vacant dwelling. Every month, two lists are imported to the Matching model: (1) a list with all the in search households (HHsearch) and (2) a list with all vacant dwellings (VacDW). After importing the lists of vacant dwellings and of applicant households, the market function is activated. Dwellings are categorised into free or subsidized market, households as well might be entitled to a subsidized apartment. Households can apply for a subsidized dwelling if they fulfil a variety of criteria concerning income, size or distance from work. The criteria are set and controlled by the city of the canton [33] (Canton Vaud, 2015; RCOL, 1991; RCOLLM, 2007). In Table 4.32, the possible combinations between the market types of dwellings and households are presented. For every vacant dwelling, the model checks for applying households (as

[33] In the context of this thesis, we used the regulation of canton Vaud and city of Lausanne regarding the access of households to subsidized dwellings. Source: Canton Vaud: https://www.vd.ch/themes/territoire-et-construction/logement/aides-et-subventions/logements-subventionnes-aide-a-la-pierre/trouver-un-logement/ and city of Lausanne: https://www.lausanne.ch/vie-pratique/logement/logements-subventionnes/conditions-demarches.html#

households apply to specific dwelling IDs). As we can see in Figure B.11 the first check the model performs is the market control. If the condition is fulfilled and the household passes the market control, it continues to the next step, the income and occupancy rules control.

Table 4.32 – Model design - Matching model - Market control

Market control - Possible combinations of market types		
Dwelling's market type	**Household's market type**	**Market control outcome**
Free	Free	The free households can only apply for a free-market dwelling. So, the household passes the control successfully.
Free	Subsidized	The free-market dwelling can be rented to both free and subsidized households. In the model if a subsidized household can't find a dwelling for six time steps then it becomes free household and can apply to free-market dwellings, keeping the information that it used to be subsidized, because it might be given priority over other free households, depending on the owner's priority criteria.
Subsidized	Free	A subsidized dwelling can never be occupied by a free household. So, the household fails to pass this step.
Subsidized	Subsidized	A subsidized dwelling can only be occupied by a subsidized household. So, the household passes the control successfully.
Source: own work		

4.6.3.3 Occupancy function

Once the market control is complete and the household successfully passes the market control, the occupancy function is activated. In this function, the income and occupancy rules are checked. These rules are set by the owners of rental dwellings to assure that tenants can afford the rent and the dwelling will not be over- or under-occupied. Owners compare the household size to the dwelling size and the household income to the gross rent. Specifically, there are two main criteria that applicant households either fail or pass:

- Physical criteria refer to the room stress which is described by the by minimum and maximum occupancy (see Table 4.33). The size of the dwelling is compared to the household size. These rules are mandatory for the subsidized dwellings by the state. Nonetheless, there is no control by the state for the free-market dwellings concerning the occupancy. However, housing cooperatives define occupancy rules also for the free-market dwellings in order to avoid over- and under-occupancy and to allocate space-efficiently their dwellings[34]. In the case of Mobiliar, there is not a clear occupancy rule as long as the tenants can afford the rent. However, they do not want to over-populate their dwellings.

- The second criterion is the financial criterion, which describes the affordability of the dwelling. The owners control whether the households are able to pay the rent. Housing

[34]The occupancy and income rules were provided by the owners. ABZ's and SCHL's occupancy regulation is available online (ABZ, 2015; SCHL, 2018*b*), Mobiliar doesn't have strict rules since the management of its stock is allocated to several agencies all over Switzerland. However, there are some basic occupancy, income and priority rules that were given to us during the owner workshops.

cooperatives demand a minimum household income of three times the gross rent and a maximum income of fifteen times the gross rent. Mobiliar asks for at least three times the rental price (see Table 4.33).

Table 4.33 – Model design - Matching model - Occupancy and income rules

Owner's occupancy rules						
	ABZ		SCHL		Mobiliar	
Number of rooms	Number of occupants					
	Min >=	Max <=	Min >=	Max <=	Min >=	Max <=
Physical criteria - Owner's min & max occupancy						
Free market & subsidized market						
1-1.5room	1	2	1	2	1	2
2-2.5room	1	4	1	3	1	3
3-3.5room	2	5	2	4	1	4
4-4.5room	3	6	3	5	2	5
5-5.5room	4	7	4	6	3	6
6-6.5room	5	8	5	7	4	7
7-7.5room	6	9	6	8	4	8
Financial criteria - Owner's income rules						
Free market						
	Household's Income					
	Min >=	Max <=	Min >=	Max <=	Min >=	Max <=
	3 x gross rent	15 x gross	3 x gross rent	15 x gross	3 x gross rent	
Subsidized						
	Fixed by the state					
Source: Workshops with the project's collaboration partners, own analysis						

4.6.3.4 Priority function

Once the applicant households have passed successfully the physical and financial criteria set by the owners, they still haven't been proposed to rent the desired dwelling. They still have to compete with the other households that applied for the same dwelling and passed the above criteria. The owners will decide which household will get the dwelling based on a variety of priority criteria[35] (ABZ, 2015). For that reason, the model creates a scoring system and and allocates a priority number (PRIO) to each household based on a list of criteria according to which priority is given, e.g., the household is already a tenant of the same owner, the household is no longer entitled of a subsidy (in the case of the housing cooperatives), the household wants to move to a smaller dwelling, the household is a family with minor children, the reason for moving was a death or divorce, etc. The household with the highest score is offered the dwelling. In case of equal score, the household living longest in a dwelling of the same owner is given priority. This is decided based on a household's attribute "Seniority"[36] that counts

[35]The details of the prioritisation of households have been defined in collaboration with the property owners during the owner workshops and in private meetings; for detailed description of the priority rules of each owner see Figure B.8, Figure B.9, Figure B.10.

[36]Seniority is defined differently for each owner. SCHL: Seniority= (2 x member days) + waiting days, ABZ: Seniority=member days + waiting days, Mobiliar doesn't use this term. Seniority is counted in days; member days

the days that each household has been a member of the same cooperative (for more details regarding the initialisation of this attribute, see section 4.6.2.1). Seniority applies only for the cooperative dwellings.

4.6.3.5 Matching Model Validation

The Matching model is validated and calibrated using data from two sources: (1) the case study owners and (2) FSO. The owners collected statistics regarding the occupancy of their building stock; detailed information can be found in chapter 3. The Federal Statistical Office publishes regularly high quality data regarding the rental building stock and its occupants in Switzerland. In order to validate the Matching model, we focused on specific indicators, e.g., floor area (m^2/dwelling), floor area per capita (m^2/capita), floor area per room (m^2/room) or persons per room. It is not possible to validate the matching model by simulating the dwelling occupancy evolution over a period of time in the past, as we did for the BS_ model (2000-2020), since there was not available data about the occupancy of the dwellings in the past.

4.6.3.6 Matching Model Assumptions and Limitations

- The model assumes that households that are interested to move apply only to three specific dwellings. A small number was chosen to decrease computational burden.
- The matching model runs for every vacant dwelling and checks all the applicant households for this dwelling. The winner household gets the offer, and the model assumes that the household accepts it. In reality, the owner or agency proposes the dwelling to the household, and the household decides whether to accept it or not.
- The model assumes that the desired dwellings of each household are located in the same canton as the previous dwelling (if this information is available).
- Mobiliar does not have fixed occupancy or income rules; the model attributes some rules that are looser compared to the cooperative rules. However, in reality, Mobiliar might apply different occupancy rules depending on the agency that manages the specific settlement. In addition, a dwelling might be allocated to a household that does not fulfil all the criteria because it was vacant for a long time.
- Due to lack of data regarding the seniority of cooperative households, the model assumes a distribution of the seniority number.
- In case of households that are entitled to a subsidy but cannot find a subsidized dwelling, the model assumes that these households start looking for free-market dwellings. Thus, their market attribute is changed to free-market.

counts how many days have passed since the moment that the household started living in a dwelling of the same owner and waiting days how many days does the household wait in order to find a dwelling.

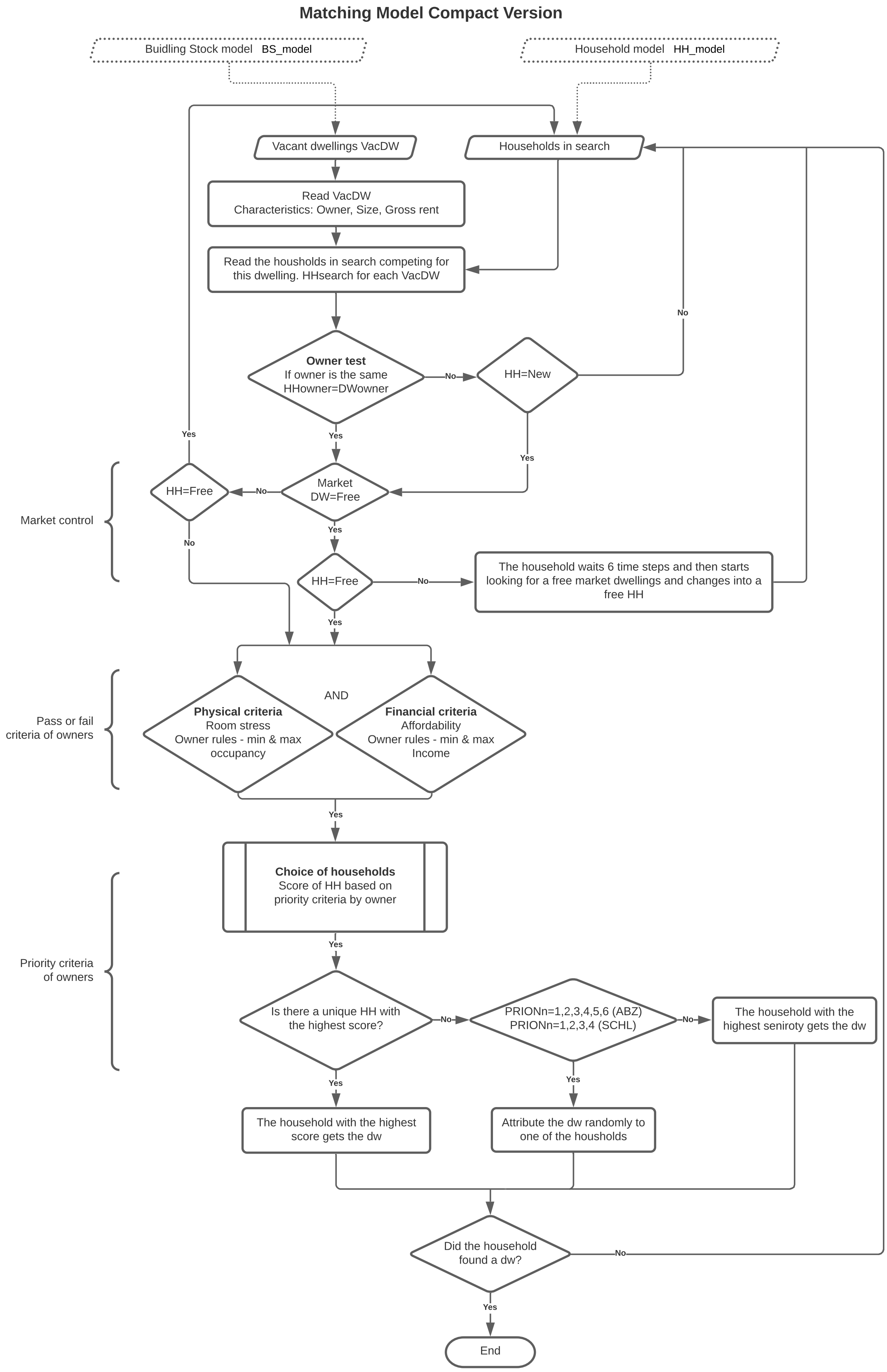


Figure 4.9 – Model design - Matching model flowchart - compact version

Based on the design of the model and the above mentioned assumptions, the model has some limitations:

- It doesn't take into consideration the possibility of households wanting to move outside of the canton. However, there are new households entering the system boundaries, but the model doesn't discriminate among the different types of residential mobility e.g internal, external, within the same canton, city, postcode or building.
- Since subsidized dwellings constitute only a very small part of the case study building stock and since the specific owners have almost stopped constructing subsidised dwellings, the residential mobility and the allocation of subsidised dwellings is understudied.
- Due to the small system under study, the model cannot describe the housing market as a whole. This implies that households looking for a dwelling for a specific period of time leave the system.

4.7 Conclusion

The three models function as an integrated model (see Figure 4.10) that gets updated every time step (1 month). In every tick, the building stock evolves and gets updated, based on the BS_ model; the households evolve and get updated according to HH_ model; the Matching model allocates the dwellings to the households. This means that in every time step the model offers a clear picture of the building stock and its tenants. The model runs on a monthly time step, however for every year a detailed report of the building stock, the households and the performance of each owner is produced. This allows to calculate a set of useful indicators, e.g., floor area (m^2/dwelling), floor area per capita (m^2/capita), floor area per room (m^2/room), persons per room, financial returns, new construction rate, etc. Specifically, the model calculates on a yearly basis (for each owner and for the total stock) the following:

- Dwelling surface indicators: average living surface (m^2/dwelling), average room surface (m^2/room).
- Occupancy indicators: m^2/capita, persons/room, rooms/person.
- Financial indicators: yearly return/owner (%), yearly return overall (%), yearly settlement return (%).
- Building stock size: New dwellings added because of new construction, demolition-reconstruction, transformation and dwellings removed because of demolition or transformation; proportion of dwellings based on size (1-room, 2-room, etc).
- Detailed list with all the dwellings and the households that occupy each dwelling.

Additionally, the model creates / exports a yearly list / report of specific characteristics of the building stock and the households. This output is imported to another model, developed by ESD Laboratory, ETH, that estimates the material and energy footprint of this housing system for every year. In the next chapter, the model simulations are presented and all these indicators are described in detail.

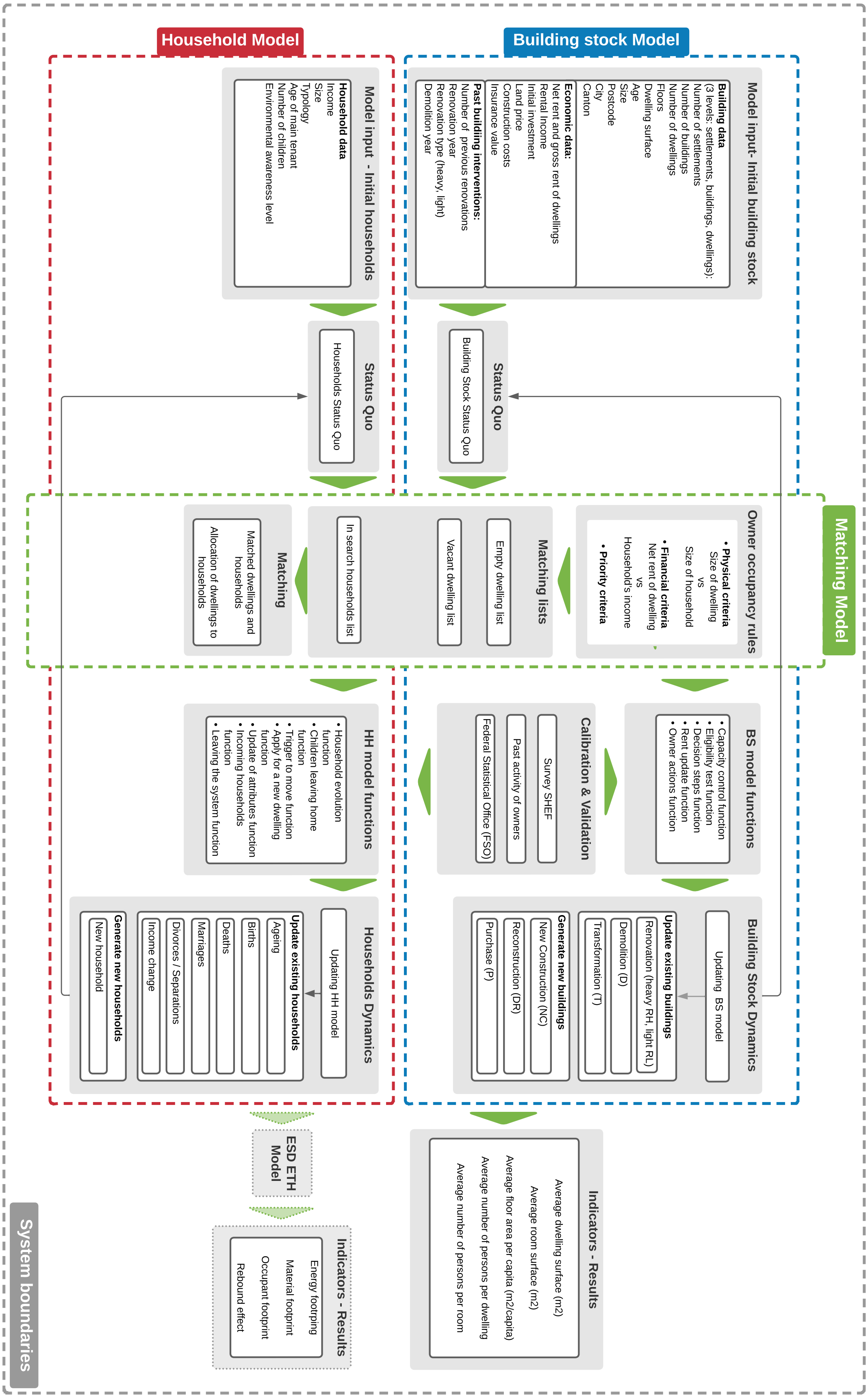


Figure 4.10 – Model design - Integrated model flowchart

5 Simulations

5.1 Introduction

Chapter 3 outlines the characteristics of the case study property owners. In the previous chapter, a detailed description of the ABM is given. This chapter presents the simulation results and is divided in three major sections: (1) the developed scenarios, (2) the simulation results of the ABM and (3) the lessons learned. Chapter 2 lays out the unique attributes of the Swiss housing market and contributes to the interpretation of the simulation results.

5.2 Methodology

The main methods used to analyse the simulation results and to synthesise these results into practical lessons and recommendations aiming to reduce the environmental impact of housing are the following:

- *Agent-based model*
  An ABM was built to describe the case study housing market (chapter 4). It runs for the baseline scenario and another four scenarios that were developed for this thesis. The ABM was coded with the help of our student assistant Andreu Arderiu.

- *The software environment*
  The ABM is built in Python and Mesa, an agent-based modelling framework in Python. The analysis of the simulation results and the visualisations are performed with Excel, R and Python.

- *Swiss housing context*
  In chapter 2, the Swiss housing market and its unique attributes are studied, which offers an overview of the housing market problems and challenges, the legal framework and the future tendencies. Understanding the Swiss housing context allows to better interpret the simulation results.

5.3 Simulations

The goal of this research project is to estimate the environmental impact of housing and to develop measures to decrease it. Our model describes the housing market of a specific housing system and aims to assess the efficiency of measures to decrease the environmental impact of housing. The boundaries of the model system include the dwellings and households of three property owners, the three collaboration partners of the SHEF project (see chapter 3). By developing several scenarios, we aim to study the effect of different measures.
The model input is the initial building stock of the three dwelling owners and the households that occupy these dwellings. The model runs for 30 years (360 monthly time steps), and during this time both dwellings and households evolve. The output of the model is the updated building stock and households, as well as the allocation of the dwellings to the households. At the end of every year (every 12 ticks), the model generates an updated inventory of matched dwellings and households with all their attributes. This allows to calculate, on a yearly basis and at the end of the model simulations, a large set of variables. The model output consists of an exhaustive list of housing characteristics that can also be grouped by property owner or settlement. However, for clarity reasons, we mainly focus on the following:

- Number of newly added dwellings as a result of new construction (NC)
- Number of newly added dwellings as a result of transformation (T+)
- Number of removed dwellings as a result of transformation (T-)
- Number of newly added dwellings as a result of reconstruction (RE)
- Number of removed dwellings as a result of demolition (D)
- Investment cost
- Rental income
- Financial return
- Proportion of household typologies
- Proportion of household sizes
- Proportion of dwelling sizes
- Vacancy rate
- Dwelling surface (m^2/dw)
- Room surface (m^2/room)

- Floor area per capita (m^2/capita)
- Number of persons per dwelling (pers/dw)
- Number of persons per room (pers/room)
- Net rent and net rent per dwelling surface (CHF and CHF/m2)

5.4 Environmental indicators

As it was described in chapter 2 and chapter 4 (section 4.3), housing in Switzerland is responsible for almost one third of the country's CO_2 emissions and 45% of the total energy demand (SFOE, 2020). In order to reduce the environmental impact of housing, the target is to reduce the operational and embodied energy of buildings, the use of materials such as concrete, rock, sand, etc., to reduce land use and to eliminate fossil fuels. At the same time, housing should cover the basic needs of humans and be affordable, so that all people can have access to decent housing.

Housing size is the largest determinant of domestic energy consumption. The larger the floor space is, the greater is the need for energy for heating, cooling, ventilation and lighting (Moreau et al., 2021; Makantasi and Mavrogianni, 2016). As mentioned in section 2.3 in chapter 2, floor area and floor area per capita are considered the largest determinants of environmental impact of housing (Wüest Partner, 2020a; IRP, 2020; Heeren and Hellweg, 2019; Saner et al., 2013; Lavagna et al., 2018). By shrinking the size of the dwelling and the floor area that corresponds to each occupant, the environmental impact of housing would be limited. But to what extent can we decrease the living space of a person? What is considered adequate housing? How many square meters are sufficient for a human being? What are the requirements for decent living? Trying to answer these questions can be challenging. It is a multifaceted subject that can be seen through a technical, ethical, ideological and political angle.

Adequate housing is a human right in the international human rights law (UN-HABITAT, 1991). Adequate housing should provide access to: sufficient living surface, sanitation, clean water, security, adequate light, low noise levels. It should ensure access to adequate, safe and affordable housing. According to the UN report "UN Habitat: Adequate Housing and Slum Upgrading", a slum is defined as *"a dwelling where households are typically squeezed, having more than three individuals sharing the same habitable room"* (UN-HABITAT, 2018).

Housing sufficiency refers to the living surface per capita, the operational energy, security, quality characteristics of the dwelling, such as light, sound and clean water. But if we focus on the floor area per capita, how much is adequate? Establishing a moral minimum is a complicated issue (Rao and Baer, 2012). It is no longer just a question of a minimum net living area, but also of a maximum depending on the household size. The main room of a dwelling should have a surface of at least 14 m^2. All additional rooms should be at least 10 m^2, unless cantonal regulations allow smaller rooms (FOH, 2015). Quantifying how much room is enough is difficult, however, there are efforts that try to address this issue. For example, based on data from India, the minimum floor area per capita is estimated to be 10 m^2 (Rao and Baer, 2012; Rao et al., 2019); another appraisal refers that rooms should not be less than 12 m^2 (Wüest Partner, 2020*i*); another estimation of the minimum dwelling size refers to a minimum dwelling surface of 30 m^2 and 10 m^2 for each additional person above three household members (Rao and Min, 2017). Another study estimates the minimum sufficient space to 15 m^2 (Millward-Hopkins et al., 2020)[1]. According to the International Code Council (ICC), the minimum requirement for residential space is estimated to 14 m^2 for the first occupant of a housing unit and 9 m^2 for every additional person[2] (Cohen, 2021). The average living surface in Switzerland was 46 m^2 per capita in 2020 (Wüest Partner, 2021*i*; FSO, 2020*m*; Moreau et al., 2021). If we were to reach 10 m^2, 15 m^2, or 20 m^2 per capita, that would entail a decrease of 78%, 67% and 57% respectively, in relation to the current floor area per capita (46m^2).

In the context of this dissertation, the environmental impact of housing is directly associated to housing size and housing sufficiency. Therefore, we assess the environmental impact of housing through a set of five environmental indicators of housing. The model calculates for every year and every owner the following indicators: (1) average dwelling surface (m^2/dw), (2) average room surface (m^2/room), (3) average floor area per capita (m^2/capita), (4) average number of persons per dwelling (pers/dw) and (5) average number of persons per room (pers/room)[3].

[1]It assumes that 10 m^2 is enough for each household member and it adds another 20 m^2 of communal space in the dwelling; for a four person household this translates into 60 m^2 divided by the four occupants, we get 15 m^2.

[2]This translates into 23 m^2 for two persons, 32 m^2 for three persons, 41 m^2 for four persons and 50 m^2 for five persons, which corresponds to approximately 10 m^2 per capita.

[3]The first two indicators (dwelling surface and room surface) are considered as surface-related indicators as they describe how large dwellings are; the last three indicators (floor area per capita, number of persons per dwelling, number of persons per room) are called occupancy-related indicators as they describe how densely occupied dwellings are. These indicators are calculated on a yearly basis for the total of the housing stock and for each owner separately. For the analysis of the results, we first compare the values of the indicators between 2020 and 2050 and then we compare the values of the indicators, as predicted by the model for the year 2050, among the various scenarios.

5.5 Scenarios

In the context of this thesis,five scenarios are developed. Each scenario makes different assumptions about the construction activity of dwelling owners, the occupancy rules and the environmental awareness of households. According to the scenario assumptions, the parameters of the model take different values. First, we run the baseline scenario where all parameters are initialised as described in the previous chapter. This scenario functions as a reference scenario. In scenario 1 "Ideal Occupancy", the occupancy rules applied by the dwelling owners become stricter. Specifically, the room stress criteria, i.e., minimum and maximum number of tenants by dwelling size[4] according to which dwellings are attributed to households, become tighter. Next, scenario 2 "Densification" refers to the urban densification in terms of regeneration and efficient exploitation of the existing urban area as a contrast to urban sprawl. In this scenario, new construction is limited and the focus of the construction activity lies on transformations and demolitions-reconstructions of buildings. Scenario 3 "Combi" is the combination of scenarios 1 and 2. In this scenario, both occupancy rules are stricter and construction activity concentrates mainly on the utilisation and densification of existing buildings. Finally, in scenario 4 "Green household", the model assumes that the environmental awareness level of households gradually increases. This implies that tenants are more sensitive to environmental issues and aware that living surface plays an important role to the protection of the environment. As a result, it is the households that take the initiative to live in a smaller dwelling. In the following sections, all scenarios are described in detail. After the scenario description, a comparative analysis of their results and a discussion with the main findings follows.

5.5.1 Baseline scenario

The reference scenario (REF) provides housing-system projections in 2050 based on current trends and policies. It assumes that there will be no significant change in property owners' priorities, or tenants' attitudes and preferences, or technology. There are no new environmental policies implemented, apart from those that are already in effect, or at least no change in policies that have an important influence on the questions being analysed. The housing market is expected to continue with the same patterns in the future. This scenario is a 'non-intervention' scenario, which implies that all model parameters remain constant. According to the baseline scenario, property owners will continue making decisions as usual, the building stock will evolve as it evolved until now, as described in the BS_ model, and households will grow as described in the HH_ model in the previous chapter (chapter 4).

[4]When we refer to occupancy rules, the dwelling size is usually counted in terms of number of rooms and not in square meters of the dwelling.

The model is initialised as shown in the previous chapter (section 4.6.1.11, section 4.6.2.12, section 4.6.3.1 and table A.5 in the appendix). All model parameters are set as described in chapter 4. We have run 50 simulations according to the baseline scenario. At the end of each simulation, an exhaustive yearly inventory of both the building stock and the households is generated. Additionally, the output of the model is the set of five environmental indicators; for each indicator, the average value of the 50 model simulations is calculated.

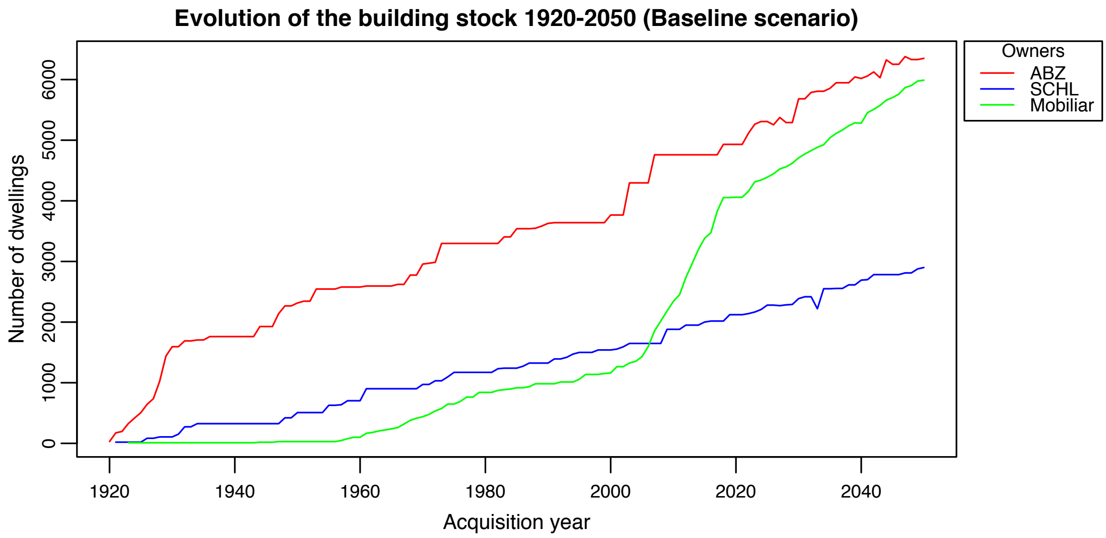


Figure 5.1 – Simulations - Evolution of the building stock - Baseline scenario

In Figure 5.1, the evolution of the building stock in terms of number of dwellings by owner is illustrated. The model's prediction is added to the known evolution of the building stock until 2020. Small fluctuations in the total number of dwellings can be explained by the dwellings that are removed from the market in the case of a heavy renovation, transformation or demolition. The settlements that are chosen for one of the previously mentioned owner actions are temporally removed from the building stock. After the completion of the construction works, the renovated or reconstructed dwellings are available for rent and announced vacant in the market, which explains the small peaks in the diagram.

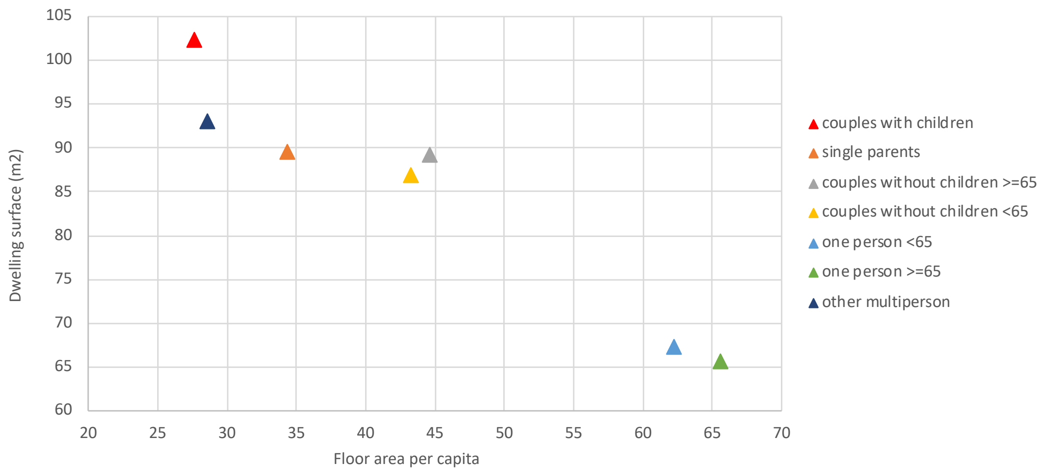
In Table 5.1, the five indicators and some representative housing attributes are outlined. The average dwelling surface increases from 81.4 m^2 in 2020 to 86.6 m^2 in 2050, which corresponds to an increase of 6.4%. This follows the current trend that predicts a constant increase of the living surface of residential units. The surface of dwellings belonging to non-profit property owners increase less than dwellings of the profit-oriented sector. This is mainly explained by the specific construction rules that the cooperatives follow. They usually have specific detailed instructions regarding the construction and renovation works, e.g., average dimensions of dwellings, rooms depending on its use (kitchen, bathroom, living room, etc.), material choice, heating sources, windows, insulation etc. As a result, although they follow the tendency of surface increase, the increase is not as sharp. Similarly, room surface augments by 5.0%, reaching 25 m^2 (23.8 m^2 in 2020). The room surface of cooperative dwellings increases less than the dwelling surface. Furthermore, the proportion of large dwellings increases, as it is shown in Table 5.1.

Table 5.1 – Simulation results - Baseline scenario

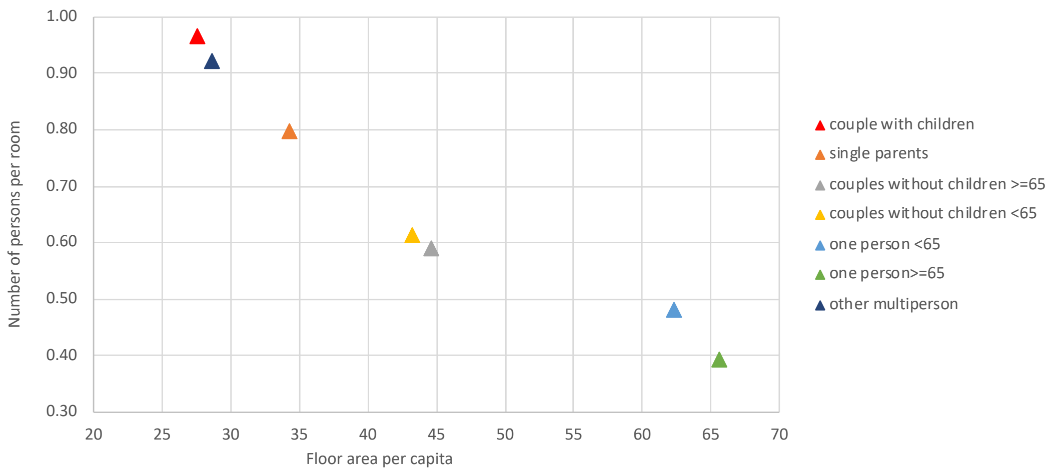
Model simulations - Baseline scenario results - average values in 2050												
	ABZ			SCHL			Mobiliar			All owners		
Indicators	2020	2050	% *	2020	2050	% *	2020	2050	% *	2020	2050	% *
Dwelling surface (m^2/dw)	78.6	82.1	+4.5%	75.5	78.3	+3.7%	87.9	95.3	+8.4%	81.4	86.6	+6.4%
Room surface (m^2/room)	22.5	22.8	+1.3%	24.9	25.3	+1.6%	24.7	26.8	+8.5%	23.8	25.0	+5.0%
Floor area per capita (m^2/capita)	35.8	39.9	+11.5%	39.5	43.9	+11.1%	42.1	46.8	+11.2%	38.8	43.1	+11.1%
Persons per dwelling (pers/dw)	2.62	2.39	-8.8%	2.33	2.13	-8.6%	2.39	2.22	-7.1%	2.48	2.28	-8.1%
Persons per room (pers/room)	0.71	0.64	-9.9%	0.72	0.66	-8.3%	0.64	0.61	-4.7%	0.69	0.64	-7.2%
Proportion of dwelling size												
1-1.5 room	3.4%	3.7%	*+8.8%*	2.5%	1.1%	*-56.0%*	5.0%	5.1%	*+2.0%*	3.8%	3.7%	*-2.6%*
2-2.5 room	17.3%	17.0%	*-1.7%*	22.8%	19.5%	*-14.5%*	19.2%	18.9%	*-1.6%*	19.0%	18.4%	*-3.2%*
3-3.5 room	40.5%	35.7%	*-11.9%*	43.7%	42.2%	*-3.4%*	37.5%	38.0%	*+1.3%*	40.0%	37.9%	*-5.3%*
4-4.5 room	30.9%	33.8%	*+9.4%*	27.6%	32.7%	*+18.5%*	32.1%	32.2%	*+0.3%*	30.7%	33.1%	*+7.8%*
5+ room	7.9%	9.8%	*+24.1%*	3.4%	4.5%	*+32.4%*	6.2%	5.8%	*-6.5%*	6.5%	6.9%	*+6.2%*
Net rent (CHF)	1,006	1,249	*+24.2%*	*1,011*	1,243	*+22.9%*	1,556	1,874	*+20.4%*	1,208	1,487	*+23.1%*
Net rent per floor area (CHF/m^2)	12.9	15.3	*+18.6%*	13.2	16.0	*+21.2%*	18.3	20.7	*+13.1%*	14.9	17.8	*+19.5%*
Yearly owner actions (number of dwellings)												
NC	32			16			53			101		
P	5			2			8			15		
RE	30			13			13			56		
T+	24			12			14			50		
D	-20			-9			-6			-35		
T-	-22			-10			-10			-42		
all owner actions (newly added dwellings)	49			24			72			145		

Source: Own work, model simulations - average values result of 50 model runs
NC: Newly Constructed, P: Purchased, RE: Reconstructed, D: Demolished, T+: Transformed, T-: Removed for transformation dwellings
** % change between 2020 and 2050*

The floor area per capita increases significantly; in 2020, a household occupied on average 38.8 m^2, while according to the baseline scenario, it will occupy 43.1 m^2 in 2050, an increase of 11.1%. The number of persons per dwelling decreases by 8.1% between 2020 and 2050. This is due to the increase of the dwelling surface, in parallel with the shrinking of the household size. In the reference scenario, the growth of the building stock is mainly due to the construction of new buildings, and a slight decrease of the proportion of small sized dwellings is observed. Although the strategy of one of the cooperatives (ABZ) is to create more small sized dwellings to accommodate small sized households that are expected to increase in the future, the other cooperative (SCHL) focuses on the construction of larger dwellings to support families. The strategy and the target group of each owner defines the future evolution of its building stock.



(a) Dwelling surface and floor area per capita



(b) Number of persons and floor area per capita

Figure 5.2 – Simulations - Baseline scenario (2050) - Indicators by household type (three owners averaged)

Figure 5.2(a) shows that space consumption of one-person households is significantly higher than other types of households. Both old and young one-person households occupy more than 60 m^2 per capita, almost double than other household types. Couples with children occupy on average the largest dwellings, but have the lowest per capita space consumption. Households aged 65 and over tend to occupy slightly more room. Figure 5.2(b) shows that one-person households and couples without children occupy relatively high living surface, and they have the lowest score of number of persons per room, especially the one-person households. This is a proof that smaller households occupy larger dwellings and that couples without any children tend to occupy larger dwellings as a result of change of life phase. Probably households under the typology "couples without children" that used to have children in the past did not move to a smaller dwelling after the children moved out. From a perspective of housing sufficiency, there is potential for improvement in these two household types.

5.5.2 Scenario 1 "Ideal occupancy"

Property owners choose their tenants, either directly on their own or indirectly through agencies. The major factors that influence the choice of tenants are the relation between the size of the dwelling and the household (number of rooms vs number of occupants) and the relation between the rent and the financial capacity of the household (net rent vs income). The occupancy rules, in terms of the minimum and maximum allowed number of tenants depending on the dwelling size, are usually set and controlled by the property owners and/or the authorities. The reference values of the parameter "occupancy rules" are shown in Table 4.33 in section 4.6.3.3. In this scenario, the occupancy rules of the owners change. Specifically, the physical criteria based on which the owners allocate their dwellings (room stress) become stricter. For the model, this implies a change of the parameter "occupancy rules" in the Matching_model. All other parameters stay unchanged.
The new updated occupancy rules aspire to increase the number of persons that occupy the dwellings and to allocate the rental units in a more space efficient way . As described in detail in section 4.6.3, where the matching model is described, housing cooperatives apply strict occupancy rules to allocate the vacant dwellings to households that express their interest for the specific dwellings. These rules are based on comparing the dwelling size to the household size and set minimum and maximum occupancy. In reality, profit-oriented owners take as well into consideration the size and the composition of the household when allocating a dwelling. However, in a liberalised free market, such an owner aims to maximise rental income and investment return, thus the financial criteria seem to be more important. As long as the tenant can afford the rent, she/he can have the dwelling irrespective of the size of the household. In order to maximise profit, the owner might allocate the dwelling space-inefficiently and end up with under-occupancy.
Scenario 1 describes the ideal occupancy as shown in Table 5.2 below. By increasing the minimum number of occupants equal to the number of rooms of the dwelling, stricter occupancy rules are applied. Regarding the upper limit, it is set as for one of the cooperatives (ABZ), which is set to avoid over-occupancy. Ideal occupancy rules aim to avoid mismatch and allocate the dwellings more space-efficiently. However, there are no specific fixed occupancy rules that guarantee the ideal occupancy.

After conducting a research about the occupancy rules of housing cooperatives in Zurich (see section 2.7), where public utility property owners represent a higher percentage of rental dwellings, the following occupancy rules are chosen. In the context of this thesis, ideal occupancy is defined as: (1) *minimum occupancy: number of occupants = number of rooms* and (2) *maximum occupancy = ABZ maximum occupancy* (Table 5.2).

Table 5.2 – Simulations - Scenario 1 occupancy rules

Ideal occupancy according to scenario 1		
Dwelling size	Minimum occupancy	Maximum occupancy
1-1.5room	1	2
2-2.5room	2	4
3-3.5room	3	5
4-4.5room	4	6
5+room	5	7

We have run 50 simulations according to the "ideal occupancy" scenario. The resulting evolution of the building stock is shown in Figure 5.3. There are no significant differences compared to REF as all parameters influencing the construction activity are static. The interest shifts mainly to the three occupancy-related environmental indicators: floor area per capita (m^2/capita), number of persons per dwelling (pers/dw) and number persons per room (pers/room).

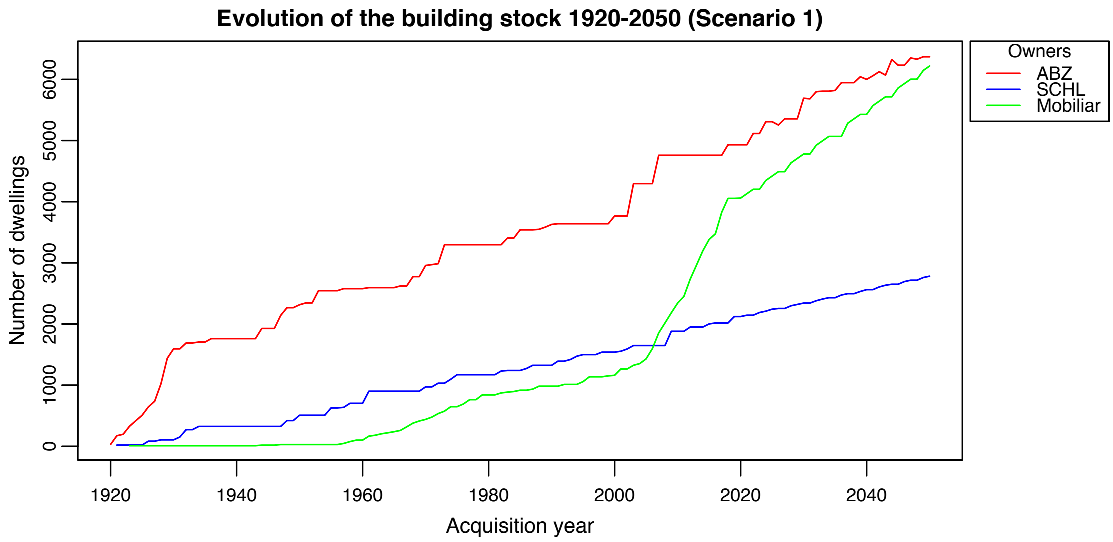


Figure 5.3 – Simulations - Evolution of the building stock - Scenario 1

As shown in Table 5.3, dwelling surface increases by almost 6% and room surface by 4.6%. However, according to the occupancy-related indicators, the average floor area per capita increases by 5.7%, while in REF the increase is 11.1%. Furthermore, the number of occupants per dwelling or per room continue to decrease, but not as sharp. The former decreases, between 2020 and 2050, by 4.8% and the latter by 4.3%. The proportion of larger dwellings augments, while smaller dwellings represent a smaller part of the pie. Dwelling growth is mainly the result of new constructions.

Table 5.3 – Simulation results - Scenario 1

Model simulations – Scenario 1 “Ideal occupancy” results - average values in 2050												
	ABZ			SCHL			Mobiliar			All owners		
Indicators	2020	2050	% *	2020	2050	% *	2020	2050	% *	2020	2050	% *
Dwelling surface (m^2/dw)	78.6	81.9	*+4.2%*	75.5	78.4	*+3.8%*	87.9	95.0	*+8.1%*	81.4	86.0	*+5.7%*
Room surface (m^2/room)	22.5	22.7	*+0.9%*	24.9	25.2	*+1.2%*	24.7	27.0	*+9.3%*	23.8	24.9	*+4.6%*
Floor area per capita (m^2/capita)	35.8	38.4	*+7.3%*	41.6	42.9	*+3.1%*	42.1	44.2	*+5.0%*	38.8	41.0	*+5.7%*
Persons per dwelling (pers/dw)	2.62	2.48	*-5.3%*	2.33	2.28	*-2.1%*	2.39	2.28	*-4.6%*	2.48	2.36	*-4.8%*
Persons per room (pers/room)	0.71	0.67	*-5.6%*	0.72	0.68	*-5.6%*	0.64	0.63	*-1.6%*	0.69	0.66	*-4.3%*
Proportion of dwelling size												
1-1.5 room	3.4%	3.5%	*+2.9%*	2.5%	1.1%	*-56.0%*	5.0%	5.2%	*+4.0%*	3.8%	3.8%	*-1.2%*
2-2.5 room	17.3%	17.1%	*-1.2%*	22.8%	19.7%	*-13.6%*	19.2%	18.9%	*-1.6%*	19.0%	18.4%	*-3.0%*
3-3.5 room	40.5%	35.8%	*-11.6%*	43.7%	42.5%	*-2.7%*	37.5%	37.1%	*-1.1%*	40.0%	38.1%	*-4.8%*
4-4.5 room	30.9%	33.8%	*+9.4%*	27.6%	32.1%	*+16.3%*	32.1%	32.5%	*+1.2%*	30.7%	32.8%	*+6.9%*
5+ room	7.9%	9.8.0%	*+24.1%*	3.4%	4.6%	*+35.3%*	6.2%	6.3%	*+1.6%*	6.5%	6.9%	*+6.8%*
Net rent (CHF)	1,006	1,272	*+26.4%*	1,011	1,255	*+24.1%*	1,556	1,841	*+18.3%*	1,208	1,482	*+22.7%*
Net rent per floor area (CHF/m^2)	12.9	15.7	*+21.7%*	13.2	16.1	*+22.0%*	18.3	20.5	*+12.0%*	14.9	17.8	*+19.5%*
Yearly owner actions (number of dwellings)												
NC	34			16			53			103		
P	5			2			8			15		
RE	32			15			14			61		
T+	24			12			14			50		
D	-22			-10			-6			-38		
T-	-22			-11			-12			-45		
all owner actions (newly added dwellings)	51			24			71			146		

Source: Own work, model simulations - average values result of 50 model runs
NC: Newly Constructed, P: Purchased, RE: Reconstructed, D: Demolished, T+: Transformed, T-: Removed for transformation dwellings
** % change between 2020 and 2050*

These results are describing the occupancy rules applied at the time of the rental lease. Still, there can be a future mismatch between dwellings and households. This is usually a result of the evolution of households and changes in their needs and preferences depending on the life phase they are in. Even owners that apply strict occupancy rules at the time of the lease fail to keep up with the future occupancy. It is difficult to apply a strict framework to motivate or force households to move to a smaller dwelling in case of an under-occupancy. It can be very challenging to check the evolution of the household size and to set a very strict follow-up occupancy framework from a practical and ethical point of view. There is potential to further decrease the occupancy of dwellings, on the one hand, by introducing measures to control the number of occupants in the course of time, and on the other hand by giving incentives to households to move voluntarily to a smaller dwelling in case of under-occupancy.

5.5.3 Scenario 2 "Densification"

In chapter 2, the main characteristics of the Swiss housing sector are briefly described. The importance of the environment protection and the potential that lies in the housing sector to decrease the GHG emissions are made clear. Protecting the environment is associated with the limitation of urban sprawl. The geomorphology of Switzerland imposes additional barriers to the development of urban settlements as land for construction and farming is limited. In Switzerland, there are strict zoning and land-use regulations. Buildable land is scarce and the land reserves decrease rapidly (see section 2.4). There have been discussions about adding more buildable land to the available land reserves for housing. However, it is not desired to decrease farming or forestry land, nor to expand the urban tissue.

Over the last decades, there has been an increasing interest to exploit the existing building stock, either by densifying existing buildings and using the maximum permissible floor area ratio (FAR) or by building in undeveloped plots or by transforming former industrial sites into residential units. The utilisation and reformation of the existing building stock is becoming progressively more common, and it is perceived as the big challenge for the future development of housing.

The "Densification" scenario (Scenario 2) refers to the shift towards the urban densification in terms of regeneration and a more efficient exploitation of the existing urban area, as a contrast to urban sprawl. This allows to increase population density and residential density[5]. Analysis up till now shows that there is great potential to increase both population and residential density by densifying the existing stock (Rey and Brenner, 2016; Rey, 2014).

The model assigns an owner attribute called “capacity” that refers to the maximum yearly number of dwellings each owner can add to its building stock (section 4.6.1.5). In the baseline scenario, all owners grow their building stock according to their construction capacity, as shown in Table 4.2 in the previous chapter. In this scenario, owners shift toward the transformation and demolition-reconstruction of their stock. For that reason, all owners decrease their new construction capacity and turn to the solutions of demolition-reconstruction and transformation not only to rejuvenate but also to densify their building stock. According to this scenario, new construction decreases to 20% of the total yearly capacity of the owners, demolition-reconstruction increases from 25% to 37.5% and transformation increases signifi-

[5]Population density refers to the number of people in a given area; Residential density refers to the number of dwelling units in a given area.

cantly from 5% to 37.5%. The total capacity of the owners doesn't change.
After a demolition, the reconstructed building has more dwellings; depending on the building, the increase of the number of reconstructed dwellings differs. For example, if the initial building was old and had large dwellings and rooms, the new floor plan will be designed more space-efficiently allowing to develop more housing units. Furthermore, it is possible that the land use regulations for the land, where the initial building was located, have changed. For example, the zone category could have changed over the years and a new floor area ratio (FER) might apply allowing to construct a larger total building surface, and thus, more dwellings.

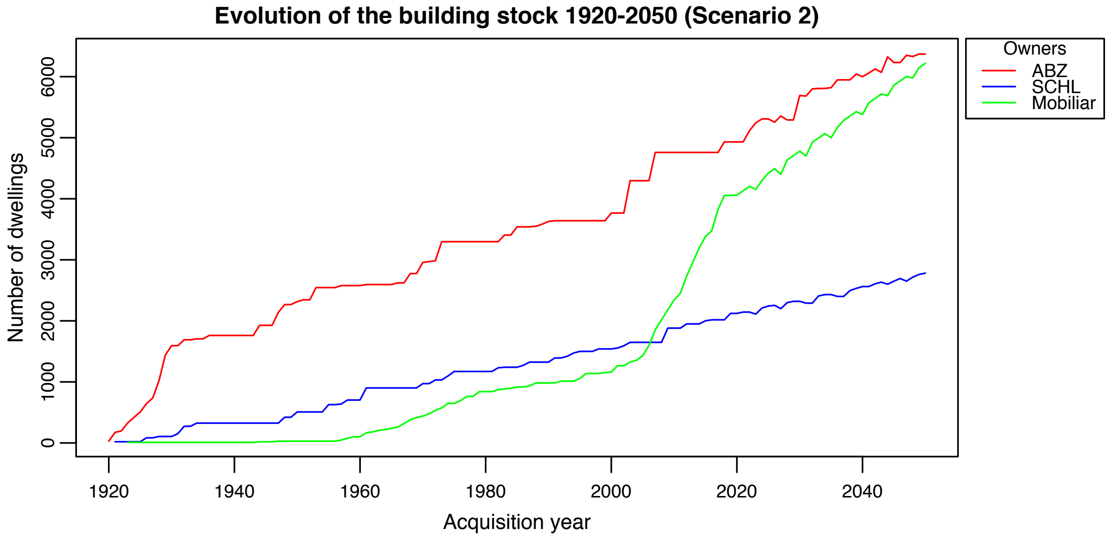


Figure 5.4 – Simulations - Evolution of the building stock - Scenario 2

We have run 50 simulations according to the densification scenario. Figure 5.4 illustrates the evolution of the building stock until 2050. In this scenario, the construction of new buildings slows down and the growth of the number of dwellings is mainly a result of demolitions and transformations, as shown in Table 5.4.
In this scenario, only the construction activity-related parameters changed, while occupancy parameters are the same as in REF. The average dwelling surface keeps following an increasing trend (+2.9%) but less steep compared to REF. Similarly, room surface increases as well but less intensely. The proportion of small sized dwellings increases significantly, and 5plus-room dwellings decrease. This is a result of the transformation and reconstruction patterns of the property owners. In the past, a demolition of a building was usually decided when the building was old and several renovations were undertaken. Buildings built before 1940 tend to have a greater proportion of large dwellings. As a result, once they are demolished, the new reconstructed buildings have a modern layout, having less large sized dwellings and more small and medium sized rental units.

Regarding the floor area per capita, it augments (+8.8%) since 2020, but not as sharply in comparison to REF. As occupancy rules do not change, this is a result of the change of housing supply that offers larger dwellings and a greater variety of dwelling sizes, i.e., more small sized dwellings. The number of persons per dwelling and per room keeps decreasing since 2020, but not as much. We observe that by densifying the building stock the occupancy-related environmental indicators show better results. The satisfactory results of this scenario led us run the following scenario 3, which is a combination of scenarios 1 and 2.

Table 5.4 – Simulation results - Scenario 2

Model simulations – Scenario 2 "Densification" results - average values in 2050												
	ABZ			SCHL			Mobiliar			All owners		
Indicators	2020	2050	% *	2020	2050	% *	2020	2050	% *	2020	2050	% *
Dwelling surface (m^2/dw)	78.6	81.2	*+3.3%*	75.5	76.8	*+1.7%*	87.9	91.1	*+3.6%*	81.4	83.8	*+2.9%*
Room surface (m^2/room)	22.5	22.1	*-1.8%*	24.9	24.2	*-2.8%*	24.7	25.5	*+3.2%*	23.8	24.0	*+0.8%*
Floor area per capita (m^2/capita)	35.8	39.1	*+9.2%*	39.5	42.9	*+8.6%*	42.1	46.1	*+9.5%*	38.8	42.2	*+8.8%*
Persons per dwelling (pers/dw)	2.62	2.42	*-7.6%*	2.33	2.19	*-6.0%*	2.39	2.21	*-7.5%*	2.48	2.30	*-7.3%*
Persons per room (pers/room)	0.71	0.65	*-8.5%*	0.72	0.67	*-6.9%*	0.64	0.62	*-3.1%*	0.69	0.65	*-5.8%*
Proportion of dwelling size												
1-1.5 room	3.4%	4.2%	*+23.5%*	2.5%	3.1%	*+24.0%*	5.0%	5.9%	+18.0%	3.8%	4.8%	*+26.3%*
2-2.5 room	17.3%	17.5%	*+1.2%*	22.8%	19.5%	*-14.5%*	19.2%	19.0%	-1.0%	19.0%	19.1%	*+0.5%*
3-3.5 room	40.5%	37.4%	*-7.7%*	43.7%	41.5%	*-5.0%*	37.5%	37.3%	-0.5%	40.0%	38.9%	*-2.8%*
4-4.5 room	30.9%	33.3%	*+7.8%*	27.6%	31.2%	*+13.0%*	32.1%	32.4%	+0.9%	30.7%	32.0%	*+4.2%*
5+ room	7.9%	7.6%	*-3.8%*	3.4%	4.7%	*+38.2%*	6.2%	5.4%	-12.9%	6.5%	5.2%	*-20.0%*
Net rent (CHF)	1,006	1,234	*+22.7%*	1,011	1,262	*+24.8%*	1,556	1,734	*+11.4%*	1,208	1,418	*+17.4%*
Net rent per floor area (CHF/m^2)	12.9	15	*+16.3%*	13.2	15.4	*+16.7%*	18.3	20.5	*+12.0%*	14.9	17	*+14.1%*
Yearly owner actions (number of dwellings)												
NC	10			4			15			29		
P	3			2			4			9		
RE	46			18			44			108		
T+	45			19			45			109		
D	-27			-11			-16			-54		
T-	-26			-10			-18			-54		
all owner actions (newly added dwellings)	51			22			74			147		

Source: Own work, model simulations - average values result of 50 model runs
NC: Newly Constructed, P: Purchased, RE: Reconstructed, D: Demolished, T+: Transformed, T-: Removed for transformation dwellings
** % change between 2020 and 2050*

5.5.4 Scenario 3 "Combi"

After analysing the results of the previous two scenarios, developing a new scenario that combines both of them seemed to be the next step. Scenario 3, named "Combi", is a scenario combining the housing supply measures taken in scenarios 1 and 2. On the one hand, occupancy rules become stricter and on the other hand, new construction is limited, whereas transformation and demolition-reconstruction projects become more frequent. That way, the building stock is increasing in terms of number of dwellings through the regeneration of existing buildings and on previously built land. Consequently, the need for new buildable land slows down, urban sprawl is limited and available living surface is allocated to tenants more efficiently, through the application of tighter occupancy rules.
We have run 50 simulations according to scenario 3, and the evolution of the building stock is shown in Figure 5.5. The evolution of the stock in terms of number of dwellings is similar to the previous scenario, and it is mainly the result of transformations and reconstructions (see Table 5.5). The majority of newly added dwellings are transformed or reconstructed dwellings. All five environmental indicators perform better in comparison to all previous scenarios, and show that the combination of densification and stricter occupancy rules achieve the best results. Both dwelling size and room size continue to grow (+2.8% and +1.3% respectively) since 2020. However, the increase is smaller, even in the case of the profit-oriented owner. Floor area per capita increases only by 3.4%, and number of persons per dwelling and room decrease by 3.2% and 2.9% respectively. The proportion of large sized dwellings decreases significantly, while the proportion of 1-room dwellings is rising strongly. The results show the importance of promoting policies that combine measures of different nature in order to tackle the issue from different sides.

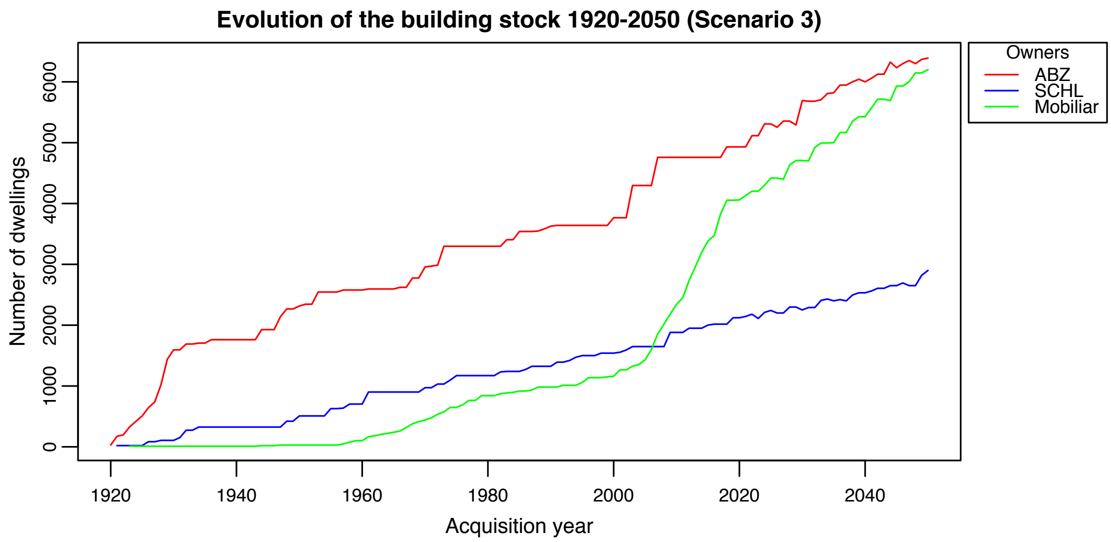


Figure 5.5 – Simulations - Evolution of the building stock - Scenario 3

Table 5.5 – Simulation results - Scenario 3

Model simulations – Scenario 3 "Combi" results - average values in 2050												
	ABZ			SCHL			Mobiliar			All owners		
Indicators	2020	2050	% *	2020	2050	% *	2020	2050	% *	2020	2050	% *
Dwelling surface (m^2/dw)	78.6	81.2	*+3.3%*	75.5	76.7	*+1.6%*	87.9	91.1	*+3.6%*	81.4	83.7	*+2.8%*
Room surface (m^2/room)	22.5	22.2	*-1.3%*	24.9	24.3	*-2.4%*	24.7	25.7	*+4.0%*	23.8	24.1	*+1.3%*
Floor area per capita (m^2/capita)	35.8	37.3	*+4.2%*	39.5	40.8	*+3.3%*	42.1	43.4	*+3.1%*	38.8	40.1	*+3.4%*
Persons per dwelling (pers/dw)	2.62	2.50	*-4.6%*	2.33	2.29	*-1.7%*	2.39	2.33	*-2.5%*	2.48	2.40	*-3.2%*
Persons per room (pers/room)	0.71	0.68	*-4.2%*	0.72	0.71	*-1.4%*	0.64	0.64	*0.0%*	0.69	0.67	*-2.9%*
Proportion of dwelling size												
1-1.5 room	3.4%	4.1%	*+20.6%*	2.5%	3.2%	*+28.0%*	5.0%	5.8%	*+16.0%*	3.8%	4.9%	*+28.9%*
2-2.5 room	17.3%	17.5%	*+1.2%*	22.8%	19.5%	*-14.5%*	19.2%	18.9%	*-1.6%*	19.0%	19.2%	*+1.1%*
3-3.5 room	40.5%	37.6%	*-7.2%*	43.7%	41.6%	*-4.8%*	37.5%	37.1%	*-1.1%*	40.0%	38.6%	*-3.5%*
4-4.5 room	30.9%	33.3%	*+7.8%*	27.6%	31.2%	*+13.0%*	32.1%	32.6%	*+1.6%*	30.7%	32.2%	*+4.9%*
5+ room	7.9%	7.5%	*-5.1%*	3.4%	4.5%	*+32.4%*	6.2%	5.6%	*-9.7%*	6.5%	5.1%	*-21.5%*
Net rent (CHF)	1,006	1,236	*+22.9%*	1,011	1,261	*+24.7%*	1,556	1,734	*+11.4%*	1,208	1,416	*+17.2%*
Net rent per floor area (CHF/m^2)	12.9	15.1	*+17.1%*	13.2	15.5	*+17.4%*	18.3	20.5	*+12.0%*	14.9	17.2	*+15.4%*
Yearly owner actions (number of dwellings)												
NC	10			4			15			29		
P	3			2			4			9		
RE	46			18			44			108		
T+	45			19			45			109		
D	-27			-11			-16			-54		
T-	-26			-10			-18			-54		
all owner actions (newly added dwellings)	51			22			74			147		

Source: Own work, model simulations - average values result of 50 model runs
NC: Newly Constructed, P: Purchased, RE: Reconstructed, D: Demolished, T+: Transformed, T-: Removed for transformation dwellings
** % change between 2020 and 2050*

5.5.5 Scenario 4 "Green household"

All above scenarios were concentrating on measures taken from the supply side, either by changing the model parameters related to housing production or indirectly by altering the occupancy rules. Tenants were considered to be relatively static in terms of their relationship to the environment. One of the households' attributes is the environmental awareness level, which can take three possible values (low, medium, high). It gets updated at every time step, depending on whether there is a trigger from the environment. The environment might send signals that lead to an increase of the environmental awareness level of households. For more details, refer to section 4.6.1.2, section 4.6.2.3 and section 4.6.2.9.

In scenario 4, named "Green household", households become gradually more environmentally aware, as a result of a set of actions administered by the environment, e.g., environmental housing taxes, incentives to downsize, to move to a smaller dwelling in case of under-occupancy, environmental campaigns, etc. The model assumes an "on-off" switch parameter of the model's environment, which is set to"off" at initialisation, as described in 4.6.1.2. Once this turns to "on", the model assumes that it starts influencing households to increase their environmental awareness level. The higher the level, the more aware is the household that the size of their dwelling impacts the environment. This means that a household with high level of environmental awareness changes its housing preferences, and looks for, and applies to rent dwellings with dwelling size close to the household size. Housing supply parameters remain unchanged having the values as they were set in the baseline scenario.
In this scenario, after some ticks all households increase their level of environmental awareness to "high". This translates into a great motivation from the households' side to choose dwellings that are tight in terms of size either at the moment of a new lease or to ask to move to a smaller dwelling. The model runs 50 simulations, and in Figure 5.6 the evolution of the building stock is illustrated.

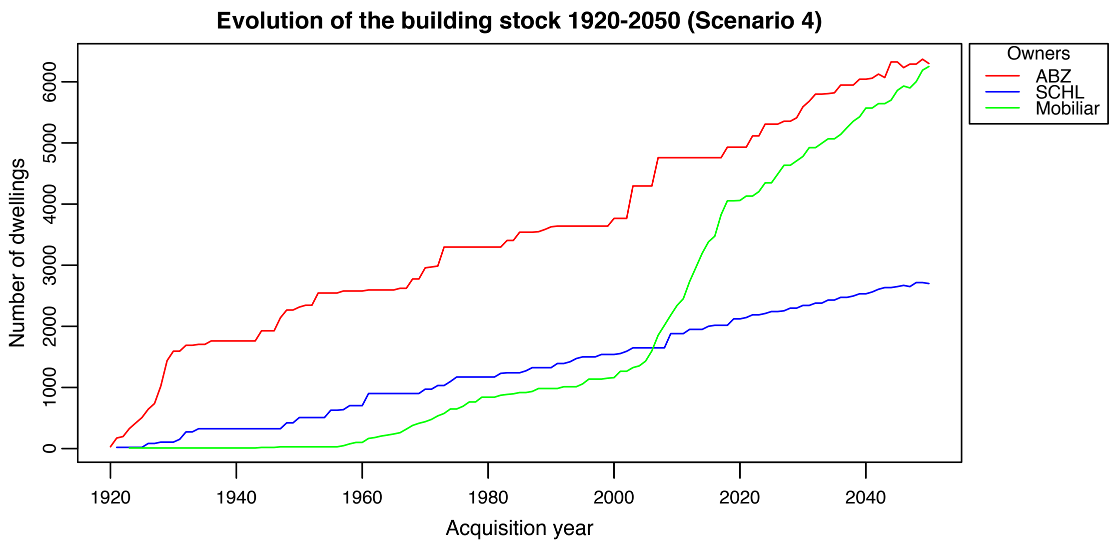


Figure 5.6 – Simulations - Evolution of the building stock - Scenario 4

The growth of the stock is mainly due to new construction; the proportion of new construction is higher than the one of transformation and reconstruction, as shown in Table 5.6. In this scenario, dwelling size indicators increase as in the reference scenario. Occupancy-related indicators show an increase of the floor area per capita (+6.3%) and a decrease of the number of occupants per dwelling and room (-4.6% and -6.4%). We notice that the effect is similar to both non-profit and profit-oriented owners. Although cooperatives apply occupancy rules at the time of the initial lease, they face great difficulties controlling whether these initial rules still apply later on. Households of this scenario are conscious enough about the environment independently and irrespective of the rules applied by the owners. This explains why the indicators of all three owners are affected by this change of preference of households.

Table 5.6 – Simulation results - Scenario 4

Model simulations - Scenario 4 "Green household" - average values in 2050												
	ABZ			SCHL			Mobiliar			All owners		
Indicators	2020	2050	% *	2020	2050	% *	2020	2050	% *	2020	2050	% *
Dwelling surface (m^2/dw)	78.6	82.2	*+4.6%*	75.5	78.2	*+3.6%*	87.9	95.1	*+8.2%*	81.4	86.5	*+6.3%*
Room surface (m^2/room)	22.5	22.8	*+1.3%*	24.9	25.4	*+2.0%*	24.7	26.7	*+8.1%*	23.8	24.9	*+4.6%*
Floor area per capita (m^2/capita)	35.8	38.3	*+7%*	39.5	41.9	*+6.1%*	44.1	44.8	*+1.6%*	38.8	41.3	*+6.4%*
Persons per dwelling (pers/dw)	2.62	2.46	*-6.1%*	2.33	2.22	*-4.7%*	2.39	2.25	*-5.9%*	2.48	2.34	*-5.6%*
Persons per room (pers/room)	0.71	0.67	*-5.6%*	0.72	0.68	*-5.6%*	0.64	0.63	*-1.6%*	0.69	0.66	*-4.3%*
Proportion of dwelling size												
1-1.5 room	3.4%	3.7%	*+8.8%*	2.5%	1.1%	*-56.0%*	5.0%	5.1%	*+2.0%*	3.8%	3.9%	*2.6%*
2-2.5 room	17.3%	17.0%	*-1.7%*	22.8%	19.5%	*-14.5%*	19.2%	18.9%	*-1.6%*	19.0%	18.5%	*-2.6%*
3-3.5 room	40.5%	35.7%	*-11.9%*	43.7%	42.2%	*-3.4%*	37.5%	38.0%	*+1.3%*	40.0%	37.5%	*-6.3%*
4-4.5 room	30.9%	33.8%	*+9.4%*	27.6%	32.7%	*+18.5%*	32.1%	32.2%	*+0.3%*	30.7%	32.9%	*7.2%*
5+ room	7.9%	9.8%	*+24.1%*	3.4%	4.5%	*+32.4%*	6.2%	5.8%	*-6.5%*	6.5%	7.2%	*10.8%*
Net rent (CHF)	1,006	1,249	*+24.2%*	*1,011*	1,243	*+22.9%*	1,556	1,874	*+20.4%*	1,208	1,487	*+23.1%*
Net rent per floor area (CHF/m^2)	12.9	15.3	*+18.6%*	13.2	16.0	*+21.2%*	18.3	20.7	*+13.1%*	14.9	17.8	*+19.5%*
Yearly owner actions (number of dwellings)												
NC	32			16			53			101		
P	5			2			8			15		
RE	30			13			13			56		
T+	24			12			14			50		
D	-20			-9			-6			-35		
T-	-22			-10			-10			-42		
all owner actions (newly added dwellings)	49			24			72			145		

Source: Own work, model simulations - average values result of 50 model runs
NC: Newly Constructed, P: Purchased, RE: Reconstructed, D: Demolished, T+: Transformed, T-: Removed for transformation dwellings
** % change between 2020 and 2050*

5.6 Comparative analysis of scenarios

In the previous section, the scenarios were presented and the results of each scenario were analysed concentrating on the five environmental indicators and their evolution between 2020 and 2050. In this section, the focus lies on the comparison among the scenarios and especially in relation to the reference scenario (REF).

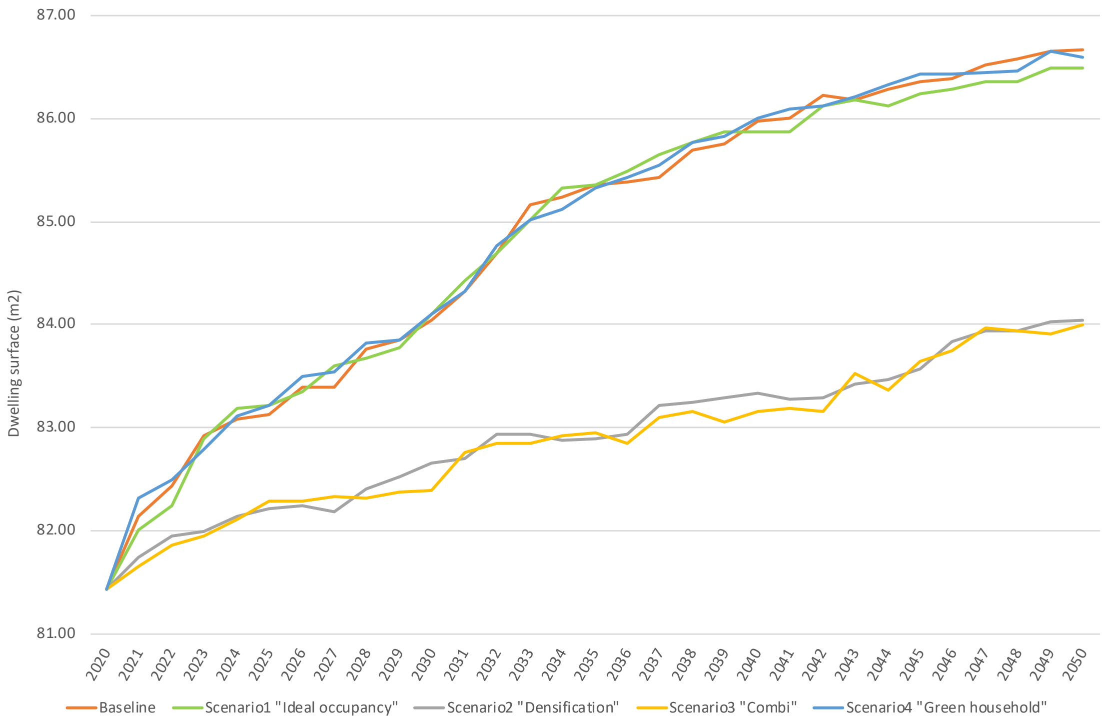
In Table 5.7, the surface-related environmental indicators (dwelling surface and room surface) are presented for all scenarios. Regarding the dwelling surface, scenario 2 "Densification" and scenario 3 "Combi" exhibit the lowest surface increase. In both scenarios the average dwelling surface is almost 3.5% smaller than in REF. The impact of the measures taken in scenarios 2 and 3 have a greater impact on the profit market dwellings (-4.4%), while the cooperative dwellings grew 1%-2% less than in REF. As shown in Figure 5.7(a), the predicted dwelling surface is approximately 83.8 m^2, if we take into consideration all dwellings; while the surface of dwellings of the profit-oriented owner is larger reaching 91 m^2 (for scenarios 2 and 3).

Similarly, the room surface grows less in scenarios 2 and 3. Specifically, according to the scenario 2, the average room surface reaches 24 m^2 and scenario 3 predicts an average of 24.1 m^2. This translates into a room surface 4% and 3.6% smaller than REF (Figure 5.7(a)) respectively. The other scenarios (scenarios 1 and 4) show similar results compared to the reference scenario, as the surface- and construction-related model parameters remain unchanged (Figure 5.8).

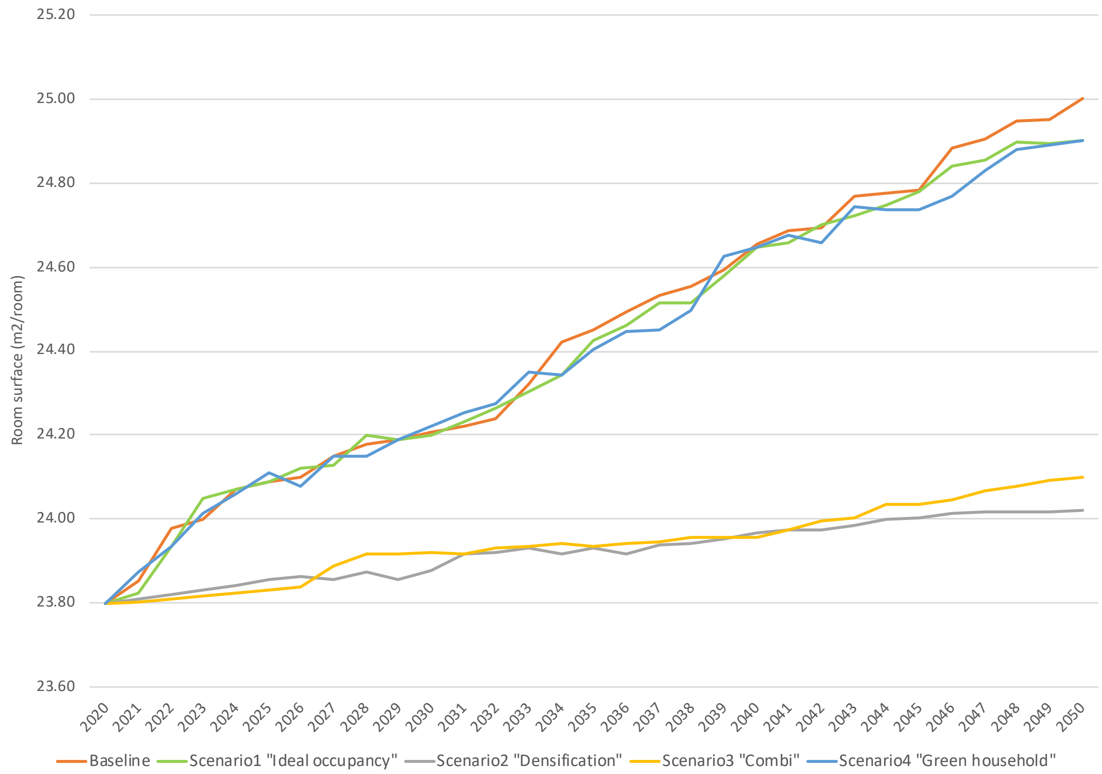
Figure 5.9 shows the relation between dwelling and room surface. Scenarios 2 and 3 score the best, however, in all scenarios the surface keeps increasing. There is no scenario predicting a decrease of dwelling and room surfaces.

Table 5.7 – Simulations - Scenario comparison - Surface indicators

Simulation results – comparative table									
Scenario	**Year**	**Dwelling surface (m^2/dw)**				**Room surface (m^2/room)**			
		ABZ	SCHL	Mobiliar	All owners	ABZ	SCHL	Mobiliar	All owners
Initial	2020	78.6	75.5	87.9	81.4	22.5	24.9	24.7	23.8
Baseline	2050	82.1	78.3	95.3	86.6	22.8	25.3	26.8	25.0
Scenario 1 “Ideal occupancy”	2050	81.9	78.4	95.0	86.0	22.7	25.2	27.0	24.9
	% change to baseline	*-0.2%*	*+0.1%*	*-0.3%*	*-0.7%*	*-0.4%*	*-0.4%*	*+0.7%*	*-0.4%*
Scenario 2 “Densification”	2050	81.2	76.8	91.1	83.8	22.1	24.2	25.5	24.0
	% change to baseline	-1.1%	-1.9%	-4.4%	-3.2%	-3.1%	-4.3%	-4.9%	-4.0%
Scenario 3 “Combi”	2050	81.2	76.7	91.1	83.7	22.2	24.3	25.7	24.1
	% change to baseline	-1.1%	-2.0%	-4.4%	-3.3%	-2.6%	-4.0%	-4.1%	-3.6%
Scenario 4 “Green household”	2050	82.2	78.2	95.1	86.5	22.8	25.4	26.7	24.9
	% change to baseline	0.1%	-0.1%	-0.2%	-0.1%	*+0.0%*	*+0.4%*	*-0.4%*	*-0.4%*



(a) Dwelling surface



(b) Room surface

Figure 5.7 – Simulations - Scenario comparison (2020-2050) - Surface indicators (three owners averaged)

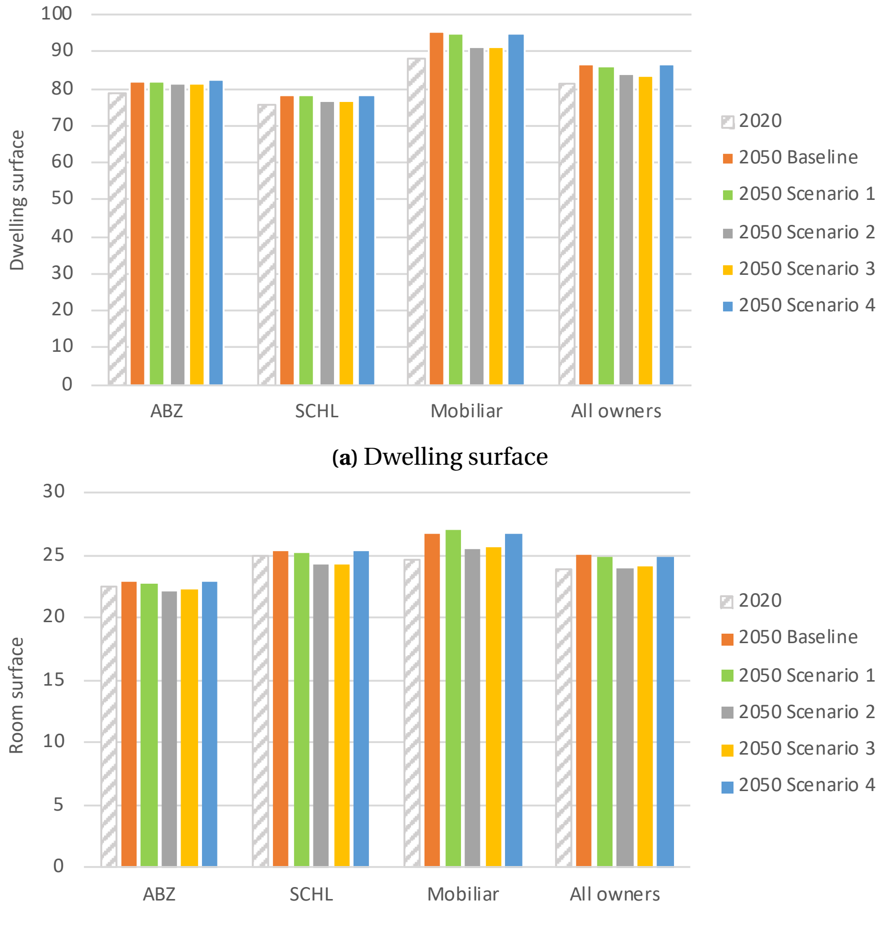


Figure 5.8 – Simulations - Scenario comparison 2050 - Surface indicators

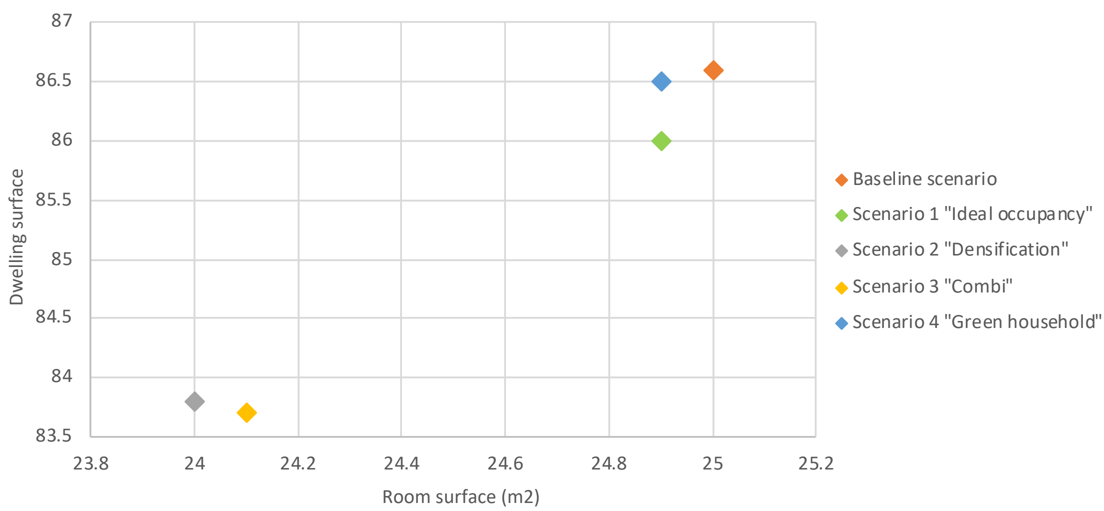


Figure 5.9 – Simulations - Scenario comparison - Dwelling and room surface (three owners averaged)

Table 5.8 shows the percentage of dwelling sizes for all scenarios. According to scenarios 2 "Densification" and 3 "Combi", the proportion of small sized rental units increases significantly, especially 1-room dwellings. This is explained mainly by the demolitions of old buildings that usually had larger dwellings and their replacement by new buildings with modern layout and more small-sized dwellings targeting to cover the rising need of modern households for smaller dwellings. The other scenarios don't show significant differences compared to REF since construction-related parameters are unchanged.

Table 5.8 – Simulations - Scenario comparison - Dwelling size

Simulation results – comparative table						
Scenario	**Year**	**1-1.5room**	**2-2.5room**	**3-3.5-room**	**4-4.5-room**	**5+room**
		All owners				
Initial	2020	3.8%	19.0%	40.0%	30.7%	6.5%
Baseline	2050	3.7%	18.4%	37.9%	33.1%	6.9%
Scenario 1 “Ideal occupancy”	2050	3.8%	18.4%	38.1%	32.8%	6.9%
	% change to baseline	*+2.7%*	*+0.0%*	*+0.5%*	*-0.9%*	*0.0%*
Scenario 2 “Densification”	2050	4.8%	19.2%	38.8%	32.0%	5.2%
	% change to baseline	*+29.7%*	*+4.3%*	*+2.4%*	*-3.3%*	*-24.6%*
Scenario 3 “Combi”	2050	4.9%	19.2%	38.6%	32.2%	5.1%
	% change to baseline	*+32.4%*	*+4.3%*	*+1.8%*	*-2.7%*	*-26.1%*
Scenario 4 “Green household”	2050	3.9%	18.5%	37.5%	32.9%	7.2%
	% change to baseline	*+5.4%*	*+0.5%*	*-1.1%*	*-0.6%*	*+4.3%*

The indicator floor area per capita depends both on construction and occupancy-related parameters. In Switzerland, dwelling surface tends to increase and household size tends to shrink (see section 2.10). As a result, the floor area per surface is expected to increase significantly. According to the reference scenario, the average floor area that corresponds to each occupant grows from 38.8 m^2 in 2020 to 43.1 m^2 in 2050.
By comparing all scenarios, the lowest living surface per capita is achieved in scenario 3 "Combi", where it is 7% lower than the reference scenario (see Table 5.9, Figure 5.11 and Figure 5.10). This decrease is justified by the strictness of the occupancy rules and the densification process - the replacement of older buildings with younger that are constructed based on different building standards. Furthermore, in scenario 4 "Green household" a significant decrease of floor area per capita, in comparison to REF, is achieved. This improvement is explained by the change of the households' preferences that become more environmentally aware and prefer dwellings that is closer to the size of their household. This shows the potential for preventing a sharp surface increase when combining this measure with the

measures applied in scenario 3.

The type of owner plays a role as well. In the case of the surface-related indicators, the owner type has a bigger influence on the average dwelling surface, as mentioned above. However, the floor area per capita of dwellings belonging to profit-oriented owners increases less steeply in scenarios 1 and 4. Housing cooperatives always apply some sort of occupancy rules, while for-profit owners rarely do so. As a result, when the latter apply stricter rules controlling the number of tenants that occupy their dwellings, there is larger margin to decrease the surface occupied per person.

Table 5.9 – Simulations - Scenario comparison - Floor area per capita

Simulation results – comparative table					
Scenario	**Year**	**Floor area per capita (m²/capita)**			
		ABZ	SCHL	Mobiliar	All owners
Initial	2020	35.8	39.5	42.1	38.8
Baseline	2050	39.9	43.9	46.8	43.1
Scenario 1 “Ideal occupancy”	2050	38.4	42.9	44.2	41
	% change to baseline	*-3.3%*	*-4.3%*	*-7.3%*	*-4.9%*
Scenario 2 “Densification”	2050	39.1	42.9	46.1	42.2
	% change to baseline	*-2.0%*	*-2.3%*	*-1.5%*	*-2.1%*
Scenario 3 “Combi”	2050	37.3	40.8	43.4	40.1
	% change to baseline	*-6.5%*	*-7.1%*	*-7.3%*	*-7.0%*
Scenario 4 “Green household”	2050	38.3	41.9	44.1	41.3
	% change to baseline	*-4.0%*	*-4.6%*	*-5.8%*	*-4.2%*

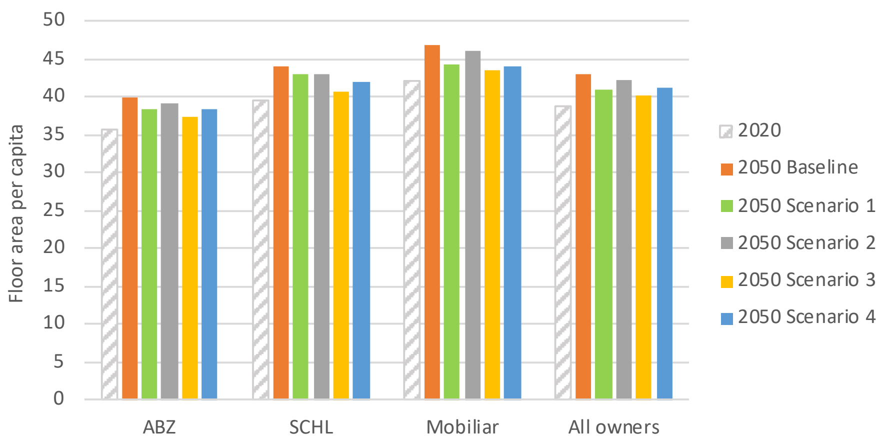


Figure 5.10 – Simulations - Scenario comparison 2050 - Floor area per capita

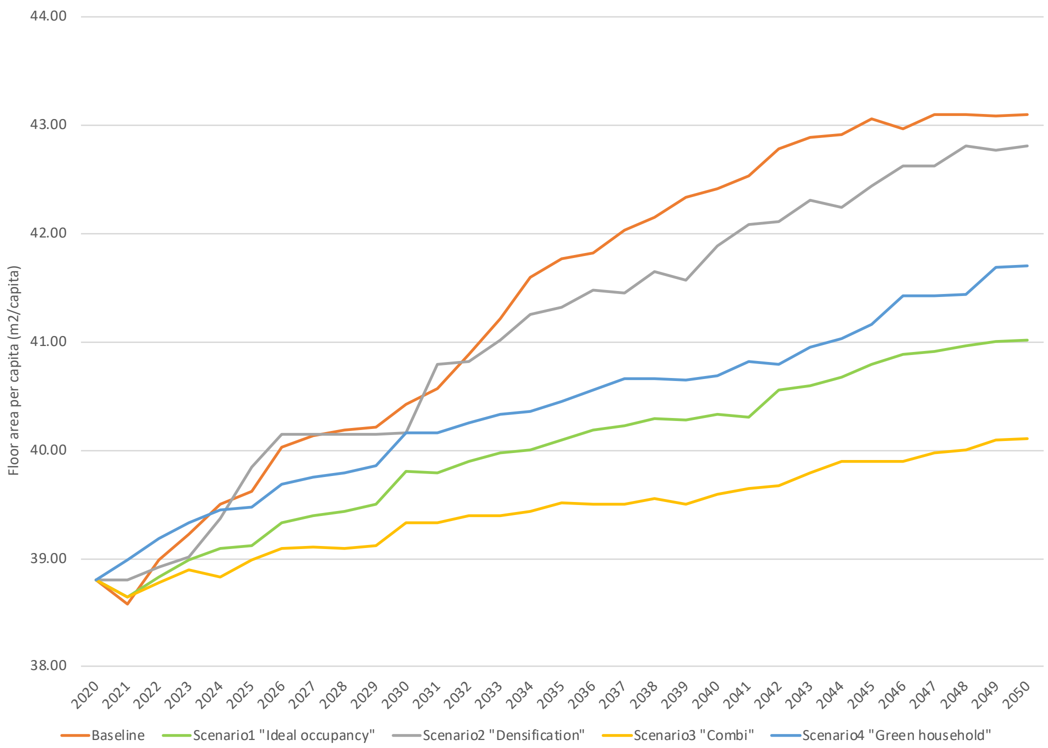


Figure 5.11 – Simulations - Scenario comparison (2020-2050) - Floor area per capita (three owners averaged)

Figure 5.12, shows clearly that scenario 3, which is a combination of measures, has the best results. Both the dwelling surface and the floor area per capita are the lowest in comparison to all other scenarios. Although scenario 2 achieves a relatively low dwelling surface, the living surface per capita remains high. It is evident that by combining measures better results can be achieved.

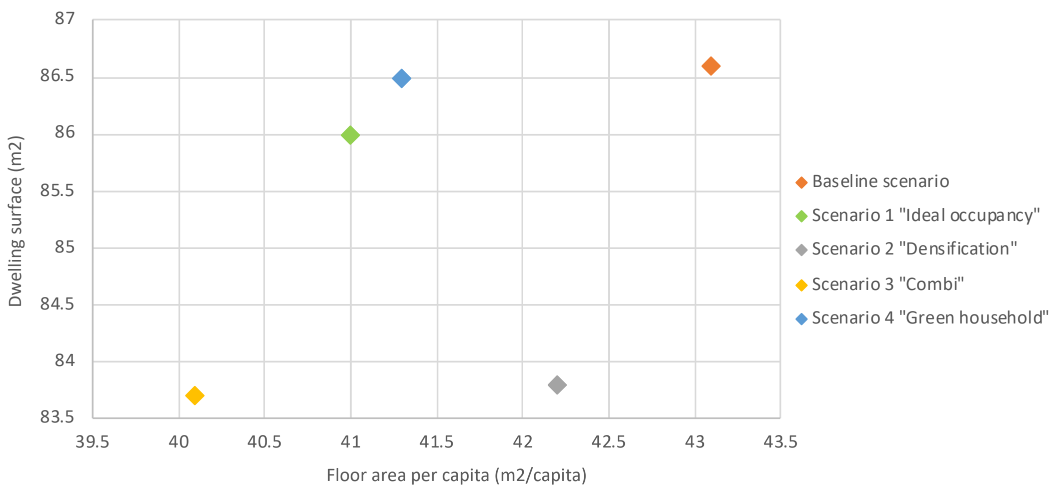


Figure 5.12 – Simulations - Scenario comparison - Dwelling surface and floor area per capita (three owners averaged)

The household size is expected to shrink further in the future (see section 2.10). In the case study housing system, the average number of persons per dwelling was 2.48 in 2020, and based on the reference scenario, it is predicted to drop to 2.28. The number of persons per room was 0.69 in 2020, and it is expected to decrease to 0.64 in 2050 according to the baseline scenario. In scenario 3, the indicator number of persons per room decreases slightly to 0.68. Scenario 3 exhibits the best results of both these indicators (Figure 5.14 and Figure 5.15); the number of persons per dwelling increases by 5.2% and the number of persons per room by 6,3%, in comparison to REF (Table 5.10).

Table 5.10 – Simulations - Scenario comparison - Occupancy indicators

Simulation results – comparative table									
Scenario	**Year**	**Number of persons per dwelling**				**Number of persons per room**			
		ABZ	SCHL	Mobiliar	All owners	ABZ	SCHL	Mobiliar	All owners
Initial	2020	2.62	2.33	2.39	2.48	0.71	0.72	0.64	0.69
Baseline	2050	2.39	2.13	2.22	2.28	0.64	0.66	0.61	0.64
Scenario 1 “Ideal occupancy”	2050	2.48	2.28	2.28	2.36	0.67	0.68	0.63	0.66
	% change to baseline	*+3.8%*	*+7.0%*	*+2.7%*	*+3.5%*	*+4.7%*	*+3.0%*	*+3.2%*	*+3.1%*
Scenario 2 “Densification”	2050	2.42	2.19	2.21	2.30	0.65	0.67	0.62	0.65
	% change to baseline	*+1.3%*	*+2.8%*	*-0.5%*	*+0.9%*	*+1.6%*	*+1.5%*	*+1.6%*	*+1.6%*
Scenario 3 “Combi”	2050	2.50	2.29	2.33	2.40	0.68	0.71	0.64	0.67
	% change to baseline	*+4.6%*	*+7.5%*	*+4.9%*	*+5.2%*	*+6.2%*	*+7.6%*	*+4.9%*	*+4.7%*
Scenario 4 “Green household”	2050	2.46	2.22	2.25	2.34	0.67	0.68	0.63	0.66
	% change to baseline	*+2.9%*	*+4.2%*	*+1.3%*	*+2.6%*	*+4.7%*	*+3.0%*	*+3.2%*	*+3.1%*

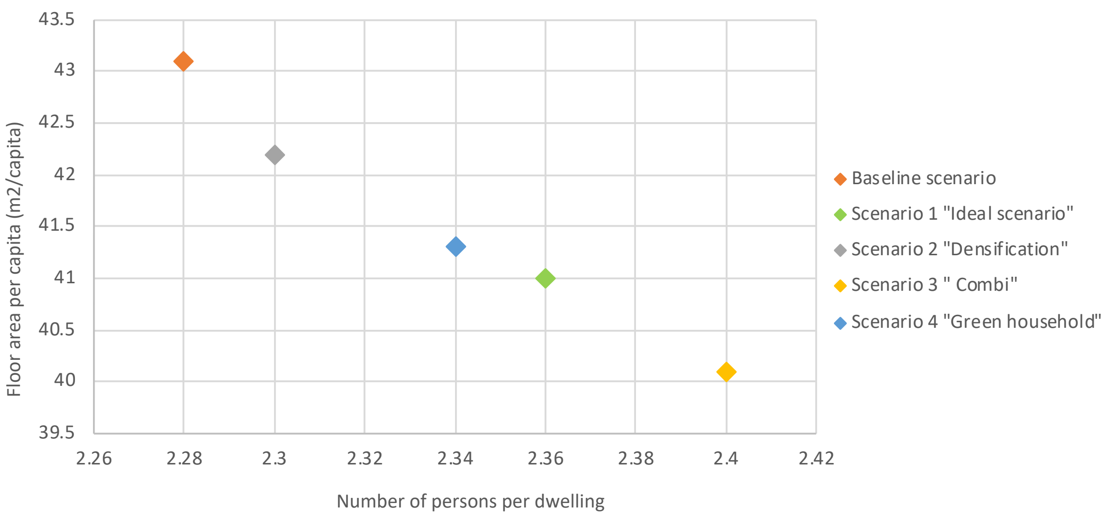
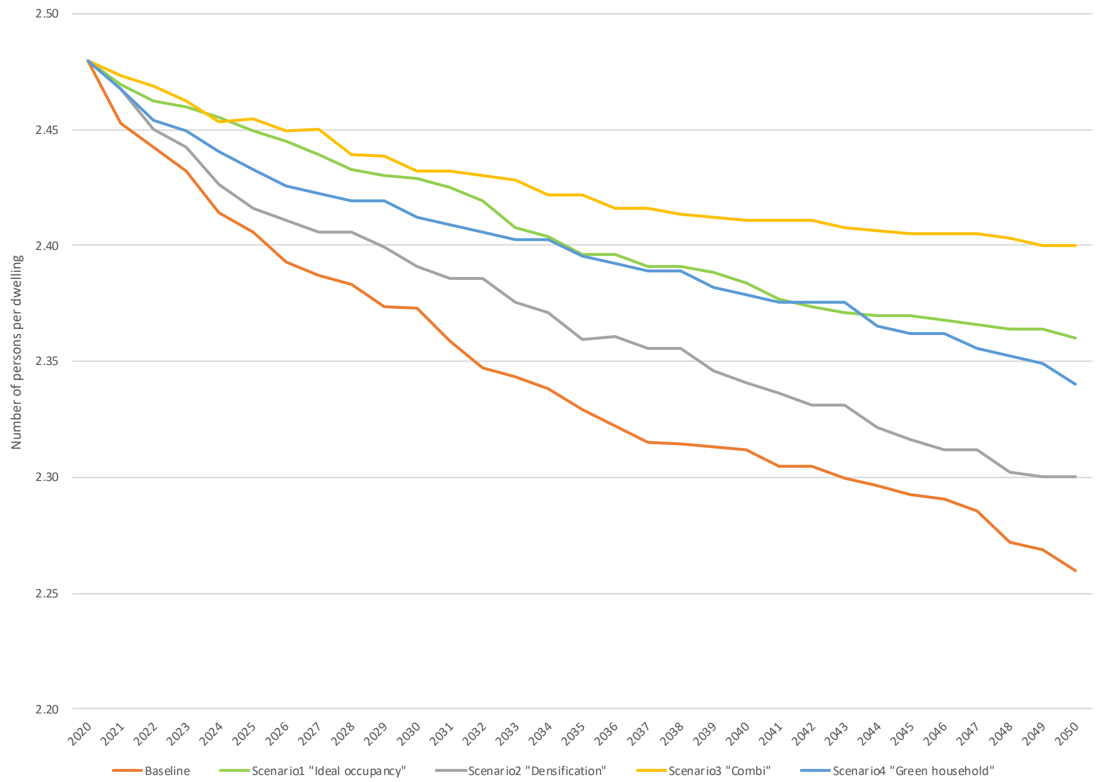
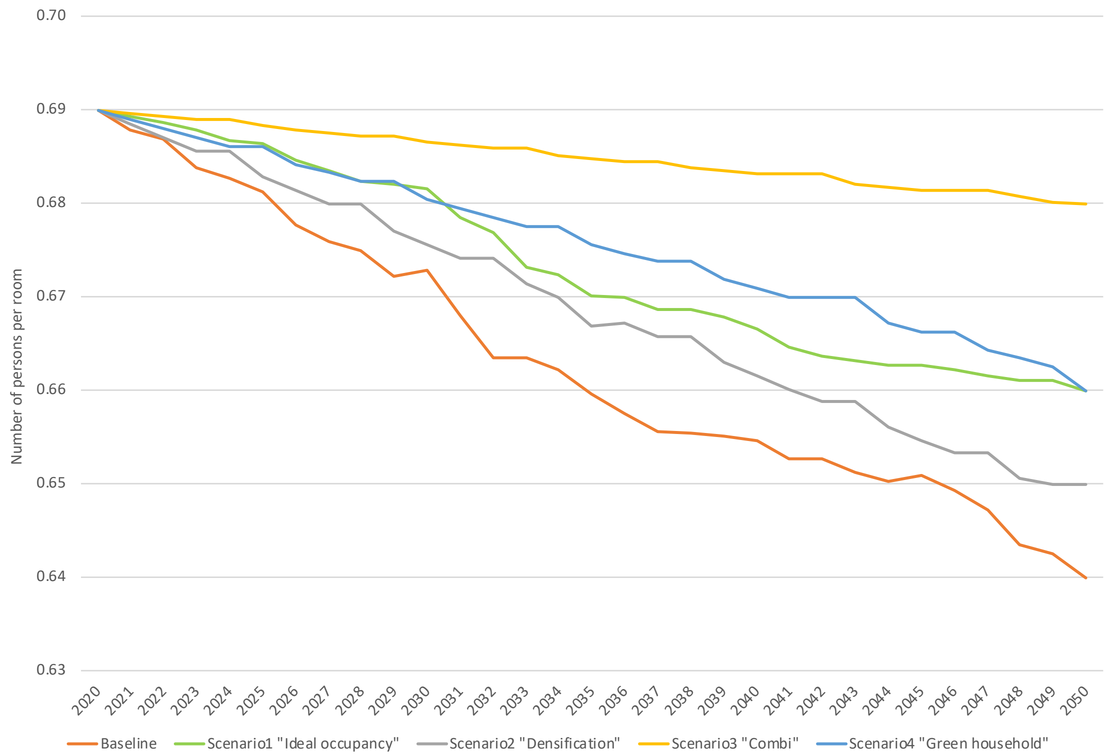


Figure 5.13 – Simulations - Scenario comparison - Floor area per capita and number of persons (three owners averaged)

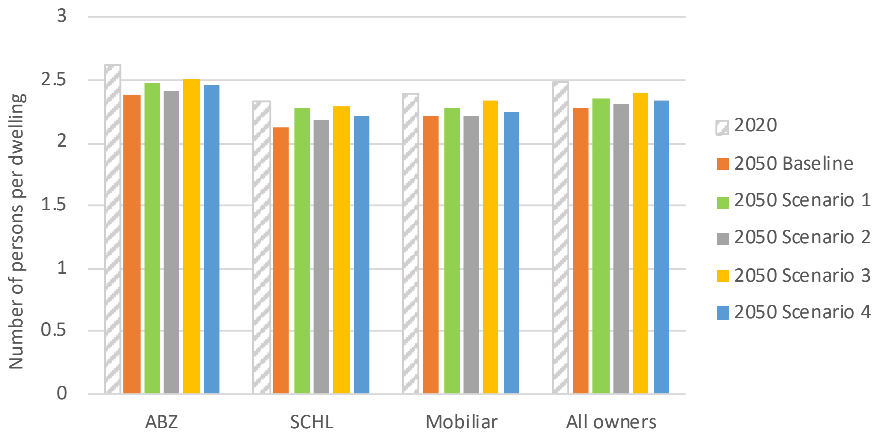


(a) Number of persons per dwelling

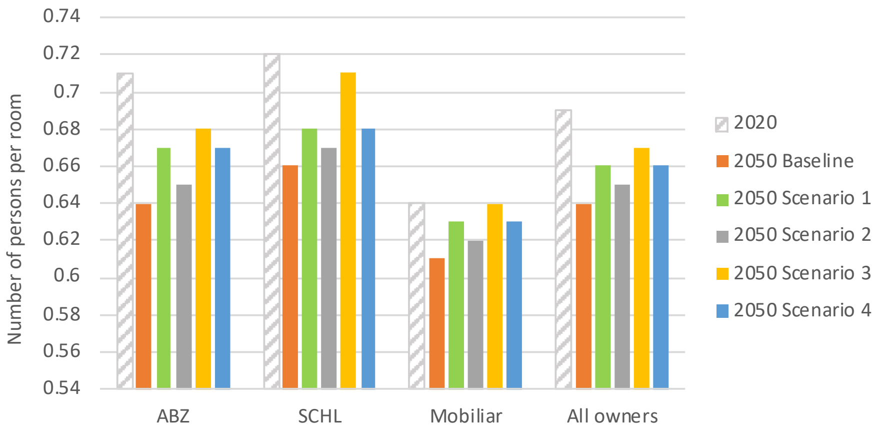


(b) Number of persons per room

Figure 5.14 – Simulations - Scenario comparison (2020-2050) - Occupancy indicators (three owners averaged)



(a) Number of persons per dwelling



(b) Number of persons per room

Figure 5.15 – Simulations - Scenario comparison 2050 - Occupancy indicators

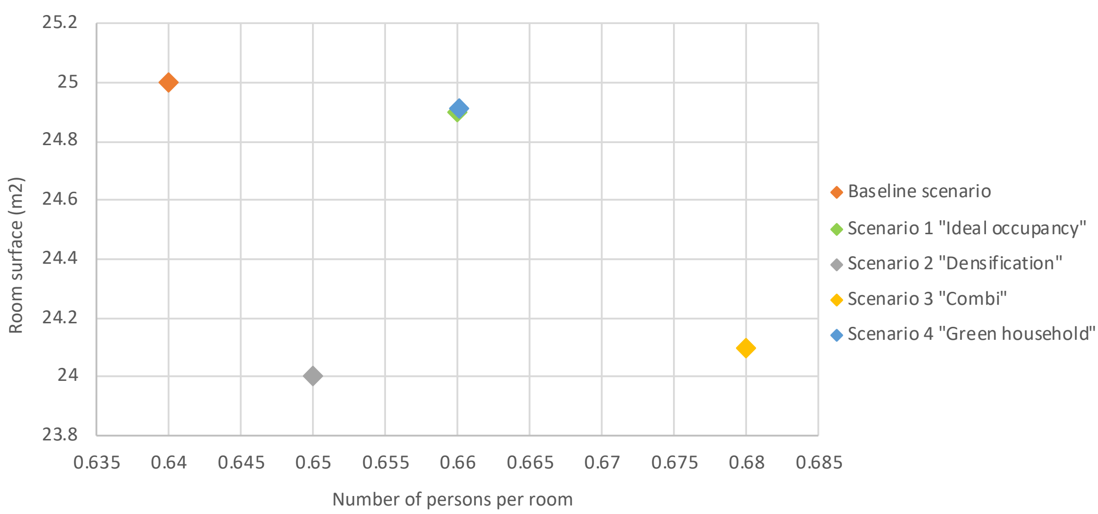


Figure 5.16 – Simulations - Scenario comparison - Room surface and number of persons (three owners averaged)

Figure 5.13 shows that scenario 3 predicts the lowest floor area per capita while expecting the highest number of persons per dwelling. The "Combi" scenario exhibits the best results regarding the two indicators number of persons per room and room surface, as shown in Figure 5.16.

5.7 Summary and lessons learned

The aim of this research project is to study the environmental impact of housing and to develop measures to shrink it. For that reason, we built an agent-based model. Apart from the baseline scenario, four additional scenarios are developed. By running different scenarios and changing the parameters of the model, we can evaluate different results. Housing size is a large determinant of energy and material consumption. In this thesis, the environmental impact of housing is assessed through a set of environmental indicators: floor area per capita, dwelling surface, room surface, number of persons per dwelling and number of persons per room.

The reference scenario predicts an increase of the dwelling surface, room surface and floor area per capita, while the number of persons per dwelling and room decreases. This confirms the predictions of FSO ((FSO, 2021*r*,*f*), as it is described in more detail in chapter 2. Applying stricter occupancy rules has a positive effect on the indicators. However, in Switzerland only a few owners or real estate agencies allocate dwellings based on room stress rules, mainly housing cooperatives and other non-profit owners (section 2.5). But even in this case, approximately 70% of all non-profit rental housing is subject to occupancy requirements (Blumer, 2012). As mentioned in section 5.5.2, occupancy rules refer to the rules applied at the time of the lease. There is limited or no control at all over the next years of tenancy. As a result, especially in the case of a long-term tenancy, it is very difficult to find out if the dwelling is under-occupied. As households evolve, their size might change over time because of different life phases of households, e.g., marriage, birth of a child, divorce, pension, children leaving the house, etc. This often leads to a mismatch of size between dwelling and household.

Scenario 1 "Ideal occupancy" shows an improvement of the indicators. This means that if all owners implement stricter occupancy rules at the time of the lease, it can have a considerable effect on limiting the floor area per capita. However, it can be very demanding for owners to impose such strict rules. Furthermore, there is potential to further increase the occupancy of dwellings either by introducing measures for owners to control the number of occupants in the course of time or by giving incentives to households to move to a smaller dwelling in case of under-occupancy. Nonetheless, it can be very challenging to develop and implement a framework that motivates or forces households to downsize and move to a smaller dwelling in case of a under-occupancy. This also raises a moral question. To what extent can households be forced or pushed to leave their dwellings in case of under-occupancy. That would imply

paying moving costs, abandoning their home, neighbours, neighbourhood, etc. This is particularly complicated for older people, who in general occupy more living surface. That could affect their sense of identity, belonging or security.
To summarize, there is great potential in a more space-efficient allocation of dwellings to households both at the time of the lease and over the course of the tenancy time. For large-scale property owners of rental dwellings, it is easier to propose to households a better fitting dwelling (in terms of size) close to their current dwelling, even in the same building, than for small property owners. This happens occasionally in cooperative housing, but the ethical and practical issues are evident; as a result, it is limited. Other large-scale owners could have the ability to propose alternative dwellings to households close by, but often households are not even aware of the owner of their dwelling as they rent, as they rent through real estate agencies. Smaller owners probably don't have the ability to offer such an alternative option. However, in the future a framework or platform could be created allowing households to exchange dwellings for reasons of under-occupancy. The big question here is how to promote public acceptance for such measures. Apart from campaigns to inform and make people aware of the environmental side and impact of their housing choices, other financial measures such as the introduction of progressive tax for households that occupy large surface per capita, or subsidies for dwellings where specific stricter occupancy rules will apply, could help towards that direction.
The second significant result is the contribution of the densification of the existing building stock to decrease the environmental impact of housing. By reusing the existing building stock, urban sprawl is limited. The vast majority of buildings chosen to be transformed or demolished-reconstructed are either old buildings or former industrial structures. The former were built according to older building and land-use regulations. Older constructions were built using dated or obsolete construction and material technology, such as insulation, windows, heating system etc. The surface of old dwellings tends to be larger; the proportion of large dwellings was higher too. This doesn't correspond to the increasing demand of smaller dwellings, which among other reasons might lead to under-occupancy. By transforming or demolishing-reconstructing old buildings, there is potential to enhance the energy performance of buildings and to create a larger variety of dwelling sizes.
The results from running scenario 2 "Densification" demonstrate that although the environmental indicators perform better, the effect is not that strong. This is mainly explained by the fact that the model is built according to the past construction activity of owners. The model assumes that developers will keep constructing as they did up till now. In the model, this is translated into that owners build according to the construction principles they applied between 1990 and 2020 [6]. If the densification process was performed following stricter con-

[6] In chapter 4, Stat1990 was defined. Stat1990 describes the construction activity of the case study property over the last 30 years (section 4.6.1.10.1, section 4.6.1.10.2 in chapter 4 and section A.4 in the appendix). In the baseline

struction guidelines, e.g., minimum and maximum square meters for each type of room[7], materials, etc. that could positively influence the environmental indicators. Construction patterns should change drastically if we want to reverse the constant and rapid increase of dwelling surface and floor area per capita.

Furthermore, the total surface area of older structures was calculated according to the construction regulations of that era. It is probable that the building zone or the floor area ratio (FAR) that corresponds to the plot changed over time. In this case, the permittable FAR might have increased, allowing to build more square meters and, thus, to increase the total building surface and as a result to accommodate more persons on the same land surface. Demolitions-reconstructions could contribute to the construction of modern energy-efficient buildings and the design of floor plans that correspond to the needs of households today. Additionally, it could allow, in certain cases, to increase the total building surface. Transformation, as defined in this model, doesn't lead to a total surface increase. However, it allows rejuvenating the building, enhancing its energy performance and modernising its layout. To this point, we should consider the grey energy entailed in a demolition- reconstruction and transformation, which means that demolitions or transformations are not panacea. Another critical point is the modularity of construction; a more flexible construction, e.g., with moving walls, separate rooms, etc. allows the adaptation of the dwellings to the needs of households in all life phases. As a consequence, the dwelling surface and floor area per capita could decrease further, without needing to move the household from its home and neighbour. Innovation of architectural plans and solutions can contribute significantly to lowering the environmental impact of housing.

Scenario 3 "Combi" is the scenario where all indicators score the best; dwelling and room surface, floor area per capita still increase but less steeply, and the number of persons per dwelling and room decrease the least. This scenario includes the combination of both measures: the implementation of stricter occupancy rules from all types of owners and the densification of the building stock through increased transformations and demolitions. The impact of these measures has a significant influence. Although it doesn't succeed to reverse the current trend of dwelling surface and floor area per capita increase, it interrupts their rapid uptrend. The model simulations show clearly that a combination of measures has the best result; all chosen environmental indicators perform the best. Such a complex system as the housing market should be assessed from many perspectives; one-sided measures are inadequate to have significant impact. However, the upward trend in surface consumption is not easily reversed, which means that additional measures need to be taken in parallel, or more active measures need to be implemented.

scenario, construction activity follows the construction pattern since 1990.

[7] Housing cooperatives already follow specific detailed construction guidelines that define the surface and volume of rooms, materials used, proportion of dwelling sizes, heating system, etc.

In this thesis, the ideal occupancy rules are selected as shown in Table 5.2 in section 5.5.2 and Table 5.11 that follows. The latter table demonstrates the minimum and maximum value of the surface of a dwelling, as calculated based on the ideal occupancy and the assumption of the minimum floor area per capita.

Table 5.11 – Dwelling surface range based on housing sufficiency

Assumption: min **10 m²/capita**				
Dwelling size	Minimum number of persons	Maximum number of persons	Minimum dwelling surface m^2	Maximum dwelling surface m^2
1-room	1	2	30*	30*
2-room	2	4	30*	40
3-room	3	5	30	50
4-room	4	6	40	60
5-room	5	7	50	70
Assumption: min **15 m²/capita**				
1-room	1	2	30*	30
2-room	2	4	30	60
3-room	3	5	45	75
4-room	4	6	60	90
5-room	5	7	75	105
Assumption: min **20 m²/capita**				
1-room	1	2	30*	40
2-room	2	4	40	80
3-room	3	5	60	100
4-room	4	6	80	120
5-room	5	7	100	140
* If the calculation results in a value less than 30 m^2, then we use the minimum value, which is 30 m^2				
Source: Own work				

For example, if we assume that the minimum space per capita should be 20 m^2 (see section 5.4), and the ideal number of occupants per dwelling size is as chosen in scenario 1 (see section 5.5.2 and Table 5.2), that allows to calculate an optimal dwelling surface range for all dwelling sizes. For a 3-room dwelling, the minimum number of tenants is set to three, which means that the minimum surface should be 60 m^2 (= 3 x 20 m^2); the maximum surface should be 100 m^2 (= 5 x 20 m^2). This way we can calculate the dwelling surface for all cases with the constraint that the minimum possible dwelling size cannot be lower than 30 m^2, as it was mentioned in section 5.4.

The above table is the combination of the ideal occupancy assumption and the housing sufficiency principles. It allows us go backwards and estimate the optimal dwelling surface. Scenarios 1, 2 and 3 show that although we apply the measures of ideal occupancy and densification, still the increase of the living surface cannot stop, the rhythm of increase slows down but the tendency to increase doesn't reverse. If we wish to reverse this situation and wish to see some results in the near future, more radical actions and a combination of measures should be taken. Scenario 2 shows that densification, as it is performed until now, is not enough. The densification process could be accompanied by a re-evaluation of the current construction patterns and habits; the establishment of a set of construction guidelines defining the optimal dwelling surface more clearly could make a difference. The latter in combination with a more space-efficient allocation of dwellings to tenants based on their size could reverse the trend of surface augmentation.

Table 5.12 – Investigation of optimal dwelling surface

Dwelling size	Minimum dwelling surface (Stat1990)	Maximum dwelling surface (Stat1990)	Average dwelling surface (Stat1990)	Optimal dwelling surface *	Required decrease of average surface**	Average decrease by owner	Difference between optimal and current***	Average difference between optimal and current
ABZ								
1-room	31	55	41	30	-27%	-27%	11	22
2-room	38	76	61	40	-34%		21	
3-room	58	102	86	60	-30%		26	
4-room	90	130	106	80	-25%		26	
5-room	115	150	126	100	-21%		26	
SCHL								
1-room	35	35	35	30	-14%	-22%	5	17.2
2-room	50	91	57	40	-30%		17	
3-room	54	128	80	60	-25%		20	
4-room	88	125	99	80	-19%		19	
5-room	113	163	125	100	-20%		25	
Mobiliar								
1-room	16	98	35	30	-14%	-27%	5	24
2-room	32	114	62	40	-35%		22	
3-room	47	147	89	60	-33%		29	
4-room	79	158	109	80	-27%		29	
5-room	95	189	135	100	-26%		35	

* Optimal dwelling surface refers to the surface calculated in the previous table for the assumption of a minimum of 20 m^2 per capita.
** It refers to the required decrease to pass from the average dwelling surface of Stat1990 to the optimal dwelling surface.
*** It refers to the difference between the optimal dwelling surface and the average surface according to Stat1990. It is calculated by subtracting the average dwelling surface with the optimal.

Source: Own work

According to the ABM developed in the context of this thesis, all construction activity of the property owners is decided based on the decisions they had taken in the previous years, specifically between 1990 and 2020 (Stat1990) (see Table 4.8 in chapter 4 and Table A.20 in the appendix). For that reason, as explained in chapter 4, the model uses the statistical results of all dwellings that were built, transformed or reconstructed as a base for the construction that follows 2020. Table 5.12 shows the dwelling surface characteristics for the three property owners according to Stat1990 and the required decrease to achieve the optimal dwelling surface as defined above. We observe that the current dwelling surface is on average 21 m^2 higher than the optimal. The profit-oriented property owner exhibits an even larger discrepancy, with 24 m^2 higher than the optimal. A decrease of 25% is required in order to reach the optimal dwelling surface. But how could owners be convinced to change the way they build? A set of measures could be introduced, such as subsidies for smaller dwelling surface, incentives for renovating and transforming existing buildings but with the obligation to respect specific space requirements, changing and adapting zoning regulations, etc. Scenario 4 "Green household" is developed to determine to what extent changes in the preferences of tenants would affect the environmental impact of housing. Under the assumption that supply and legal framework stay constant, a shift of households towards smaller dwellings has a considerable effect within the assumptions of the ABM. The results are comparable to the results of scenario 1, where only the occupancy rules for the allocation of dwellings to households change. This underlines the necessity to focus not only on the supply side of housing but also on the demand. We return to the same question. What are the measures that could promote the acceptability of tenants to live in smaller dwellings? This could happen by promoting the awareness to households that by living in a more suitable in terms of size dwelling, which corresponds to less floor area per capita, entails great advantages for the environment. However, this might prove to be inadequate. Additionally, offering incentives to households that decide to downsize could motivate even more households to act and decide to move to a smaller dwelling in case of under-occupancy. Incentives can be financial, e.g., tax relief, financial aid for moving costs, developing measures to reduce rents of dwellings with floor area per capita less than 20 m^2, apply progressive taxes for dwellings with floor area per capita less than 20 m^2. Apart from financial incentives, social incentives exist as well, such as reputation gain or loss; additionally, moral incentives are defined by what tenants perceive as good or bad. Social and moral incentives are difficult to be assessed, as they are related to how tenants perceive their home; for tenants, a dwelling can be a symbol of status, shelter, privacy, self-representation, etc. (Pagani and Binder, 2021). A thorough study of the tenants' side, the housing decisions of households and the symbolic meaning of housing to tenants is studied by Anna Pagani (HERUS Laboratory EPFL) (Thesis no. 9279 presented in February 2022) (Pagani, 2022). Finally, the outcome of this model is passed to PhD student Rhythima Shinde (ESD Laboratory ETHZ), who is estimating the environmental impact and more specifically the energy and material footprint of the housing system in terms or CO_2 equivalent (Thesis expected within 2022). This will complete this research as it will allow to quantitatively estimate, in terms of CO_2 equivalent, the environmental impact of housing as well as the detailed impact of demolitions-reconstructions, transformations, renovations and new constructions.

6 Conclusion

The goal of this thesis is to develop measures and recommendations to reduce the environmental impact of housing. For that purpose, a bottom-up agent-based model was built. This ABM is a computational model that describes the housing preferences and decisions of both households and large-scale property owners of rental dwellings. The model describes a subset of the Swiss housing market and simulates the housing supply (BS_ model) and demand (HH_ model).

The input of the model is the building stock and the households of three Swiss property owners (profit and non-profit), and it runs for thirty years (360 ticks). Owners make decisions about the evolution of the building stock (new constructions, renovations, demolitions, transformations) and the allocation of their dwellings to households, while in parallel, households evolve over time and are looking for dwellings based on their needs and preferences. The output of the model is the updated building stock and households as well as the matching between them; this allows to estimate a set of environmental indicators. Apart from the baseline scenario, four additional scenarios are developed.

This dissertation examines measures for reducing the consumption of resources in housing. Therefore, we develop a range of approaches for residents, building owners and authorities. The measures relate to the construction, use and renovation phases of residential buildings. By identifying the investment decisions of property owners with multiple objectives and numerous constraints as well as their housing management practices (maintenance, renovation, dwelling attribution), we develop a systematic representation of the supply side of the housing market. By identifying a set of indicators for environmental impacts, we provide a simple mapping of the management and occupation of a stock of dwellings to its environmental footprint.

6.1 Research questions and key findings

- *Research question RQ1*

  The first important research question (RQ1) is directly associated with the methods chosen to assess the problem. ***How can the housing market with its actors be modelled in such a way that the environmental impacts of different development scenarios can be compared?***

  The high level of complexity that characterises the Swiss housing market led us to adopt a transdisciplinary approach that allows to combine the theoretical background and modelling techniques from the engineering, economic and social science disciplines. Therefore, in the context of this thesis, we found ways to overcome the disciplinary fragmentation and developed a framework describing the housing market in Switzerland for profit and non-profit oriented rental dwelling owners. For this purpose, we developed a dynamic-accounting model of the seven owner actions (renovation, transformation, demolition, reconstruction, purchase, sale and new construction) that describes the evolution of the building stock of the case study property owners.

  The major achievement is the development of an empirical agent-based model that is built based on real-world data provided by the collaboration partners of this research project (two housing cooperatives and one private large-scale dwelling owner). The housing market is a complex system with a plethora of interrelations among the housing actors. The behaviour and the housing decisions of both the property owners and the tenants is difficult to describe only with a set of mathematical equations. The ABM we built allows to model a system with such complexity. The state of an agent at a given time point is determined by a set of rules that describe the agent's decisions and the interaction with other agents. These rules may be deterministic and/or stochastic. The high complexity of the housing system and the interrelation of housing actors drove us to develop an ABM and not a traditional model.

  The environmental assessment is performed through five environmental indicators, which are directly associated with housing sufficiency. Housing size is considered as the strongest determinant of energy consumption. In this thesis, we aim to explore measures targeting the reduction of dwelling size and floor area per capita to mitigate the energy and material consumption of housing. The environmental impact of housing is assessed based on the dwelling size (dwelling and room surface) and the occupancy (floor area per capita and number of occupants per dwelling and room).

- *Research question RQ2*
  This thesis focuses on the study of housing supply. The next set of research questions (RQ2) is: ***How do large scale property owners make decisions about the management of their existing housing stock and its future development? and what is the environmental impact of such decisions?***
  Among the key findings is the crucial importance of land. Buildable land in Switzerland is scarce and very expensive, and therefore, is a critical factor in the development of housing. Finding affordable land is a point of competition between owners, which determines both the final rental price and the profit margin of investors. In addition, cheaper land could give a greater margin for investment in the building stock, which would provide more energy-efficient or better quality dwellings. This is where the state steps in and offers land for building at a preferential price through leasing, mainly to non-profit developers, while at the same time, it requires certain standards such as energy labels or the application of occupancy rules.
  Buildable land for housing is in short supply. Given that the population of Switzerland continues to grow, the demand for housing will remain on the rise. Although housing construction is ongoing, it often fails to keep pace with the ever-increasing demand, often leading to very low vacancy rates and shortage of housing. Another finding of this thesis is that because land is scarce and land reserves for housings are shrinking, the turn towards the exploitation of the existing building stock, which is already taking place, can have a positive effect on shrinking the environmental impact. In particular, if demolitions-reconstructions and transformations are carried out with more stringent construction standards in terms of materials, dwelling size and layout, the impact is more substantial. The simulation results demonstrate that if the construction activity continues in the same way as today, i.e. construction of new dwellings with large surface, resource consumption of housing will keep increasing. Drastic measures should be taken from the supply side in order to limit the environmental footprint of housing. Construction should follow a set of construction guidelines targeting to create a greater variety of dwelling sizes to cover the needs of the shrinking households; dwelling and room surface should be re-evaluated based on the principle of housing sufficiency; the materials should be chosen carefully. Additionally, innovative solutions should be promoted in order that supply offers alternative types and more adaptable dwellings that are flexible enough to adjust to the changing needs of households. That way, a space-efficient matching between dwellings and households can be achieved without obliging households to relocate. Finally, it is evident that only through a combination of measures a significant reduction of the environmental impact of housing can be accomplished.

- *Research question RQ3*
  This brings us to the next major research question (RQ3) that concerns the allocation of dwellings to households. ***How do property owners allocate their dwellings to households and what is its contribution to the environmental impact of housing?***
  The architectural and construction decisions made by owners and developers are of great importance in shaping the supply of housing, and therefore, determining resource consumption. There have been many studies investigating the profitability of investments in housing and energy enhancement of buildings. In addition, a plethora of building models focusing on the evolution of the building stock and its environmental impact have been developed, mainly focusing on the energy consumption and less on the material side. Furthermore, the behaviour of tenants has been in the focus of research since years. However, a holistic approach combining all these aspects is rare. Specifically, the allocation of dwellings to tenants in a space-efficient way has been under-studied. No matter how cutting-edge, material and energy efficient a building is, if it is not inhabited by a sufficient number of people, it ends up being under-occupied and having a very high per capita resource consumption. Usually, the focus lies on the building stock, the energy enhancement of buildings, the profitability of energy enhancement renovations or the behaviour of tenants whereas the importance of the allocation of dwellings is neglected. Such a complex system like the housing market should be studied holistically.
  The ABM built in this thesis consists of three sub-models for reasons of clarity. The building stock model (BS_ model) that corresponds to RQ2, the household model (HH_ model) that refers to RQ4, which follows, and the matching model that replies to RQ3. The matching model is where supply and demand meet; it brings together dwellings and households, and it comprises all the allocation rules set by the owners. The property owners directly or indirectly choose their tenants based on a set of rules; in this model, there are two kinds of rules: financial and space-related. The latter influence greatly the space-efficient allocation of dwellings and prevent dwellings from being over- or under-occupied. A major finding of this research is the quantification of the effect of occupancy rules to the environmental impact of housing. A more space-efficient allocation of dwellings achieves a lower per capita dwelling surface, and thus, decreases per capita resource consumption. This dissertation proposes a set of ideal occupancy rules that apply at the lease time. As described in the previous chapter, the ideal occupancy rules refer to a stricter occupancy in comparison to the one that is applied currently. It was developed based on the occupancy rules of housing cooperatives in the canton of Zurich by assuming that housing cooperatives allocate their dwellings in a more space efficient way. The occupancy rules tested in the model are stricter than the current ones, and demonstrate the possibility for improvement even if these occupancy rules

are applied at the time of lease. The margin for further improvement is greater if the occupancy rules are being applied in the course of the tenancy time.

- *Research question RQ4*
  The next research question (RQ4) focuses on the matching between the dwellings and households but this time from the housing demand perspective. ***How do households choose a dwelling and what is the contribution of households' housing choices to the environmental impact of housing?***
  Demand and supply are interdependent. In an economy market, tenants have to choose among the available dwellings according to their needs, preferences and willingness to pay; supply follows the needs of demand and offers dwellings that will be absorbed by the market, otherwise owners risk having vacancies and loss of income. In theory, households choose the dwelling that will provide the highest utility. However, households evolve over time, their needs change; or they don't always decide rationally when it comes to choosing their dwelling; or they don't always find the dwelling they wish for. As a result, residential mobility is generated and households compete to rent a dwelling that fits their needs. This competition is even stronger in markets with housing shortage, as in Switzerland. Our ABM, the HH_ model describes the evolution and the housing preferences of households.
  Although the focus of this thesis lies on the supply side, the model addresses households in detail, and scenario 4 ("Green household") has been developed to investigate the effect of households to the environmental impact. The key findings are that by increasing the environmental awareness of households, there is a significant influence to the environmental indicators. Actually, the results are comparable to the case of applying stricter occupancy rules. The environmental impact decreases in both cases: (1) when households become conscious of the fact that larger space consumption burdens the environment, they are willing to downsize and voluntarily move to a smaller dwelling in the case of under-occupancy and (2) when households are pushed to downsize because they no longer meet the minimum the occupancy rule. The big question here is how to promote public acceptance for such measures. Apart from organising campaigns to inform and make people aware of the environmental aspect and impact of their housing choices, incentives can be also financial, e.g., tax relief, financial aid for moving costs, the development of measures to reduce rents of dwellings with floor area per capita less than a threshold or the introduction of progressive taxes for dwellings with floor area per capita less than a threshold. Except for financial, incentives can be as well social, such as reputation gain or loss; or moral incentives that are defined by what tenants perceive as good or bad. Social and moral incentives are difficult to be assessed as they are related to how tenants perceive their home, which could be a symbol of status, shelter, privacy,

self-representation, etc.

The research findings are relevant for any type of property owner who wishes to manage its housing stock more efficiently in terms of resource use per inhabitant. Additionally, the findings provide guidance for applying dwelling occupancy rules and assessing their implications. The results of this thesis are equally relevant for public authorities wishing to reduce the environmental impact related to housing. They address urban sprawl, population density and residential density, management of housing stocks and sustainable development. Furthermore, it was demonstrated that promoting cooperative housing is an effective lever for more sustainable housing. Although measures applied independently have an impact on reducing the environmental impact of housing, this thesis points out that only through a combination of measures a significant change can be accomplished.
From the supply side, construction patterns should be re-evaluated, and owners should adopt guidelines for constructing high quality, energy efficient, comfortable dwellings at a price that households can afford. Strictly enforced dwelling occupancy rules not only at the attribution of dwellings but also during occupancy are a powerful lever for a more efficient utilisation of housing stocks. Additionally, incentives should be given to households to downsize in case of under-occupancy, as owners' efforts to improve the sustainability of their housing stocks can only be successful if the tenants can be made to endorse these objectives and participate. The combination of measures in the long-term could have a considerable effect on reversing the increasing trend of resource consumption, as it takes time for the measures to show results.
In this thesis, a framework describing the housing market in Switzerland for profit and non-profit oriented rental dwelling owners was developed. It underlines as well the advantages of a bottom-up approach in a complex system such as that of housing. In addition, collaborating closely with the project partners has proven to be very valuable. We worked closely with large building owners who might implement the measures developed by the research team, thereby creating a real-world laboratory.

6.2 Limitations and future work

The findings of this research study provide the following insights for future research:
A major feature of this research project is the inclusion of two housing cooperatives: ABZ in Zurich and SCHL in Lausanne, and the insurer and asset manager Swiss Mobiliar. Their housing stocks (a total of approximately 10,000 dwellings) were examined in depth and were used as the initialisation data for the agent-based model. The model describes the decision-making processes of these three property owners, their building stock and their tenants, which represents a small subset of the Swiss housing market. Thus, the results are context-dependent and cannot be generalised. In the future, the model could be extended to integrate all types of

rental dwelling owners, e.g., private individuals, public sector, construction companies and real estate agencies. The dynamics of the whole Swiss housing stock could be described more realistically by including all owners and dwellings of the Swiss housing market.
Additionally, location plays an important role to many of the model parameters, e.g., taxes, construction costs, land availability, land price, vacancies, rent, etc. A model that considers and studies more thoroughly the spatial diversity of these factors would allow a better representation of the Swiss housing market.
Some aspects of housing supply were omitted or under-studied. For example, a future model could study the competition among the property owners. Developers of rental units compete on many levels: while trying to acquire buildable land; seeking to ensure access to funding in order to grow or renovate their building stock; while trying to offer attractive dwellings to potential tenants. Real estate investors compete to acquire a piece of the housing market, minimise their vacancies and increase rental income in order to maximise profits. This certainly merits further investigation especially in problems related to housing shortage and low vacancy rates.
Moreover, the building stock model assumes that land is available to all owners that wish to construct. However, land is scarce and land reserves dedicated to housing and residential use are decreasing. Additionally, land availability and price determines significantly future rents, construction, demolition and transformation rates. A future research could model the land market (supply and demand), land availability and land prices in detail, where all potential buyers compete among them to find buildable land. In addition, other paths that offer access to housing land, such as land leasing, could be studied in more depth.
Furthermore, the building stock model considers that developers exploit the maximum of the permissible height and floor area ratio, as defined by the zone and land use regulations. A future model could develop different scenarios of new construction patterns, allowing to increase the maximum permissible construction rates. That way, land use regulations could come into focus and the environmental impact of zoning choices could be studied.
The focus of this research lies on rental dwellings located in multi-family buildings. However, single-family houses (SFH) still represent a considerable part of the housing market. This housing typology is connected to high environmental impact in terms of floor area per capita and land area per capita. A thorough study of rental single-family houses would provide a more complete analysis of the environmental impact of housing, its contribution of SFH and the potential that exists in the densification of areas with high proportion of SFH.
Finally, although Switzerland is a country of tenants, homeownership represents almost 40% of the dwellings and is responsible for a good part of resource consumption. Dwellings that are occupied by their owner exhibit the highest floor area per capita, thus it is a key factor towards sustainable housing. Measures targeting the shrinking of the environmental impact of homeowned housing can differ significantly from the rental sector.

Appendix

A Additional tables

A.1 Housing in Switzerland

Table A.1 – Swiss housing - Dwelling surface by construction year and dwelling size

Dwelling surface							
Construction period	Average dwelling surface (m^2)						
	total	**1-room**	**2-room**	**3-room**	**4-room**	**5-room**	**6plus-room**
Total	*99*	*36*	*58*	*80*	*106*	*138*	*177*
before 1919	*97*	37	58	79	103	128	173
1919 - 1945	92	38	57	76	100	126	168
1946 - 1960	84	36	55	72	93	122	164
1961 - 1970	83	34	54	74	94	122	170
1971 - 1980	93	34	56	78	101	131	173
1981 - 1990	107	36	59	83	109	140	179
1991 - 2000	113	39	60	86	112	146	184
2001 - 2005	131	49	64	92	121	153	192
2006 - 2010	125	41	64	93	122	156	196
2011 - 2015	113	38	64	93	123	159	203
2016- 2019	115	35	62	90	120	156	202
Source: FSO Building and dwelling statistics 2020							

Table A.2 – Swiss housing - Floor area per capita by construction year

Floor area per capita			
Construction period	Average floor area per capita (m^2)		
	Multi-family houses (MFH)	**Single-family houses (SFH)**	**% SFH / MFH**
before 1919	44	54.3	23%
1919 - 1945	41.2	50.1	22%
1946 - 1960	37.6	49.4	31%
1961 - 1970	38	55.8	47%
1971 - 1980	41	60	46%
1981 - 1990	43.5	59.5	37%
1991 - 2000	44.9	54.2	21%
2001 - 2010	47.2	50.6	7%
2011 - 2019	47.3	51.6	9%
Source: FSO Building and dwelling statistics 2020			

Table A.3 – Swiss housing - Dwelling and room surface by tenure type and dwelling size

Average dwelling and room surface by tenure type and dwelling size			
Tenure type			
	Dwelling size	**Average dwelling surface**	**Average room surface (m^2)**
Tenants	*total*	*83.4*	*27.6*
	1-room	40.4	41.5
	2-room	61.4	30.8
	3-room	79.1	26.4
	4-room	100.0	25.0
	5-room	121.3	24.3
	6plus- room	144.9	23.2
Owners	*total*	*134.4*	*29.4*
	1-room	83.0	84.7
	2-room	77.4	39.0
	3-room	96.9	32.4
	4-room	120.2	30.1
	5-room	143.2	28.6
	6plus- room	168.6	25.7
Other	*total*	*114.2*	*30.6*
	1-room	68.5	81.8
	2-room	75.7	38.3
	3-room	92.8	31.0
	4-room	111.7	28.0
	5-room	134.1	26.8
	6plus- room	160.0	23.7
Source: FSO 2018			

Table A.4 – Swiss housing - Number of dwellings by dwelling size and tenure type

Number of dwellings by tenure type and dwelling size							
Tenure type	Dwelling size						
	1-room	**2-room**	**3-room**	**4-room**	**5-room**	**6-room+**	**total**
Total	*154'334*	*477'680*	*993'987*	*1'095'660*	*599'067*	*395'203*	*3'715'931*
	4.0%	*13.0%*	*27.0%*	*29.0%*	*16.0%*	*11.0%*	*100%*
Tenant	140'267	413'509	753'345	599'632	152'069	38'996	2'097'818
	7.0%	20.0%	36.0%	29.0%	7.0%	2.0%	56.0%
Tenant a cooperative	2'502	16'500	43'747	35'691	7'600	1'079	107'119
	2.0%	15.0%	41.0%	33.0%	7.0%	1.0%	3.0%
Total of tenants	*142'769*	*430'009*	*797'092*	*635'323*	*159'669*	*40'075*	*2'204'937*
	6.0%	*20.0%*	*36.0%*	*29.0%*	*7.0%*	*2.0%*	*59.0%*
Owner of dwelling in MFH	3'766	22'544	104'388	201'395	85'823	27'644	445'560
	1%	5%	23%	45%	19%	6%	12%
Owner of SFH	4'027	14'366	70'804	232'248	335'368	310'980	967'793
	0.40%	1.50%	7.30%	24%	34.70%	32.10%	26%
Total of owners	*7'793*	*36'910*	*175'192*	*433'643*	*421'191*	*338'624*	*1'413'353*
	0.6%	*2.6%*	*12.4%*	*30.7%*	*29.8%*	*24.0%*	*38.0%*
Other	3'772	10'761	21'704	26'695	18'206	16'504	97'642
	4.0%	11.0%	22.0%	27.0%	19.0%	17.0%	3.0%
Source: FSO 2019							

Table A.5 – Swiss housing - Number of occupants per dwelling and room by dwelling size and period

Number of occupants per dwelling and room					
Dwelling size	Year				
	1970	**1980**	**1990**	**2000**	**2020**
Number of occupants per room					
total	*0.79*	*0.7*	*0.63*	*0.59*	*0.6*
1-room	1.23	1.12	1.18	1.19	1.26
2-room	0.93	0.76	0.71	0.66	0.7
3-room	0.87	0.75	0.67	0.61	0.64
4-room	0.82	0.75	0.68	0.62	0.63
5-room	0.72	0.64	0.6	0.56	0.56
6plus- room	0.59	0.55	0.49	0.46	0.46
Number of occupants per dwelling					
total	*2.9*	*2.6*	*2.4*	*2.3*	*2.2*
1-room	*1.3*	*1.2*	*1.2*	*1.2*	*1.2*
2-room	*1.9*	*1.6*	*1.4*	*1.4*	*1.4*
3-room	*2.7*	*2.3*	*2.0*	*1.9*	*1.9*
4-room	*3.4*	*3.0*	*2.7*	*2.5*	*2.5*
5-room	*3.7*	*3.3*	*3.0*	*2.8*	*2.8*
6plus- room	*4.3*	*3.8*	*3.3*	*3.1*	*3.0*
Sources: FSO - Federal Population Census, Buildings and dwellings statistics 2021					

Table A.6 – Swiss housing - Number of dwellings by canton and tenure type

Tenure type of households										
Tenure type	**Switzerland**		**Canton Zurich**		**Canton Bern**		**Canton Vaud**		**Canton Geneva**	
	number	%	number	%	number	%	number	%	number	%
Tenant	2'097'81		417'47		254'413		221'707		144'388	
Cooperative tenant	107'119		49'665		9'729		3'900		7'307	
Total of tenants	*2'204'93*	*59%*	*467'13*	*70%*	*264'142*	*57%*	*225'607*	*66%*	*151'695*	*78%*
Owner of the apartment	445'559		76'563		50'825		41'085		16'855	
Owner of the house	967'793		119'22		137'023		65'637		19'654	
Total of owners	*1'413'35*	*38%*	*195'78*	*29%*	*187'848*	*40%*	*106'722*	*31%*	*36'509*	*19%*
Other	97'643	3%	8'480	1%	14'572	3%	11'667	3%	6'163	3%
Total	*3'715'93*	*100%*	*671'40*	*100%*	*466'562*	*100%*	*343'997*	*100*	*194'367*	*100%*
Source: FSO 2019										

Table A.7 – Swiss housing - Number of dwellings by construction year, dwelling size and canton

SWITZERLAND

Construction year	1-1.5-room		2-2.5-room		3-3.5-room		4-4.5-room		5-5.5-room		6+-room		all dwellings	
	dwellings	%	dwellings	%	dwellings	%	dwellings	%	dwellings	%	dwellings	%	dwellings	%
before 1919	49908	7%	107912	15%	196373	28%	169045	24%	95927	14%	86537	12%	**705702**	100%
1919-1945	24479	6%	71715	17%	129925	31%	92684	22%	52588	13%	44610	11%	**416001**	100%
1946-1960	36916	7%	83437	16%	171530	34%	126206	25%	54298	11%	37804	7%	**510191**	100%
1961-1970	60567	10%	96303	16%	195714	32%	164734	27%	60111	10%	40067	6%	**617496**	100%
1971-1980	57619	10%	83956	14%	141930	24%	159313	27%	83975	14%	53944	9%	**580737**	100%
1981-1990	23542	5%	62412	13%	102600	22%	141073	30%	90445	19%	53357	11%	**473429**	100%
1991-2000	14806	3%	49252	12%	91927	22%	135762	32%	87009	21%	44879	11%	**423635**	100%
2001-2010	6785	2%	29481	7%	74175	19%	138767	35%	104260	26%	46063	12%	**399531**	100%
2011-2018	12993	3%	65327	16%	115813	29%	123972	31%	58632	15%	25443	6%	**402180**	100%
total	**287615**	**6%**	**649795**	**14%**	**1219987**	**27%**	**1251556**	**28%**	**687245**	**15%**	**432704**	**10%**	**4528902**	**100%**

CANTON ZURICH

Construction year	1-1.5-room		2-2.5-room		3-3.5-room		4-4.5-room		5-5.5-room		6+-room		all dwellings	
	dwellings	%	dwellings	%	dwellings	%	dwellings	%	dwellings	%	dwellings	%	dwellings	%
before 1919	9256	9%	15645	15%	29318	28%	24898	24%	13007	13%	10974	11%	**103098**	100%
1919-1945	3334	5%	13373	19%	26096	37%	15562	22%	7108	10%	5998	8%	**71471**	100%
1946-1960	7457	8%	16408	17%	36281	38%	23584	25%	7114	7%	5040	5%	**95884**	100%
1961-1970	10824	11%	16719	17%	33661	34%	25752	26%	8377	8%	5041	5%	**100374**	100%
1971-1980	11094	12%	14254	15%	23014	24%	24942	26%	13620	14%	7481	8%	**94405**	100%
1981-1990	2989	4%	9375	14%	15468	23%	19982	30%	12413	19%	6415	10%	**66642**	100%
1991-2000	1990	3%	7094	11%	14284	22%	21687	33%	13531	21%	6677	10%	**65263**	100%
2001-2010	1256	2%	6355	8%	16377	21%	28382	37%	17429	23%	6792	9%	**76591**	100%
2011-2018	2499	3%	14049	19%	23511	32%	22474	30%	7988	11%	3204	4%	**73725**	100%
total	**50699**	**7%**	**113272**	**15%**	**218010**	**29%**	**207263**	**28%**	**100587**	**13%**	**57622**	**8%**	**747453**	**100%**

CANTON VAUD

Construction year	1-1.5-room		2-2.5-room		3-3.5-room		4-4.5-room		5-5.5-room		6+-room		all dwellings	
	dwellings	%	dwellings	%	dwellings	%	dwellings	%	dwellings	%	dwellings	%	dwellings	%
before 1919	6439	8%	13413	17%	21492	27%	17861	23%	10600	13%	9347	12%	**79152**	100%
1919-1945	3411	9%	8219	23%	11406	32%	6399	18%	3602	10%	3076	9%	**36113**	100%
1946-1960	4632	10%	12707	27%	15922	34%	7492	16%	3332	7%	2556	5%	**46641**	100%
1961-1970	7824	13%	12645	21%	20387	34%	11204	19%	4345	7%	3430	6%	**59835**	100%
1971-1980	4824	11%	6988	16%	11862	27%	10387	23%	5691	13%	4535	10%	**44287**	100%
1981-1990	2404	5%	6893	15%	12460	27%	12353	27%	7652	16%	4747	10%	**46509**	100%
1991-2000	1250	5%	3617	14%	6850	26%	7152	28%	4504	17%	2614	10%	**25987**	100%
2001-2010	628	2%	2252	6%	6258	18%	12530	36%	8990	26%	4460	13%	**35118**	100%
2011-2018	2541	7%	6688	18%	10745	28%	10564	28%	4972	13%	2373	6%	**37883**	100%
total	**33953**	**8%**	**73422**	**18%**	**117382**	**29%**	**95942**	**23%**	**53688**	**13%**	**37138**	**9%**	**411525**	**100%**

Source: FSO

A.2 Case Study

Table A.8 – Case study - Building stock descriptive statistics

Key figures per owner – Case study – Initial building stock						
Market	Owner		Minimum	Maximum	Mean	Std. Deviation
Free market	ABZ	Number of dwellings = 4770				
		Number of dwellings per settlement	8.0	371.0	159.5	100.6
		Number of dwellings per building	1.0	36.0	12.1	7.2
		Number of buildings per settlement	1.0	57.0	17.4	13.1
		Dwelling floor	0.0	8.0	2.8	1.5
		Number of rooms	1.0	6.5	3.5	1.0
		Dwelling surface (m^2)	26.0	149.8	78.0	21.8
		Square meters per room (m^2/room)	16.5	37.3	22.5	3.2
		Net rent (CHF)	348.0	2902.0	1005.8	328.8
		Net rent per square meter (CHF/m^2)	6.8	22.6	12.9	2.0
		Additional costs (CHF)	25.0	240.0	98.8	34.0
		Additional costs per m^2 (CHF/m^2)	0.4	3.3	1.3	0.5
		Gross rent (CHF)	0.0	3126.0	1145.7	331.8
		Gross rent per m^2 (CHF/m^2)	0.0	26.1	14.8	2.0
		Reference year	1922	2018	1970	30
	Mobiliar	Number of dwellings = 4059				
		Number of dwellings per settlement	5.0	225.0	55.0	49.1
		Number of dwellings per building	1.0	57.0	15.5	10.0
		Number of buildings per settlement	1.0	13.0	4.2	3.0
		Dwelling floor	-1.0	9.0	2.1	1.7
		Number of rooms	1.0	8.0	3.6	1.0
		Dwelling surface (m^2)	10.0	206.0	87.9	25.9
		Square meters per room (m^2/room)	10.0	98.0	24.7	4.3
		Net rent (CHF)	166.7	4540.0	1555.8	476.6
		Net rent per square meter (CHF/m^2)	6.8	35.1	18.3	4.6
		Additional costs (CHF)	0.0	1627.7	226.4	70.9
		Additional costs per m^2 (CHF/m^2)	0.0	22.9	2.6	0.6
		Gross rent (CHF)	192.7	4840.0	1781.7	516.4
		Gross rent per m^2 (CHF/m^2)	9.1	38.5	20.9	4.7
		Reference year	1907	2018	2000	20
	SCHL	Number of dwellings = 1792				
		Number of dwellings per settlement	8.0	233.0	100.6	72.7
		Number of dwellings per building	2.0	121.0	42.7	29.8
		Number of buildings per settlement	1.0	10.0	3.2	2.9
		Dwelling floor	-1.0	8.0	2.3	1.8
		Number of rooms	1.0	5.0	3.1	0.9
		Dwelling surface (m^2)	28.9	163.1	75.3	20.6
		Square meters per room (m^2/room)	17.0	47.0	24.8	3.6
		Net rent (CHF)	329.0	2859.0	1030.2	415.1
		Net rent per square meter (CHF/m^2)	7.2	21.6	13.4	3.0
		Additional costs (CHF)	40.0	330.0	131.8	42.0
		Additional costs per m^2 (CHF/m^2)	0.9	4.6	1.8	0.4
		Gross rent (CHF)	308.0	3109.0	1157.4	441.4
		Gross rent per m^2 (CHF/m^2)	7.9	24.0	15.1	2.9
		Reference year	1906	2019	1976	30
Subsidized	ABZ	Number of dwellings = 161				
		Number of dwellings per settlement	16.0	212.0	128.2	66.2
		Number of dwellings per building	2.0	27.0	12.9	5.5
		Number of buildings per settlement	1.0	17.0	10.9	4.9
		Dwelling floor	0.0	5.0	2.2	1.0
		Number of rooms	1.5	6.5	4.2	1.3
		Dwelling surface (m^2)	41.0	398.0	98.1	34.6
		Square meters per room (m^2/room)	20.3	61.2	23.8	3.5
		Net rent (CHF)	559.0	4044.0	1023.1	344.6
		Net rent per square meter (CHF/m^2)	7.4	16.5	10.7	1.8
		Additional costs (CHF)	30.0	350.0	87.4	45.6
		Additional costs per m^2 (CHF/m^2)	0.4	1.6	0.9	0.4
		Gross rent (CHF)	640.0	4311.0	1103.8	373.9
		Gross rent per m^2 (CHF/m^2)	7.1	18.7	11.7	2.5
		Reference year	1985	2017	2007	11
	SCHL	Number of dwellings = 330				
		Number of dwellings per settlement	28.0	87.0	61.1	18.4
		Number of dwellings per building	4.0	87.0	37.7	29.9
		Number of buildings per settlement	1.0	4.0	2.3	1.0
		Dwelling floor	0.0	5.0	1.8	1.4

		Number of rooms	2.0	5.0	3.0	0.8
		Dwelling surface (m^2)	39.0	137.7	76.3	18.7
		Square meters per room (m^2/room)	19.5	35.3	25.3	2.7
		Net rent (CHF)	498.0	1698.0	904.3	281.7
		Net rent per square meter (CHF/m^2)	9.1	16.8	11.8	1.6
		Additional costs (CHF)	100.0	310.0	168.2	51.6
		Additional costs per m^2 (CHF/m^2)	1.4	3.9	2.2	0.3
		Gross rent (CHF)	416.0	2010.0	1017.8	379.1
		Gross rent per m^2 (CHF/m^2)	7.7	19.0	13.1	2.6
		Reference year	1947	1994	1967	20

Location: Postcodes of the case study dwellings

Market	Owner	Postcode	Frequency	Percent	Postcode	Frequency	Percent
Free market	ABZ	8003	121	2.5	8050	431	9
		8004	290	6.1	8055	143	3
		8005	128	2.7	8057	77	1.6
		8006	8	0.2	8134	179	3.8
		8008	68	1.4	8152	172	3.6
		8037	177	3.7	8304	59	1.2
		8038	728	15.3	8305	69	1.4
		8041	28	0.6	8307	125	2.6
		8044	154	3.2	8600	36	0.8
		8046	463	9.7	8802	17	0.4
		8048	304	6.4	8810	530	11.1
		8049	463	9.7	5417	38	0.9
	Mobiliar	1008	64	1.6	5734	67	1.7
		1022	40	1	6000	10	0.2
		1028	58	1.4	6030	96	2.4
		1180	35	0.9	6060	5	0.1
		1196	53	1.3	6280	45	1.1
		1204	40	1	6300	27	0.7
		1260	120	3	6430	19	0.5
		1470	14	0.3	6598	44	1.1
		1630	118	2.9	7000	22	0.5
		1700	193	4.8	7012	26	0.6
		1752	32	0.8	8002	5	0.1
		1815	21	0.5	8008	6	0.1
		1920	6	0.1	8051	24	0.6
		2036	42	1	8053	14	0.3
		2504	54	1.3	8055	30	0.7
		2543	24	0.6	8126	16	0.4
		2562	14	0.3	8155	25	0.6
		2800	50	1.2	8180	74	1.8
		2900	8	0.2	8193	56	1.4
		3008	30	0.7	8200	57	1.4
		3012	38	0.9	8280	186	4.6
		3013	31	0.8	8307	15	0.4
		3014	18	0.4	8360	15	0.4
		3053	21	0.5	8400	26	0.6
		3072	9	0.2	8404	189	4.7
		3073	57	1.4	8500	21	0.5
		3074	26	0.6	8570	53	1.3
		3075	15	0.4	8580	36	0.9
		3084	44	1.1	8600	247	6.1
		3098	24	0.6	8610	6	0.1
		3113	32	0.8	8620	43	1.1
		3176	60	1.5	8630	23	0.6
		3210	34	0.8	8645	36	0.9
		3250	30	0.7	8707	18	0.4
		3312	7	0.2	8882	33	0.8
		3360	28	0.7	8902	27	0.7
		3600	11	0.3	8910	43	1.1
		3960	73	1.8	9000	61	1.5
		4133	46	1.1	9030	46	1.1
		4147	10	0.2	9242	100	2.5
		4410	48	1.2	9300	73	1.8
		4800	9	0.2	9320	65	1.6

		4900	28	0.7	9443	31	0.8
		5036	28	0.7	9450	83	2
		5406	42	1	9470	92	2.3
	SCHL	1004	404	22.5	1022	28	1.6
		1006	54	3	1024	75	4.2
		1007	314	17.5	1030	60	3.3
		1008	120	6.7	1032	16	0.9
		1009	97	5.4	1033	51	2.8
		1010	62	3.5	1052	174	9.7
		1012	9	0.5	1066	56	3.1
		1018	272	15.2			
Subsidized	ABZ	8038	61	37.9	8050	52	32.3
		8044	33	20.5	8057	3	1.9
		8048	12	7.5			
	SCHL	1004	87	26.4	1018	44	13.3
		1007	66	20	1052	28	8.5
		1010	105	31.8			
Location: Municipality of the case study dwellings							
Market	Owner	Municipality	Frequency	Percent	Municipality	Frequency	Percent
Free market	ABZ	Adliswil	179	3.8	Horgen	530	11.1
		Dietlikon	69	1.4	Kilchberg	17	0.4
		Dübendorf	36	0.8	Wallisellen	59	1.2
		Effretikon	125	2.6	Zurich	3583	75.1
		Glattpark	172	3.6			
	Mobiliar	Abtwil	46	1.1	Neuenegg	60	1.5
		Aesch	10	0.2	Niederhasli	25	0.6
		Affoltern am Albis	43	1.1	Nyon	120	3
		Altstätten SG	83	2	Oberentfelden	28	0.7
		Amriswil	36	0.9	Oberuzwil	51	1.3
		Arbon	65	1.6	Oberuzwil SG	49	1.2
		Baden-Rütihof	42	1	Ostermundigen	9	0.2
		Bern	117	2.9	Porrentruy	8	0.2
		Biel-Mett	54	1.3	Port	14	0.3
		Buchs	48	1.2	Pratteln	46	1.1
		Buchs SG	44	1.1	Préverenges	58	1.4
		Bülach	74	1.8	Prilly	64	1.6
		Bulle	118	2.9	Rapperswil-Jona	36	0.9
		Chavannes-Rennens	40	1	Reinach	67	1.7
		Chur	22	0.5	Rolle	35	0.9
		Clarens	21	0.5	Rubigen	32	0.8
		Corcelles-Cormondrèche	42	1	Rüfenacht	15	0.4
		Delémont	50	1.2	Rüti	23	0.6
		Dübendorf	247	6.1	Sarnen	5	0.1
		Ebikon	96	2.4	Schaffhausen	57	1.4
		Effretikon	15	0.4	Schliern	24	0.6
		Eglisau	56	1.4	Schwyz	19	0.5
		Eschlikon	15	0.4	Siders	73	1.8
		Estavayer-le-Lac	14	0.3	St. Gallen	61	1.5
		Felsberg	26	0.6	Tenero	44	1.1
		Fraubrunnen	7	0.2	Thun	11	0.3
		Frauenfeld	21	0.5	Uetikon am See	18	0.4
		Fribourg	193	4.8	Untersiggenthal	38	0.9
		Genève	40	1	Unterterzen	33	0.8
		Gland	53	1.3	Urdorf	27	0.7
		Gümligen	57	1.4	Uster	6	0.1
		Herzogenbuchsee	28	0.7	Villars-sur-Glâne	32	0.8
		Hochdorf	45	1.1	Wabern	44	1.1
		Kerzers	34	0.8	Weinfelden	53	1.3
		Kreuzlingen	186	4.6	Wetzikon	43	1.1
		Langenthal	28	0.7	Widnau	31	0.8

		Lengnau	24	0.6	Winterthur	215	5.3
		Liestal	48	1.2	Wittenbach	73	1.8
		Luzern	10	0.2	Zofingen	9	0.2
		Lyss	30	0.7	Zug	27	0.7
		Martigny	6	0.1	Zumikon	16	0.4
		Münchenbuchsee	21	0.5	Zurich	79	1.9
		Muri BE	26	0.6	Bussigny	60	3.3
	SCHL	Chavannes-Rennens	28	1.6	Mont-sur-Lausanne	174	9.7
		Cheseaux-Lausanne	51	2.8	Prilly	120	6.7
		Ecublens	75	4.2	Pully	97	5.4
		Epalinges	56	3.1	Romanel-sur-Lausanne	16	0.9
		Lausanne	1115	62.2			
Subsidized	ABZ	Zurich	161	100			
	SCHL	Lausanne	302	91.5			
		Mont-sur-Lausanne	28	8.5			
Location: Canton of the case study dwellings							
Market	Owner	Canton	Frequency	Percent	Canton	Frequency	Percent
Free market	ABZ	Zurich	4770	100			
	Mobiliar	Aargau	194	4.8	Obwalden	5	0.1
		Abtwil	46	1.1	Schaffhausen	57	1.4
		Basel-Landschaft	104	2.6	Schwyz	19	0.5
		Bern	601	14.8	St. Gallen	574	14.1
		Fribourg	391	9.6	Thurgau	367	9
		Geneva	40	1	Ticino	44	1.1
		Graubünden	48	1.2	Valais	79	1.9
		Jura	58	1.4	Vaud	391	9.6
		Luzern	141	3.5	Zug	27	0.7
		Neuchatel	42	1	Zurich	831	20.5
	SCHL	Vaud	1792	100			
Subsidized	ABZ	Zurich	161	100			
	SCHL	Vaud	330	100			
Source: own analysis							

Table A.9 – Case study - Renovation history by owner

Number of dwellings depending on the last renovation/transformation year						
Period of renovation or transformation	**ABZ**		**SCHL**		**Mobiliar**	
	Number of dwellings	%	Number of dwellings	%	Number of dwellings	%
No intervention	1,651	33.5%	714	33.6%	3,374	83.1%
1970-1979	205	4.2%	86	4.1%	0	0.0%
1980-1989	297	6.0%	109	5.1%	9	0.2%
1990-1999	917	18.6%	465	21.9%	100	2.5%
2000-2009	1245	25.2%	535	25.2%	445	11.0%
2010-2020	616	12.5%	213	10.0%	131	3.2%
Total	*4,931*	*100.0%*	*2,122*	*100.0%*	*4,059*	*100.0%*
Source: Own analysis based on the partner's data						

Table A.10 – Case study - Age of the building stock by owner

Age of the building stock - Case study				
Period	**CH-rental**	**ABZ**	**SCHL**	**Mobiliar**
before 1946	23%	23%	16%	1%
1946-1980	43%	43%	39%	19%
1981-2000	17%	9%	13%	12%
after 2000	17%	25%	32%	68%
Source: Own analysis based on the partner's data and FSO				

Table A.11 – Case study - Dwelling surface by dwelling size and construction period

Dwelling surface by dwelling size and construction period					
Construction period	Dwelling surface (m^2)				
	1room	**2-room**	**3-room**	**4-room**	**5room+**
ABZ					
1920-1939	34	54	64	78	114
1940-1959	32	52	63	77	95
1960-1979	34	56	75	89	108
1980-1999	36	62	89	105	135
2000-2020	42	62	85	105	126
SCHL					
1920-1939	42	52	68	79	105
1940-1959		51	67	89	
1960-1979	31	54	70	90	109
1980-1999	35	60	82	100	124
2000-2020		57	80	99	125
Mobiliar					
1920-1939		98		93	106
1940-1959	29	58	78	97	115
1960-1979	34	54	75	94	120
1980-1999	48	68	87	104	131
2000-2020	34	61	89	110	134
Source: Own analysis based on the partner's data					

Table A.12 – Case study - Dwelling size by construction period

Dwelling size by construction period						
Construction period	Dwelling size (number of rooms)					
	1-room	**2-room**	**3room**	**4-room**	**5-room+**	**total**
ABZ						
1920-1939	0%	13%	54%	27%	6%	100%
1940-1959	1%	19%	55%	23%	1%	100%
1960-1979	7%	17%	41%	31%	4%	100%
1980-1999	5%	27%	28%	32%	7%	100%
2000-2020	2%	17%	26%	37%	17%	100%
Mobiliar						
1920-1939	0%	47%	0%	26%	26%	100%
1940-1959	10%	21%	52%	10%	7%	100%
1960-1979	8%	22%	37%	27%	6%	100%
1980-1999	3%	12%	30%	43%	12%	100%
2000-2020	4%	19%	38%	33%	5%	100%
SCHL						
1920-1939	4%	29%	55%	10%	2%	100%
1940-1959	0%	41%	42%	17%	0%	100%
1960-1979	8%	25%	46%	19%	3%	100%
1980-1999	0%	11%	38%	47%	3%	100%
2000-2020	0%	12%	41%	40%	7%	100%
All dwellings						
1920-1939	1%	17%	54%	23%	5%	100%
1940-1959	2%	26%	51%	20%	2%	100%
1960-1979	8%	20%	41%	28%	4%	100%
1980-1999	3%	17%	32%	40%	8%	100%
2000-2020	3%	18%	35%	35%	9%	100%
Source: Own analysis based on the partner's data						

Table A.13 – Case study - Occupant statistics ABZ

ABZ households	
Income distribution of ABZ households - Case study	
Yearly income	Percentage of households %
0-19,999 CHF	22.6%
20,000-39,999 CHF	32.3%
40,000-59,999 CHF	26.9%
60,000-79,999 CHF	11.6%
80,000-99,999 CHF	4.5%
100,000-149,000 CHF	1.8%
>=150,000 CHF	0.3%
Types of ABZ households - Case study	
Type of household	Percentage of households %
One-person household	31%
Couples without children	22%
Couples with children	32%
Single-parent households	13%
Other household types	2%
Age distribution of ABZ occupants - Case study	
Age group	Percentage of occupants %
0-5	3%
6-12	8%
13-17	7%
18-39	30%
40-64	37%
65-79	11%
80+	4%
Source: ABZ yearly report 2019	

Table A.14 – Case study - Occupant statistics SCHL

SCHL households	
Age distribution of SCHL occupants - Case study	
Age group	Percentage of SCHL occupants
19-45	35%
46-65	33%
65+	32%
Size of SCHL households - Case study	
Household size	Percentage of households
1-person households	29%
2-person households	36%
3-person households	14%
4-person households	15%
5+person households	6%
Source : SCHL Survey 2009	

Table A.15 – Case study - Number of dwellings by canton and by owner

Number of dwellings by owner and construction year												
Construction period	Switzerland		Zurich canton		Vaud canton		ABZ		SCHL		Mobiliar	
	N	%	N	%	N	%	N	%	N	%	N	%
Total	*4,528,902*	*100%*	*747453*	*100%*	*411525*	*100%*	*4931*	*100%*	*2019*	*100%*	*4134*	*100%*
<1919	705,702	16%	103,098	14%	79,152	19%			15	1%	14	0%
1919 - 1945	416,001	9%	71,471	10%	36,113	9%	1,026	21%	326	16%	50	1%
1946 - 1960	510,191	11%	95,884	13%	46,641	11%	624	13%	391	19%	179	4%
1961 - 1970	617,496	14%	100,374	13%	59,835	15%	909	18%	260	13%	362	9%
1971 - 1980	580,737	13%	94,405	13%	44,287	11%	513	10%	149	7%	295	7%
1981 - 1990	473,429	10%	66,642	9%	46,509	11%	396	8%	142	7%	259	6%
1991 - 2000	423,635	9%	65,263	9%	25,987	6%	187	4%	210	10%	217	5%
2001 - 2005	171,984	4%	34,964	5%	14,672	4%	66	1%	90	4%	117	3%
2006 - 2010	227,547	5%	41,627	6%	20,446	5%	463	9%	241	12%	882	21%
2011 - 2015	249,053	5%	46,312	6%	22,374	5%	363	7%	118	6%	1,069	26%
2016 - 2018	153,127	3%	27,413	4%	15,509	4%	384	8%	77	4%	690	17%
Source: FSO 2018, all dwellings rental and owner occupied												

Table A.16 – Case study - Building stock descriptive statistics by market type

Key figures (free-market/subsidized) – Case study – Initial building stock					
Free market	Number of dwellings = 10621	Minimum	Maximum	Mean	Std. Deviation
	Number of dwellings per settlement	5.0	371.0	109.6	92.9
	Number of dwellings per building	1.0	121.0	18.6	18.2
	Number of buildings per settlement	1.0	57.0	9.9	11.3
	Dwelling floor	-1.0	8.0	2.5	1.6
	Number of rooms	1.0	8.0	3.5	1.0
	Dwelling surface (m^2)	10.0	206.0	81.3	23.9
	Square meters per room (m^2/room)	10.0	98.0	23.7	3.9
	Net rent (CHF)	166.7	4540.0	1220.1	483.9
	Net rent per square meter (CHF/m^2)	6.8	35.1	15.1	4.2
	Additional costs (CHF)	0.0	1627.7	153.1	78.6
	Additional costs per m^2 (CHF/m^2)	0.0	22.9	1.9	0.8
	Gross rent (CHF)	0.0	4840.0	1390.8	528.0
	Gross rent per m^2 (CHF/m^2)	0.0	38.5	17.2	4.5
	Reference year	1906	2019	1982	29.9
Subsidized	Number of dwellings = 491				
	Number of dwellings per settlement	16.0	212.0	83.1	51.5
	Number of dwellings per building	2.0	87.0	29.6	27.3
	Number of buildings per settlement	1.0	17.0	5.2	5.0
	Dwelling floor	0.0	5.0	1.9	1.3
	Number of rooms	1.5	6.5	3.4	1.1
	Dwelling surface (m^2)	39.0	398.0	83.4	27.0
	Square meters per room (m^2/room)	19.5	61.2	24.8	3.0
	Net rent (CHF)	498.0	4044.0	943.3	308.5
	Net rent per square meter (CHF/m^2)	7.4	16.8	11.4	1.7
	Additional costs (CHF)	30.0	350.0	141.7	62.5
	Additional costs per m^2 (CHF/m^2)	0.4	3.9	1.8	0.7
	Gross rent (CHF)	416.0	4311.0	1046.0	379.2
	Gross rent per m^2 (CHF/m^2)	7.1	19.0	12.6	2.7
	Reference year	1947	2017	1980	25.4

Table A.17 – Case study - Key figures by owner and market type

Net rent CHF							
	ABZ	ABZ free-market	ABZ subsidized	SCHL	SCHL free-market	SCHL subsidized	Mobiliar
All stock	1006.40	1005.8	1023.1	1012.4	1030.5	912.4	1597.4
1room	617.3	617.6	659.0	452.2	452.2		770.1
2room	777.7	782.6	782.6	924.8	931.2	623.5	1174.6
3room	883.1	884.0	948.3	1103.5	1106.6	898.0	1459.2
4room	1080.5	1087.2	1026.4	1516.7	1535.6	1151.0	1604.9
5room	1452.4	1470.0	1254.1	1735.4	1746.7	1592.8	2225.1
6room	1571.6	1609.0	1493.9	2859.0	2859.0		2788.3
Net rent per square meter CHF/m^2							
	ABZ	ABZ free-market	ABZ subsidized	SCHL	SCHL free-market	SCHL subsidized	Mobiliar
All stock	12.9	12.9	10.7	13.1	13.4	11.8	18.4
1room	16.8	16.9	13.4	14.1	14.1		22.6
2room	13.8	13.9	13.0	16.2	16.4	11.6	21.3
3room	12.3	12.4	11.4	13.9	14.0	11.8	18.9
4room	12.2	12.2	9.8	15.1	15.3	12.0	16.1
5room	12.6	12.8	10.2	14.3	14.5	12.2	18.9
6room	12.7	13.2	9.2	17.5	17.5		17.7
Average dwelling surface m^2							
	ABZ	ABZ free-market	ABZ subsidized	SCHL	SCHL free-market	SCHL subsidized	Mobiliar
All stock	78.6	77.9	98.1	75.8	75.6	76.8	88.1
1room	37.1	37.0	49.3	32.9	32.9		34.5
2room	56.4	56.3	54.9	56.2	56.2	53.9	56.4
3room	70.9	70.9	82.9	78.4	78.1	75.8	79.0
4room	88.0	87.8	104.3	99.7	99.6	95.5	99.3
5room	115.2	115.1	122.6	119.9	119.0	130.7	119.5
6room	124.6	122.4	159.3	163.1	163.1		161.5
Source: Own analysis based on project partner's data							

A.3 SHEF Survey

Table A.18 – Case study - SHEF Survey - Building stock and occupancy

Descriptive Statistics of Building stock & Occupancy - SHEF Survey Results								
	Total		ABZ		SCHL		Mobiliar	
	N	%	N	%	N	%	N	%
Number of households and valid answers (N=945)	*945*	*100%*	*322*	*34%*	*379*	*40%*	*244*	*26%*
Living in free-market dwelling	887	94%	313	35%	330	37%	244	28%
Living in subsidized dwelling	58	6%	9	16%	49	84%	-	-
Size of dwelling (N=945)								
1-1.5room dwelling	18	1.9%	7	2.2%	7	1.8%	4	1.6%
2-2.5 room dwelling	165	17.5%	53	16.5%	78	20.6%	34	13.9%
3-3.5 room dwelling	408	43.2%	129	40.1%	165	43.5%	114	46.7%
4-4.5 room dwelling	298	31.5%	107	33.2%	117	30.9%	74	30.3%
5-5.5 room dwelling	53	5.6%	24	7.5%	12	3.2%	17	7.0%
6-6.5 room dwelling	3	0.3%	2	0.6%	-	-	1	0.4%
Equipment (N=870):								
Standard Minergie	268	28.4%	76	23%	99	26%	93	38%
Standard Minergie P	64	6.8%	22	7%	27	7%	15	6%
Standard LEED	38	4%	16	5%	18	5%	4	2%
Private washing machine	280	29.6%	44	14%	95	25%	141	58%
Shared washing machine	746	79%	280	88%	342	90%	124	50%
Dish washer	780	82.5%	264	82%	278	73%	238	98%
Microwave	513	54.3%	128	40%	254	68%	131	53%
Fridge	939	99.4	322	100%	373	98.5%	244	100%

Occupancy (N=945)				
	Total Mean	ABZ Mean	SCHL Mean	Mobiliar Mean
Rooms per person (rooms/person)	1.9	1.8	1.9	2.2
Number of persons per dwelling (persons/dwelling)	2.2	2.5	2.1	2.1
Living surface per person (m^2/person)	45.8	40.2	46.8	51.7
Dwelling size - surface (m^2)	82	82	78	89
Dwelling size - number of rooms	3.3	3.3	3.3	3.3
Rent (N=875)				
Average net rent	1189	1089	1057	1581
Average net rent/m^2 (CHF/ m^2)	14.4	13.2	13.3	18.2
Average gross rent	1362	1226	1188	1817
Average gross rent/m^2 (CHF/ m^2)	16.5	14.9	14.9	20.8

Table A.19 – Case study - SHEF Survey - Households

Descriptive Statistics of Households - SHEF Survey Results								
	Total		ABZ		SCHL		Mobiliar	
	N	%	N	%	N	%	N	%
Number of households and valid answers (N=945)	*945*	*100%*	*322*	*34%*	*379*	*40%*	*244*	*26%*
Living in free-market dwelling	887	94%	313	35%	330	37%	244	28%
Living in subsidized dwelling	58	6%	9	16%	49	84%	-	-
Average size of household (N=945)								
1-person	327	34.6%	88	27%	160	42%	79	32%
2-persons	304	32.2%	94	29%	109	29%	101	42%
3-persons	161	17%	68	21%	58	15%	35	14%
4-persons	110	11.6%	52	16%	36	10%	22	9%
5plus-persons	43	4.5%	20	7%	16	4%	7	3%
Age of main tenant (N=945)								
<20	1	0.1%	-	-	1	0.3%	-	-
20-29	60	6.3%	14	4.35%	19	5.0%	27	11.1%
30-39	185	19.6%	53	16.46	61	16.1%	71	29.1%
40-49	201	21.3%	71	22.05	77	20.3%	53	21.7%
50-59	191	20.2%	74	22.98	79	20.8%	38	15.6%
60-69	165	17.5%	64	19.88	74	19.5%	27	11.1%
70-79	106	11.2%	38	11.80	47	12.4%	21	8.6%
80+	36	3.6%	8	2.48%	21	5.5%	7	2.9%
Language (N=945)								
Number of German answers	428	45%	317	98.4%	2	0.5%	109	44.7%
Number of French answers	517	55%	5	1.6%	377	99.5%	135	55.3%
Gender of main tenant (N=945)								
Women	496	52.5%	182	56.5	199	53%	115	47.1%
Men	449	47.5%	140	43.5	180	47%	129	52.9%
Typology (N=871)								
Number of valid answers	*871*	*100%*	*303*	*34.5%*	*320*	*37%*	*248*	*28.5%*
One person's household < 65 years old	202	23%	58	19%	93	29%	52	21%
One person's household >= 65 years old	93	11%	24	8%	42	13%	27	11%
Couples without children < 65 years old	121	14%	30	10%	38	12%	52	21%
Couples without children >= 65 years old	39	5%	9	3%	13	4%	17	7%
Single parents with at least one child	92	11%	42	14%	32	10%	17	7%
Couples with at least one child	292	34%	124	41%	96	30%	72	29%
Other multi-person households	31	4%	15	5%	6	2%	10	4%
Civil status (N=945)								
Single	219	23.2%	60	18.6%	83	21.9%	76	31.1%
Married or in couple	467	49.4%	167	51.9%	175	46.2%	125	51.2%
Widowed	52	5.5%	15	4.7%	25	6.6%	12	4.9%
Divorces or separated	202	21.4%	78	24.2%	94	24.8%	30	12.3%
Other	5	0.5%	2	0.6%	2	0.5%	1	0.4%
Gross income (N=734)								
Number of valid answers	*734*	*100%*	*249*	*34%*	*297*	*40%*	*188*	*26%*
<=60 000 CHF/year	251	34%	98	40%	124	42%	29	16%
60 001 – 88 000 CHF/year	216	29%	82	33%	91	31%	43	23%
88 001 – 120 000 CHF/year	153	21%	45	18%	48	16%	60	30%
120 001 – 164 999 CHF/year	70	10%	14	6%	21	7%	35	18%
>=165 000 CHF/year	44	6%	10	4%	13	4%	21	13%
Swiss nationality – C permit (N=919)								
Number of valid answers	919	100%	311	34%	368	40%	240	26%
Swiss nationality or swiss permit	660	72%	209	67%	292	79%	159	66%
Employment (N=896)								
Full-time (80-100%)	420	49.5%	126	44%	149	45%	153	66%
Part-time (less than 80%)	174	20.5%	84	29.5%	66	20%	26	11%
Full-time housewife/househusband	21	2.5%	4	1.5%	8	2.5%	5	2%
In training (paid job less than a day a week)	8	1%	4	1.5%	2	0.5%	5	2%
Currently unemployed	21	2.5%	4	1.5%	13	4%	5	2%
Retired	204	24%	63	22%	92	28%	39	17%

Number of children per household (N=405)								
	437	100%	180	41%	167	38%	90	21%
1	130	30%	48	27%	46	28%	36	40%
2	229	52%	95	53%	94	56%	40	45%
3	63	14%	30	17%	20	12%	13	14%
4+	15	4%	7	3%	7	4%	1	1%
Times of changing dwelling during the last ten years (N=945)								
0	303	32%	125	39%	132	35%	46	18%
1	284	31%	98	31%	116	31%	70	30%
2	161	17%	52	16%	61	16%	48	20%
3+	197	20%	47	14%	70	18%	80	32%
Willingness to move to a smaller dwelling if the household decreases (N=606)								
Not at all ready	105	17%	34	15%	52	24%	19	13%
Not ready	129	21%	44	19%	48	22%	37	23%
Neutral	228	38%	83	36%	75	35%	70	43%
Ready	107	18%	53	23%	30	14%	24	14%
Very willing	37	6%	17	7%	11	5%	9	7%
Months waiting to find a dwelling								
<3months	449	47.5%	138	43%	144	38%	167	68%
3-6 months	237	25%	74	23%	113	29%	50	21%
>6months	259	27.5	110	34%	122	33%	27	11%

Average values	Total Mean	ABZ Mean	SCHL Mean	Mobiliar Mean
Years living in the same dwelling (years) (N=890)	10	10.5	11.2	7.6
Age of main tenant (N=890)	52	53	54	47
Satisfaction with current dwelling (N=920)	3.9	3.9	4.1	3.9
Number of children per household (if any) (N=896)	1.92	1.99	1.94	1.77
Number of cars per household (N=720)	1.86	1.69	1.88	2.04

A.4 Model design

Table A.20 – Model design - Building stock data 1990-2020 (Stat1990) - Key figures

Stat1990 - Key figures					
Owner	**Variable/Characteristic**	**Minimum**	**Maximum**	**Mean**	**Std. Dev.**
ABZ	Number of dwellings = 1291				
	Number of dwellings per settlement	16.0	277.0	175.3	74.2910
	Number of dwellings per building	2.0	27.0	13.4	4.5990
	Number of buildings per settlement	1.0	20.0	13.9	4.8990
	Dwelling floor	0	6.0	3.2	1.4290
	Dwelling surface (m^2)	30.5	149.8	93.2	23.5279
	Square meters per room (m^2/room)	16.5	36.3	24.0	2.28129
	Number of rooms	1.0	6.5	3.9	1.1196
	Net rent (CHF)	348.0	2181.0	1324.5	289.0341
	Net rent per square meter (CHF/m^2)	10.4	20.9	14.5	1.7102
	Additional costs (CHF)	25.0	190.0	69.3	29.7796
	Gross rent (CHF)	406.0	2338.5	1447.3	298.8014
SCHL	Number of dwellings = 701				
	Number of dwellings per settlement	8.0	233.0	117.1	85.4220
	Number of dwellings per building	4.0	79.0	29.7	20.3150
	Number of buildings per settlement	1.0	10.0	5.0	3.7670
	Dwelling floor	-1.0	5.0	2.0	1.4860
	Dwelling surface (m^2)	35.4	163.1	87.7	18.7462
	Square meters per room (m^2/room)	17.9	45.7	25.9	3.01059
	Number of rooms	1.0	5.0	3.4	0.8140
	Net rent (CHF)	428.0	2859.0	1400.8	311.5824
	Net rent per square meter (CHF/m^2)	9.7	21.0	16.0	1.5000
	Additional costs (CHF)	55.0	270.0	130.5	37.5112
	Gross rent (CHF)	593.0	3109.0	1538.6	334.4272
Mobiliar	Number of dwellings = 2968				
	Number of dwellings per settlement	6.0	225.0	65.3	53.1720
	Number of dwellings per building	1.0	57.0	16.2	10.7990
	Number of buildings per settlement	1.0	13.0	4.9	3.1850
	Dwelling floor	0	9.0	2.1	1.6440
	Dwelling surface (m^2)	16.0	189.0	90.7	25.2817
	Square meters per room (m^2/room)	15.7	98	25.1	4.15853
	Number of rooms	1.0	6.5	3.6	0.9720
	Net rent (CHF)	360.0	4540.0	1654.7	446.7683
	Net rent per square meter (CHF/m^2)	8.4	33.1	18.9	4.4796
	Additional costs (CHF)	40.0	1627.7	227.8	70.4521
	Gross rent (CHF)	400.0	4840.0	1882.0	486.2547

Stat1990 - Number of buildings					
Owner	**Frequency**	**Minimum**	**Maximum**	**Mean**	**Std. Dev.**
ABZ	13	1	20	13.93	4.899
Mobiliar	70	1	13	4.86	3.185
SCHL	15	1	10	5.04	3.767

Stat1990 - Number of rooms per dwelling			
Owner	**Number of rooms**	**Frequency**	**Percent**
ABZ	1-1.5 room	38	2.9
	2-2.5 room	240	18.6
	3-3.5 room	353	27.3
	4-4.5 room	465	36
	5+ room	195	15.1
	Total	1291	100
SCHL	1-1.5 room	1	0.1
	2-2.5 room	94	13.4
	3-3.5 room	272	38.8
	4-4.5 room	290	41.4
	5+ room	44	6.3
	Total	701	100
Mobiliar	1-1.5 room	125	4.2
	2-2.5 room	550	18.5
	3-3.5 room	1129	38
	4-4.5 room	1015	34.2
	5+ room	149	5
	Total	2968	100

Stat1990 - Dwelling size (m^2)						
Owner	**Number of rooms**	**Frequency**	**Minimum**	**Maximum**	**Mean**	**Std. Dev.**
ABZ	1-1.5 room	38	31	55	41	5.8
	2-2.5 room	240	38	76	61	6.7
	3-3.5 room	353	58	102	86	7.0
	4-4.5 room	465	90	130	106	6.5
	5+ room	195	115	150	126	8.4
SCHL	1-1.5 room	1	35	35	35	
	2-2.5 room	94	50	91	57	7.0
	3-3.5 room	272	54	128	80	9.8
	4-4.5 room	290	88	125	99	6.2
	5+ room	44	113	163	125	7.9
Mobiliar	1-1.5 room	125	16	98	35	16.2
	2-2.5 room	550	32	114	62	11.7
	3-3.5 room	1129	47	147	89	9.9
	4-4.5 room	1015	79	158	109	10.7
	5+ room	149	95	189	135	19.7

Stat1990 - Canton			
Owner	**Canton**	**Frequency**	**Percent**
ABZ	Zurich	1291	100
SCHL	Vaud	701	100
Mobiliar	Aargau	175	5.9
	Basel-Landschaft	46	1.5
	Bern	292	9.8
	Fribourg	238	8
	Geneva	40	1.3
	Graubünden	26	0.9
	Jura	50	1.7
	Luzern	128	4.3
	Neuchatel	42	1.4
	Schaffhausen	37	1.2
	St. Gallen	503	16.9
	Thurgau	334	11.3
	Ticino	44	1.5
	Valais	79	2.7
	Vaud	291	9.8
	Zug	27	0.9
	Zurich	616	20.8

Stat1990 - Postcode						
Owner	**Postcode**	**Frequency**	**Percent**	**Postcode**	**Frequency**	**Percent**
ABZ	8038	262	20.3	8050	199	15.4
	8044	136	10.5	8057	15	1.2
	8046	463	35.9	8152	172	13.3
	8049	44	3.4			
SCHL	1006	8	1.1	1030	60	8.6
	1009	65	9.3	1033	51	7.3
	1018	260	37.1	1052	174	24.8
	1024	27	3.9	1066	56	8
Mobiliar	1022	40	1.3	6030	96	3.2
	1028	58	2	6280	32	1.1
	1180	35	1.2	6300	27	0.9
	1196	53	1.8	6598	44	1.5
	1204	40	1.3	7012	26	0.9
	1260	105	3.5	8180	74	2.5
	1630	109	3.7	8193	56	1.9
	1700	95	3.2	8200	37	1.2
	1920	6	0.2	8280	186	6.3
	2036	42	1.4	8404	189	6.4
	2504	54	1.8	8500	21	0.7
	2562	14	0.5	8570	35	1.2
	2800	50	1.7	8580	36	1.2
	3008	30	1	8600	247	8.3
	3053	21	0.7	8610	6	0.2
	3073	57	1.9	8620	30	1

	3176	60	2	8882	33	1.1
	3210	34	1.1	8902	27	0.9
	3360	28	0.9	8910	43	1.4
	3960	73	2.5	9000	26	0.9
	4133	46	1.5	9242	100	3.4
	4900	28	0.9	9300	73	2.5
	5036	28	0.9	9320	65	2.2
	5406	42	1.4	9443	31	1
	5417	38	1.3	9450	83	2.8
	5734	67	2.3	9470	92	3.1
Stat1990 - City						
Owner	**City**	**Frequency**	**Percent**	**City**	**Frequency**	**Percent**
ABZ	Glattpark	172	13.3			
	Zurich	1119	86.7			
SCHL	Bussigny-Lausanne	60	8.6	Lausanne	268	38.2
	Cheseaux-Lausanne	51	7.3	Mont-sur-Lausanne	174	24.8
	Ecublens	27	3.9	Pully	65	9.3
	Epalinges	56	8			
Mobiliar	Affoltern am Albis	43	1.4	Langenthal	28	0.9
	Altstätten SG	83	2.8	Martigny	6	0.2
	Amriswil	36	1.2	Münchenbuchsee	21	0.7
	Arbon	65	2.2	Neuenegg	60	2
	Baden-Rütihof	42	1.4	Nyon	105	3.5
	Bern	30	1	Oberentfelden	28	0.9
	Biel-Mett	54	1.8	Oberuzwil	51	1.7
	Buchs	48	1.6	Oberuzwil SG	49	1.7
	Buchs SG	44	1.5	Port	14	0.5
	Bülach	74	2.5	Pratteln	46	1.5
	Bulle	109	3.7	Préverenges	58	2
	Chavannes-Renens	40	1.3	Reinach	67	2.3
	Corcelles-	42	1.4	Rolle	35	1.2
	Delémont	50	1.7	Schaffhausen	37	1.2
	Dübendorf	247	8.3	Siders	73	2.5
	Ebikon	96	3.2	St. Gallen	26	0.9
	Eglisau	56	1.9	Tenero	44	1.5
	Felsberg	26	0.9	Untersiggenthal	38	1.3
	Frauenfeld	21	0.7	Unterterzen	33	1.1
	Fribourg	95	3.2	Urdorf	27	0.9
	Genève	40	1.3	Uster	6	0.2
	Gland	53	1.8	Weinfelden	35	1.2
	Gümligen	57	1.9	Wetzikon	30	1
	Herzogenbuchsee	28	0.9	Widnau	31	1
	Hochdorf	32	1.1	Winterthur	189	6.4
	Kerzers	34	1.1	Wittenbach	73	2.5
	Kreuzlingen	186	6.3	Zug	27	0.9

Stat1990 - Dwelling floor			
Owner	**Dwelling floor**	**Frequency**	**Percent**
ABZ	0	192	14.9
	1	268	20.8
	2	293	22.7
	3	298	23.1
	4	176	13.6
	5	57	4.4
	6	7	0.5
SCHL	-1	14	2
	0	100	14.6
	1	158	22.5
	2	160	22.8
	3	139	19.8
	4	92	13.1
	5	36	5.1
Mobiliar	0	548	18.5
	1	668	22.5
	2	691	23.3
	3	553	18.6
	4	249	8.4
	5	148	5
	6	66	2.2
	7	33	1.1
	8	10	0.3
	9	1	0
Source: Own analysis based on the partner's data			

Table A.21 – Model design - Building stock model - Variables

Variables for the building stock – Data collected		
Building stock characteristics - Variables	**Description**	**Metrics**
Settlements		
Number of settlements	The number of settlements – groups of buildings owned by each owner - partner	
Number of buildings per settlement	The number of buildings in each settlement	
Number of dwellings per settlement	The number of dwellings in each settlement	
Number of dwellings per building	The number of dwellings in each building	
Height of the building (m)	The total height of the building	Meters (m)
Construction year	The year the settlement was constructed	year
Renovation year(s)	The year or years a light or heavy renovation was undertaken	year
Demolition year	The year the settlement was demolished	year
Reconstruction year	The year the settlement was reconstructed after its demolition	year
Sale year	The year a settlement was sold	year
Purchase year	The year a settlement was bought	year
Address	The location of the settlement	
City	The location of the settlement	
Canton	The location of the settlement	
Postcode	The location of the settlement	
Typology of the municipality (9 FSO categories)	Typology of the municipality, based on the 9 FSO categories (Urban, Peri-urban, Rural & Big, Medium, Small municipalities)	{Urban, Peri-urban, Rural & Big, Medium, Small municipalities}
Typology of the municipality (2 FSO categories)	Typology of the municipality, based on 2 FSO categories (Urban – Rural)	{Urban – Rural}
Cultural heritage protected (Yes – No)	Whether the settlement or part of it is protected for its cultural heritage value	{Yes – No}
Land surface (m^2)	The surface of the land the settlement is built on (SIA: Grundstücksfläche (GF) in German, Surface de terrain (ST) in French)	(Square meters) m^2
Main surface area of the settlement (m^2)	The main surface of all the floors of all the buildings of the settlement (SIA: Hauptnutzfläche (HNF) in German, Surface Utile Principale (SUP) in French)	(Square meters) m^2
Footprint surface of the settlement (m^2)	The surface all the buildings occupy on the land	(Square meters) m^2
Volume of the settlement (m^3)	The sum of the volume of all buildings of a settlement	(Cubic meters) m^3
Energy performance labels (Yes – No)	Whether the settlement has an energy performance label (Minergie, Minergie-P)	{Yes – No}
Land Price (CHF)	The price at which the land was bought at the moment of the land purchase	CHF
Investment Value		CHF
Insurance Value		CHF
Rental income yearly	Yearly income from renting the dwellings taking into consideration the vacancies	CHF
Land property	The land is acquired by leasing or not	{Own, Leasing}
Market type	Is the settlement subsidized or not	{Free, Subsidized, Mixed}
Geo-coordinates		

Building (additional to the settlement characteristics)		
EGID building number	The unique number to identify all buildings in Switzerland	
Number of dwellings	The number of dwellings per building	
Number of floors	The number of floors in each building	
Height	The height of the building	Meters (m)
Heating source	The type of heating source	{District heating, Gas, Oil, Heat pumps}
Dwellings		
EWID numbers of the dwelling	The unique number to identify all dwellings in Switzerland	
Size: Living surface of the dwelling (m^2)	The surface of each dwelling	(Square meters) m^2
Volume of the dwelling (m^3)	The volume of each dwelling	(Cubic meters) m^3
Size: Number of rooms of the dwelling	The number of rooms of each dwelling (1-1.5,2-2.5,3-3.5,4-4.5,5plus room dwellings)	{1-1.5room,2-2.5 room,3-3.5 room,4-4.5 room,5+ room}
Floor of the dwelling	The floor where the dwelling is situated	
Type of dwelling (Single-family, Multi-family house)	Whether the dwelling is single- or in a multi-family building	
Dwelling in the free-market or subsidized	Whether the dwelling is a free-market (in the context of this study a free-market dwelling is available to a broad population) or subsidized (a subsidized dwelling is addressed only to households entitled to apply to a subsidized apartment that is decided upon control of the respective municipality)	
Net monthly rent of the dwelling (CHF)	The rent before any additional charge or subsidy	CHF
Additional monthly charges (Heating and water) (CHF)	Additional monthly charges for heating and hot water	CHF
Gross monthly rent of the dwelling (CHF)	The final monthly rent the tenant has to pay, after calculating additional charges	CHF
Vacancy	The dwelling is occupied or not at the time of the data collection	{Yes – No}
Source: Own work		

Table A.22 – Model design - Household model - Variables

HH_model variables		
Household	**Attribute**	**Value & metrics**
	Typology	{One-person household < 65 years old, One-person household >= 65 years old, Couples without children < 65 years old, Couples without children >= 65 years old, Single parents with at least one child, Couples with at least one child, Other multi-person households}
	Size	{1,2,3,4,5+}, number of occupants
	Income group	{<=60 000 CHF/year, 60 001 – 88 000 CHF/year, 88 001 – 120 000 CHF/year, 120 001 – 164 999 CHF/year, >= 165 000 CHF/year}
	Income	CHF
	Market	{Free, Sub}
	Dwelling owner	{ABZ, SCHL, Mobiliar}
	Seniority	days
	Environmental awareness level	{1: low, 2: medium, 3: high}
	Satisfaction level	{1: low, 2: medium, 3: high}
	Status (trigger class)	{on, off}
	Reason (trigger class)	{Demolition or Renovation, Stop of subsidy, Birth, Death, Divorce, Typology is couple with children or single parent with children, Cooperative member}
	Type of reason (trigger class)	{Opportunity change, Imperative change}
	Timer (trigger class)	Months waiting
Source: Own work		

A.5 Model Initialisation

Table A.23 – Model design - Initialisation - Descriptive statistics of the building stock and households at t=0

Initialization	
Number of households - Initialization	
Owner	**Number of households**
ABZ	4931 (4770 free-market, 161 subsidized)
SCHL	2122 (1792 free-market, 330 subsidized)
Mobiliar	3887
total	*10940*

Key figures - initialization					
Variable	ABZ Free-market	SCHL Free-market	Mobiliar	ABZ Subsidized	SCHL Subsidized
Number of dwellings	4770	1792	4059	161	330
Number of dwellings per settlement	160	100	55	128	61
Number of dwellings per building	12	43	16	13	38
Number of buildings per settlement	17	3	4	11	2
Number of rooms	3.5	3.1	3.6	4.2	3.1
Dwelling surface (m2)	78	75	88	98	76
Square meters per room (m2/room)	22.5	24.8	24.7	23.8	25.3
Net rent (CHF)	1006	1030	1556	1023	904
Net rent per square meter (CHF/m2)	12.9	13.4	18.3	10.7	11.8
Additional costs (CHF)	99	132	226	87	168
Additional costs per m2 (CHF/m2)	1.3	1.8	2.6	0.9	2.2
Gross rent (CHF)	1145	1157	1780	1104	1018
Gross rent per m2 (CHF/m2)	14.7	15.1	20.9	11.7	13.1
Reference year	1970	1976	2000	2007	1967
Persons/room	0.71	0.72	0.64	0.72	0.56
Floor area per capita (m^2/capita)	35.8	39.5	42.1	37.7	42.1
Monthly Income (CHF)	6424.2	7225.3	8607.2	4733.5	4583.3
Environmental awareness level	2.5	2.5	2.5	2.5	2.5
Satisfaction level	2.6	2.7	2.6	2.7	2.6

Typologies of households - Initialization						
Typology	Number of households	Percentage	Minimum	Maximum	Mean	Std. Dev.
Couple >=65 no children	543	5%	2	2	2	0
Couple <65 with children	1631	15%	2	2	2	0
Couple with children	3817	35%	3	5	3.71	0.683
One person >65	933	9%	1	1	1	0
One person <65	2181	20%	1	1	1	0
Other multi-person	579	5%	2	5	3.5	1.118
Single parent	1256	11%	2	5	2.76	0.811
total	*10940*	100%				

Typologies of households – per owner - Initialization										
Typologies	ABZ		SCHL		Mobiliar		ABZ sub		SCHL sub	
	N	%	N	%	N	%	N	%	N	%
Couple >=65 no children	152	3%	295	8%	86	5%	6	4%	4	1%
Couple <65 with children	472	10%	886	23%	267	15%	1	1%	5	2%
Couple with children	1961	41%	1135	29%	587	33%	72	45%	62	19%
One person >65	395	8%	307	8%	147	8%	7	4%	77	23%
One person <65	903	19%	723	19%	388	22%	34	21%	133	40%
Other multi-person	232	5%	253	7%	49	3%	18	11%	27	8%
Single parent	655	14%	288	7%	268	15%	23	14%	22	7%
total	4770	100%	3887	100%	1792	100%	161	100%	330	100%

Income groups per owner – Initialization											
Owner	Income group										
	1		2		3		4		5		Total
	N	%	N	%	N	%	N	%	N	%	N
Free-market											
ABZ	1840	39%	1474	31%	930	19%	314	7%	212	4%	4770
SCHL	565	32%	510	28%	381	21%	199	11%	137	8%	1792
Mobiliar	629	16%	890	23%	1248	32%	666	17%	454	12%	3887
Total	*3034*	*29%*	*2874*	*28%*	*2559*	*24%*	*1179*	*11%*	*803*	*8%*	*10449*
Subsidized											
ABZ	291	59%	200	41%							
SCHL	90	56%	71	44%							
Total	201	61%	129	39%							

Key figures – per owner - Initialization					
Owner	**Key figures**	**Minimum**	**Maximum**	**Mean**	**Std. Dev.**
ABZ free-market	Number of households = 4931				
	Size	1.0	5.0	2.6	1.3
	Income (CHF)	2000	20895	6424	3286
	Environmental awareness level	1.0	3.0	2.5	0.5
	Satisfaction level	1.0	3.0	2.7	0.7
	Surface per person (m2/person)	12.7	94.6	35.8	14.8
	Number of rooms	1.0	6.5	3.6	1.0
	Rooms per person	0.5	3.5	1.6	0.6
SCHL free-market	Number of households = 2122				
	Size	1.0	5.0	2.4	1.2
	Income (CHF)	2001	20895	7225	3720
	Environmental awareness level	1.0	3.0	2.5	0.5
	Satisfaction level	1.0	3.0	2.7	0.7
	Surface per person (m2/person)	15.7	127.9	39.5	16.9
	Number of rooms	1.0	5.0	3.1	0.9
	Rooms per person	0.7	3.5	1.6	0.6
Mobiliar	Number of households = 3887				
	Size	1.0	5.0	2.4	1.2
	Income (CHF)	2000	20835	8607	3832
	Environmental awareness level	1.0	3.0	2.5	0.5
	Satisfaction level	1.0	3.0	2.7	0.7
	Surface per person (m2/person)	8.0	192.0	42.3	15.4
	Number of rooms	1.0	8.0	3.6	1.0
	Rooms per person	0.5	3.5	1.7	0.5
ABZ sub	Number of households = 161				
	Size	1.0	5.0	3.2	1.5
	Income (CHF)	2104	7233	4733	1477
	Environmental awareness level	1.0	3.0	2.5	0.5
	Satisfaction level	1.0	3.0	2.7	0.6
	Surface per person (m2/person)	23.6	87.5	37.6	16.4
	Number of rooms	1.5	6.5	4.2	1.3
	Rooms per person	0.5	3.5	1.6	0.6
SCHL sub	Number of households = 330				
	Size	1.0	5.0	1.8	1.1
	Income (CHF)	2000	7253	4583	1487
	Environmental awareness level	1.0	3.0	2.5	0.5
	Satisfaction level	1.0	3.0	2.6	0.7
	Surface per person (m2/person)	17.4	90.5	24.7	13.3
	Number of rooms	2.0	5.0	3.0	0.8
	Rooms per person	0.7	3.5	1.6	0.6
Source: Own analysis based FSO and SHEF survey					

A.6 Simulations

Table A.24 – Simulation results - Scenario comparison - Net rent

Simulation results – comparative table									
Scenario	**Year**	**Net rent (CHF)**				**Net rent per living surface (CHF/m²)**			
		ABZ	SCHL	Mobiliar	All owners	ABZ	SCHL	Mobiliar	All owners
Initial	2020	1,006	1,011	1,556	1,208	12.9	13.2	18.3	14.9
Baseline	2050	1,249	1,243	1,874	1,487	15.3	16.0	20.7	17.8
Scenario 1 “Ideal occupancy”	2050	1,272	1,255	1,841	1,482	15.7	16.1	20.5	17.8
	% change to baseline	*+1.8%*	*+1.0%*	*-1.8%*	*-0.3%*	*+2.6%*	*+0.6%*	*-1.0%*	*0.0%*
Scenario 2 “Densification”	2050	1,234	1,262	1,734	1,418	15.0	15.4	20.5	17.0
	% change to baseline	*-1.2%*	*+1.5%*	*-7.5%*	*-4.6%*	*-2.0%*	*-3.8%*	*-1.0%*	*-4.5%*
Scenario 3 “Combi”	2050	1,236	1,261	1,733	1,416	15.1	15.5	20.5	17.2
	% change to baseline	*-1.0%*	*+1.4%*	*-7.5%*	*-4.8%*	*-1.3%*	*-3.1%*	*-1.0%*	*-3.4%*
Scenario 4 “Green household”	2050	1,258	1,249	1,872	1,495	15.6	16.2	20.6	17.9
	% change to baseline	*+0.7%*	*+0.5%*	*-0.1%*	*+0.5%*	*+2.0%*	*+1.3%*	*-0.5%*	*+0.6%*

B Additional figures

B.1 Case Study

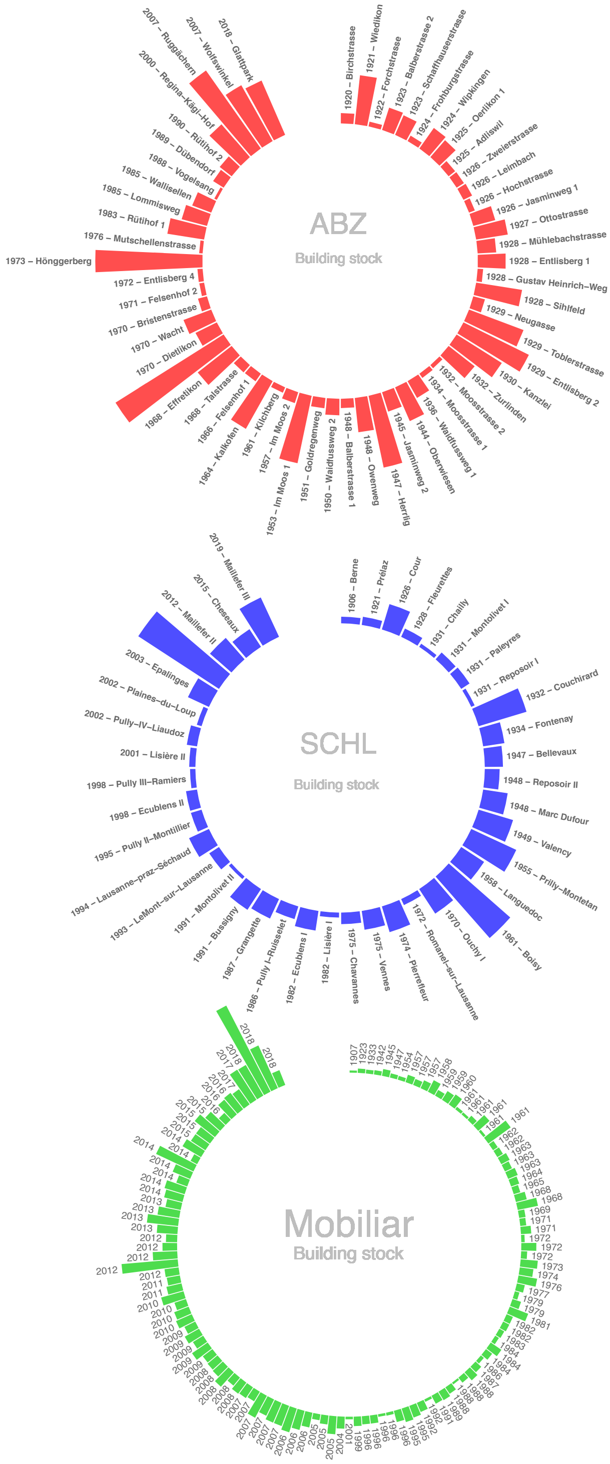


Figure B.1 – Case study - Building stock -Settlements by owner

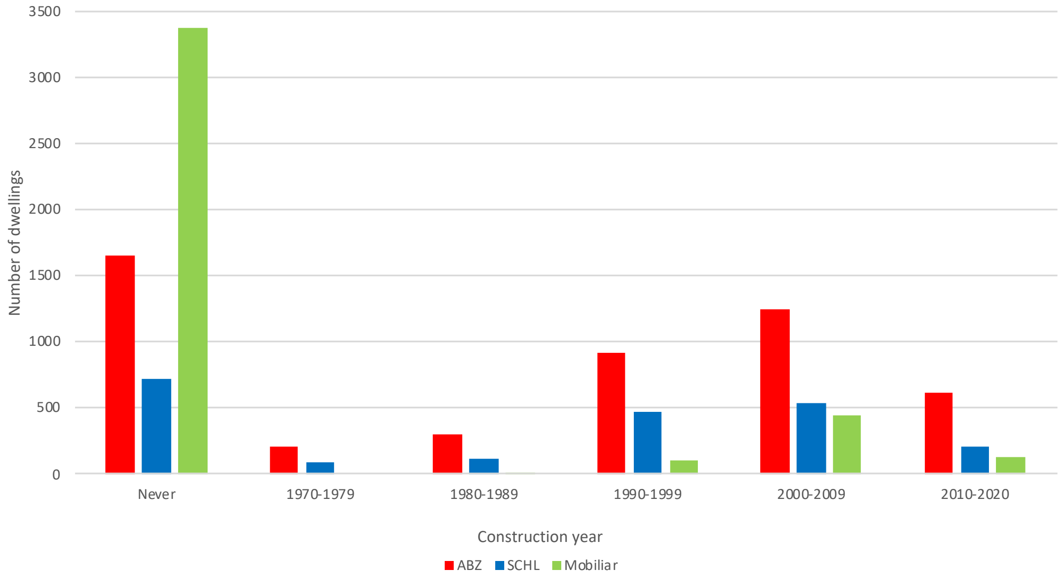


Figure B.2 – Case study - Renovation history by owner and construction period

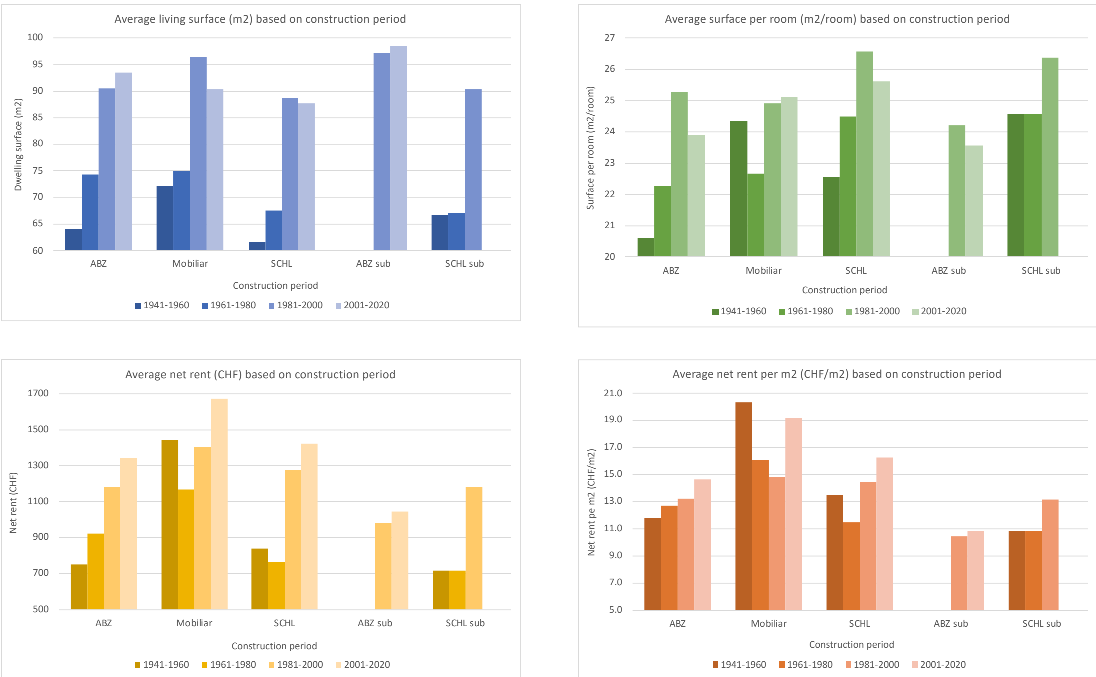


Figure B.3 – Case study - Average size and average net rent

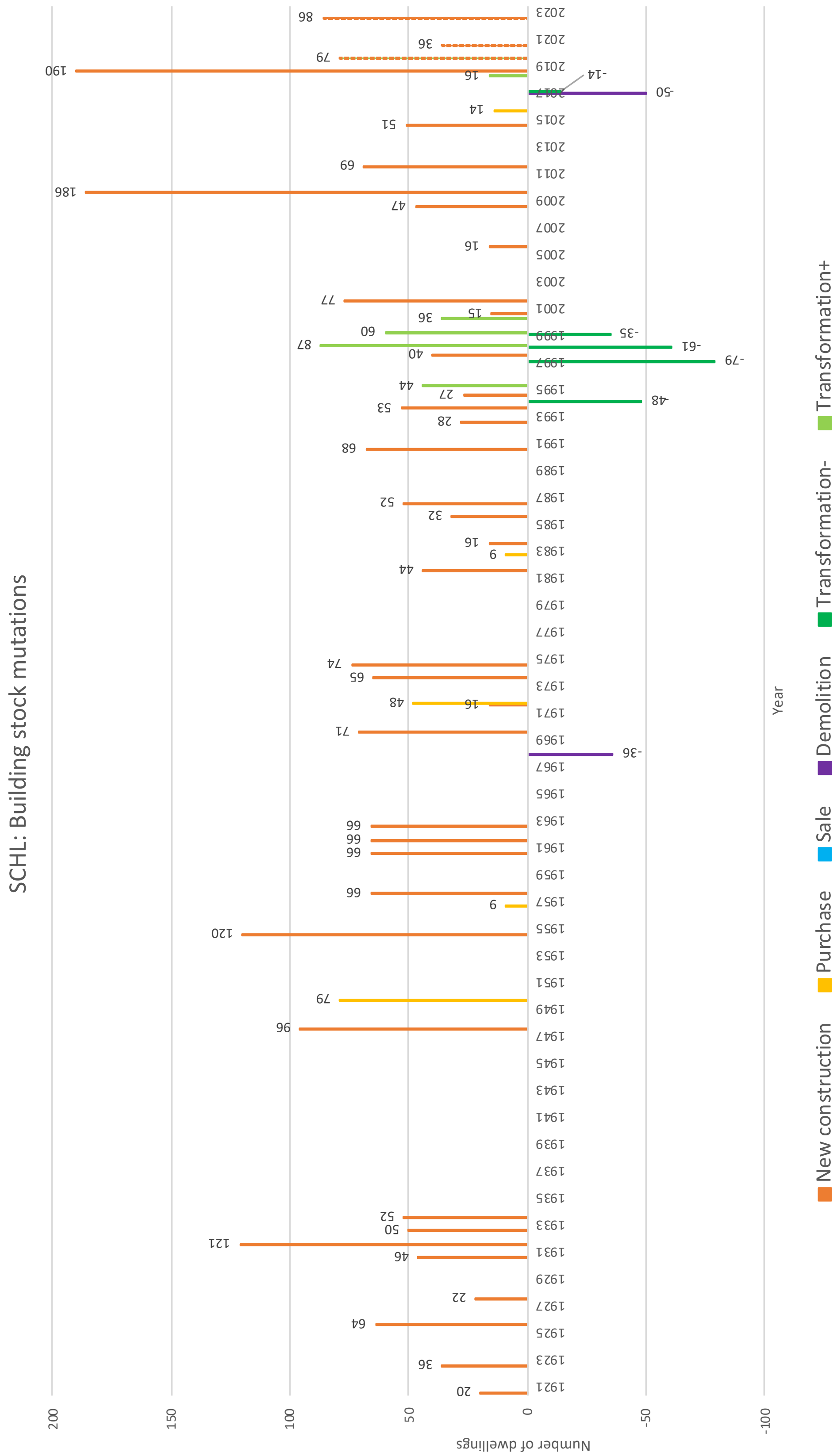


Figure B.4 – Case study - Building stock mutations - SCHL

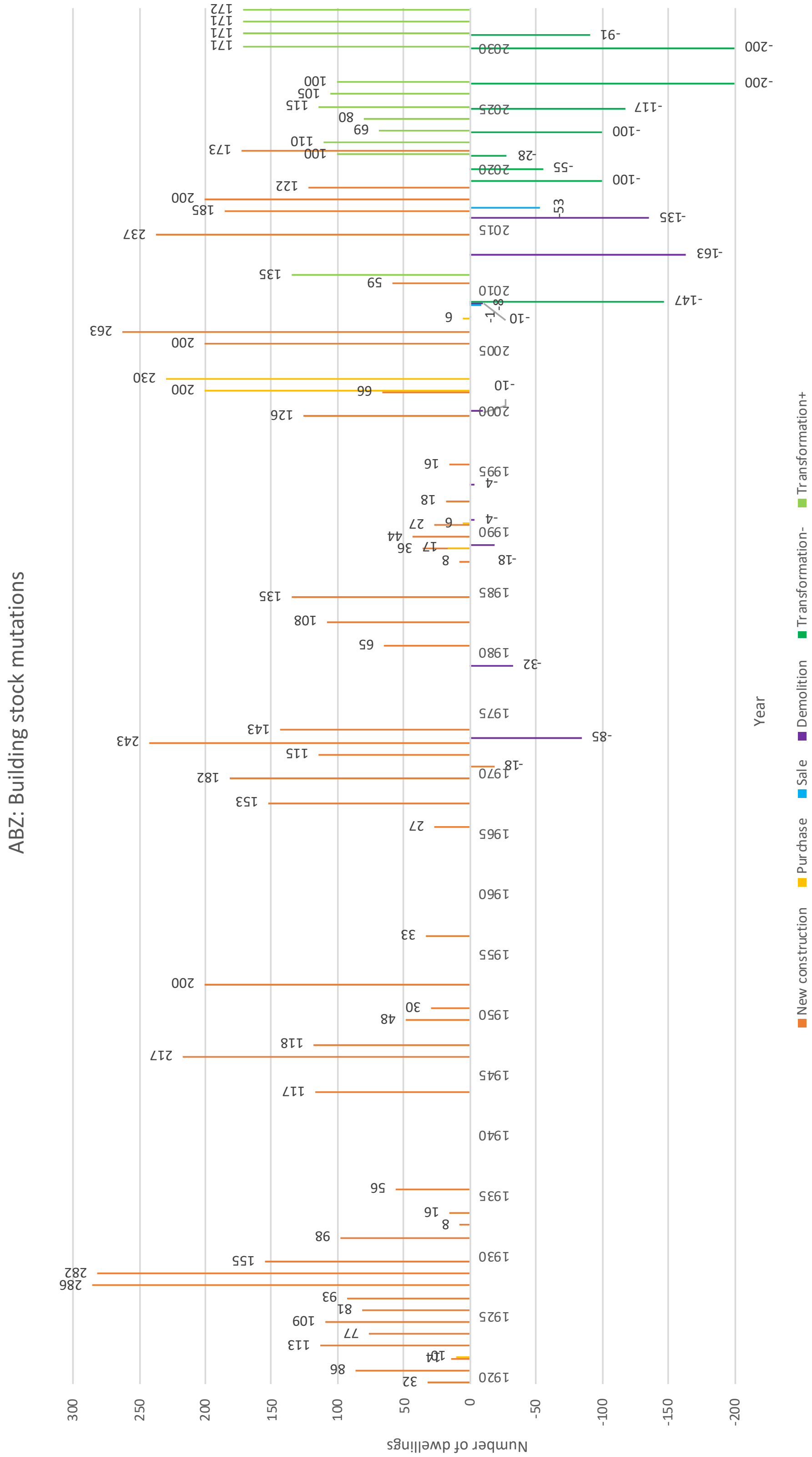
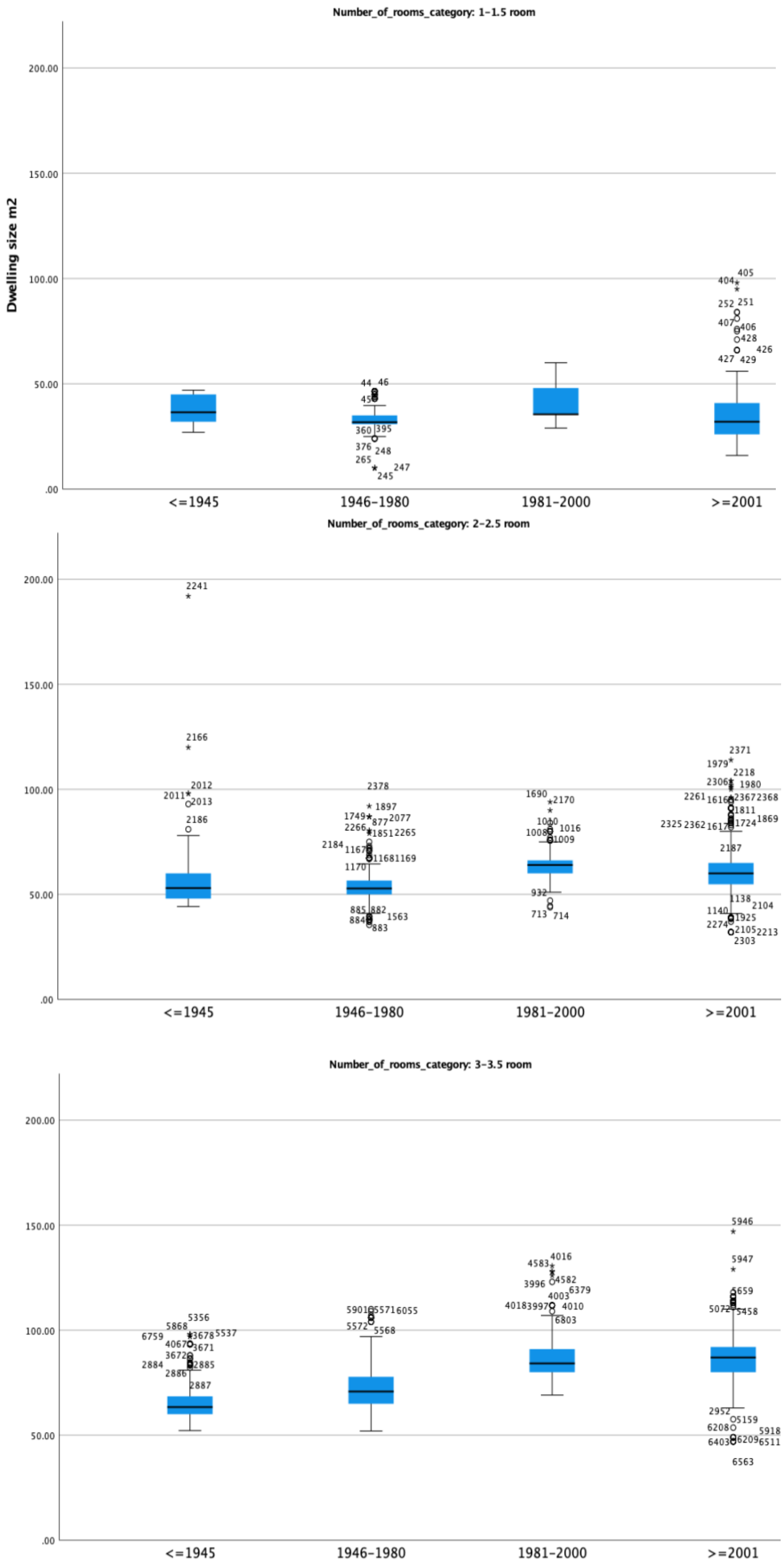
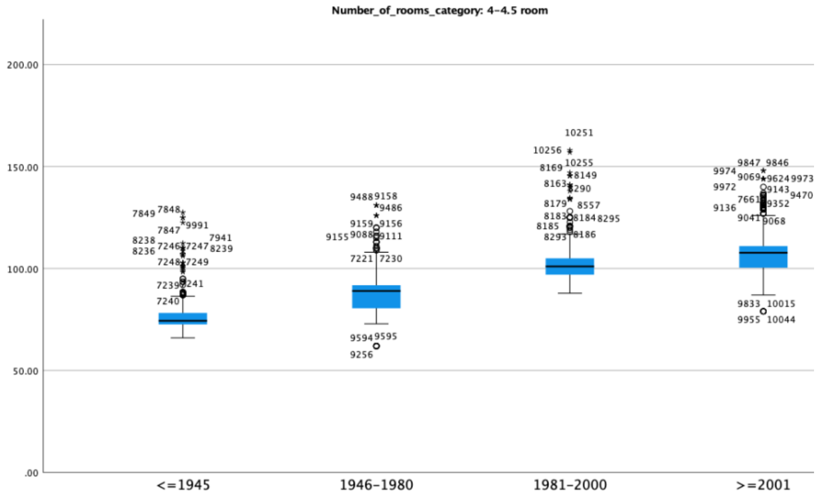


Figure B.5 – Case study - Building stock mutations - ABZ


Number_of_rooms_category: 1-1.5 room
Dwelling size m2
200.00
150.00
100.00
50.00
.00
<=1945
1946-1980
1981-2000
>=2001
Number_of_rooms_category: 2-2.5 room
200.00
150.00
100.00
50.00
.00
<=1945
1946-1980
1981-2000
>=2001
Number_of_rooms_category: 3-3.5 room
200.00
150.00
100.00
50.00
.00
<=1945
1946-1980
1981-2000
>=2001



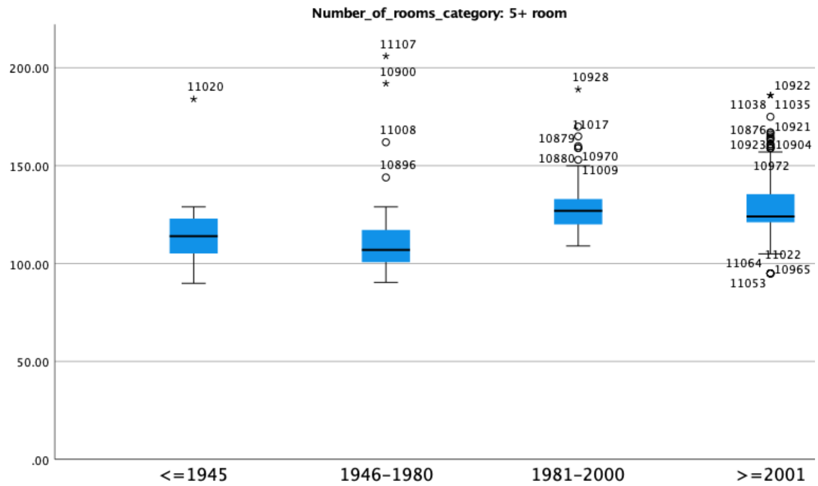
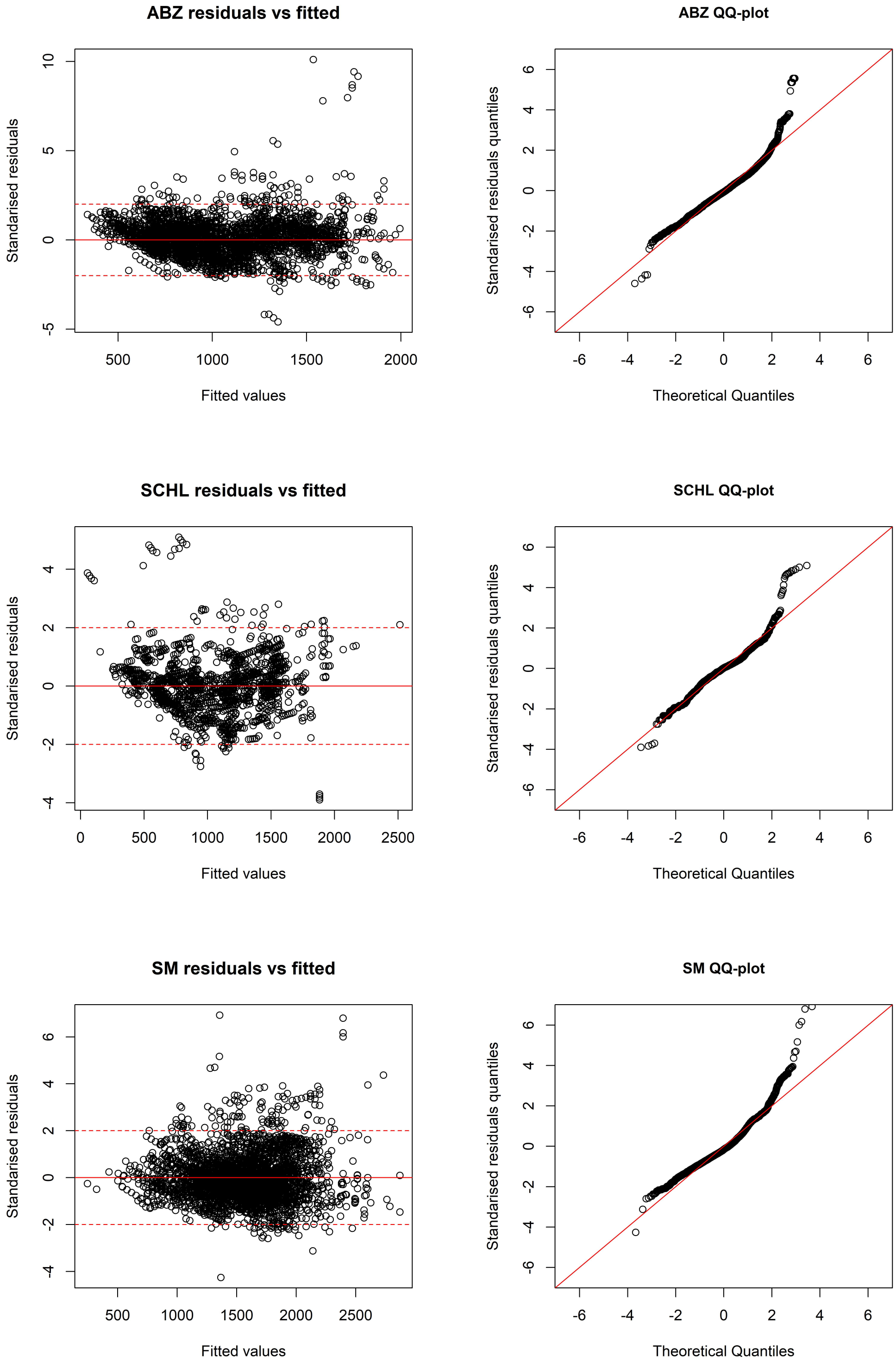


Figure B.6 – Case study - Dwelling surface by construction period

Figure B.7 – Case study - Regression model for net rent (Standardised residuals vs fitted values and standardised residuals quantiles vs standard normal quantiles)



B.2 Model design

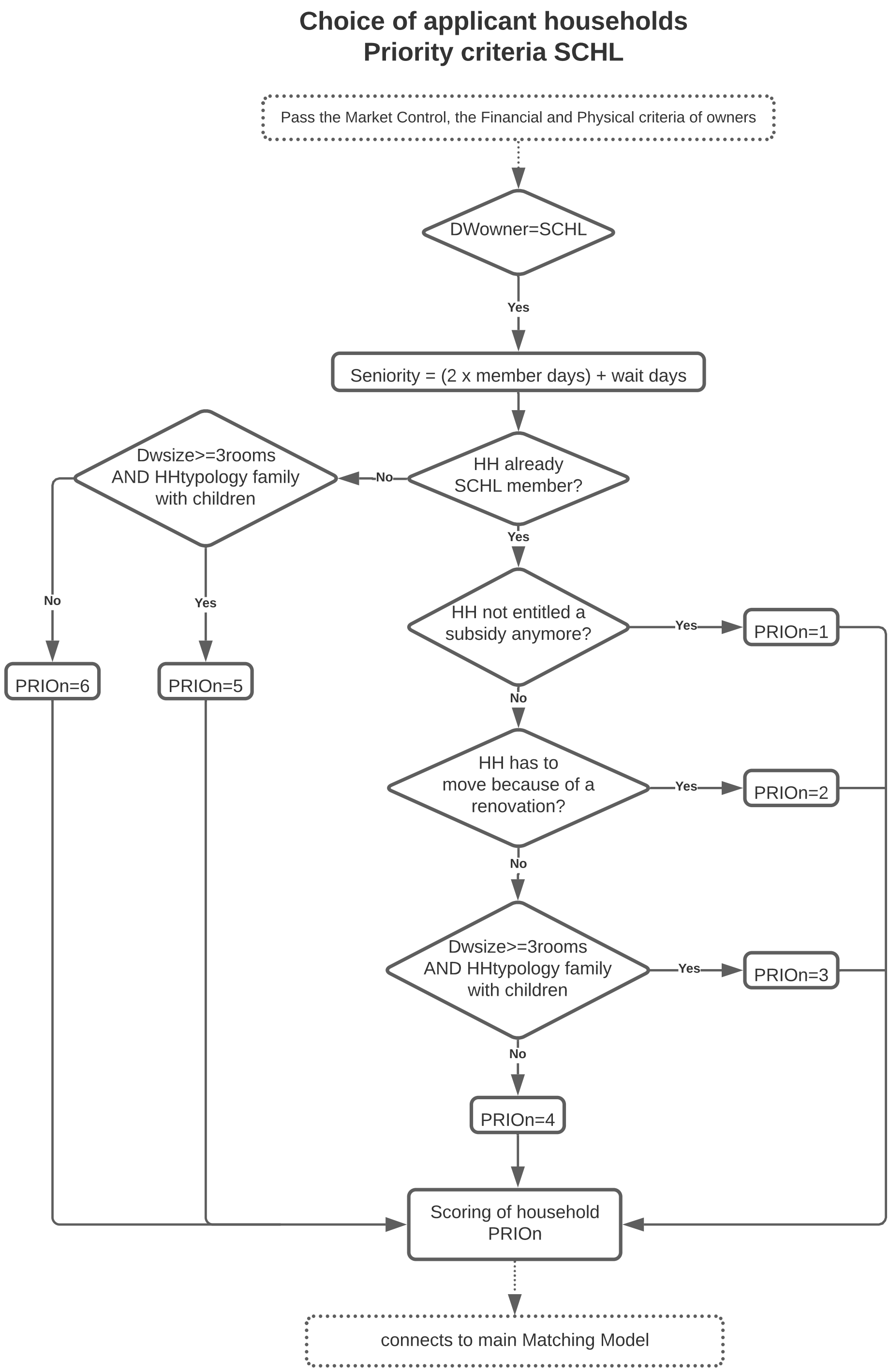


Figure B.8 – Model design - Matching model - SCHL priority criteria

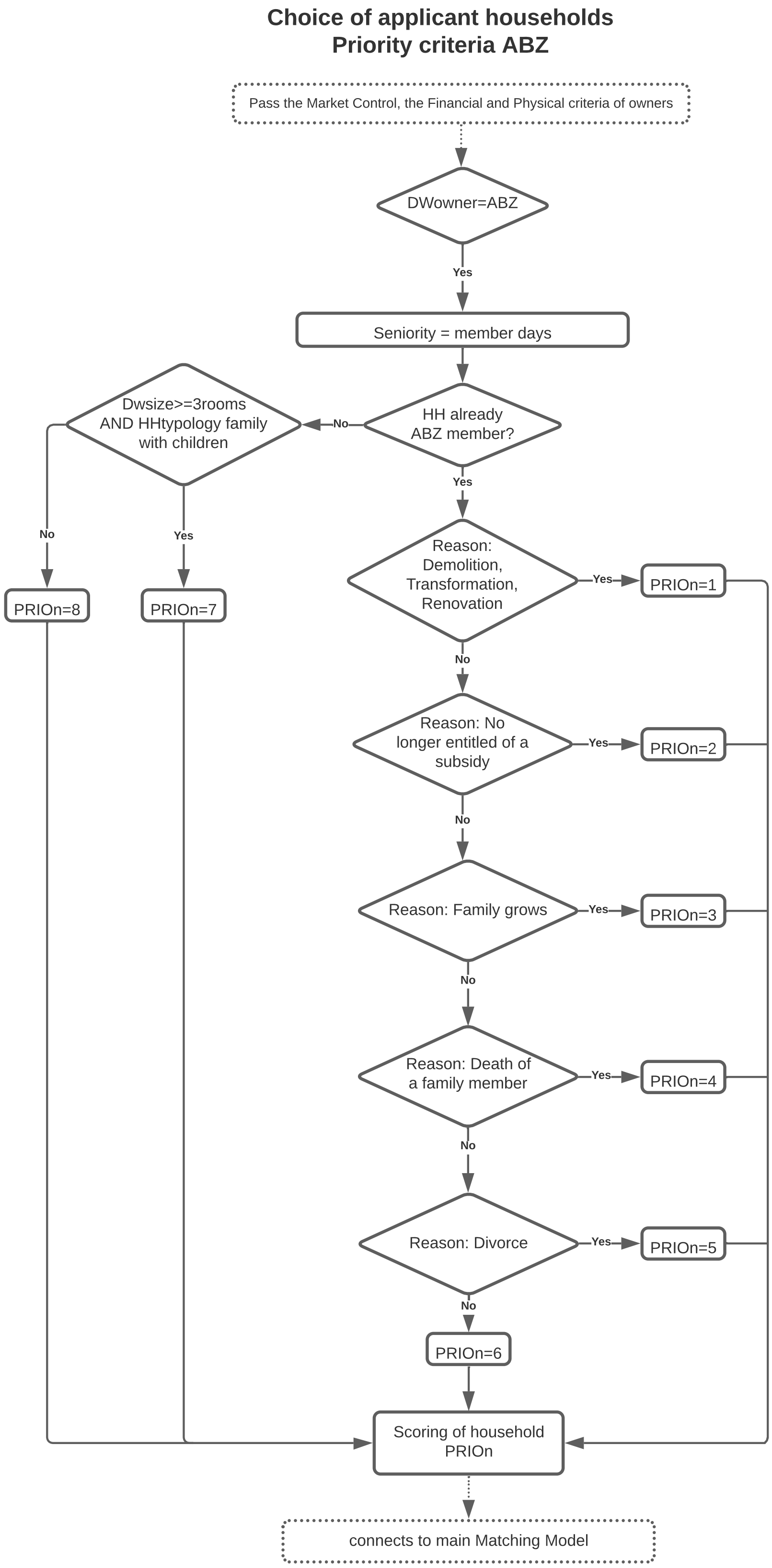


Figure B.9 – Model design - Matching model - ABZ priority criteria

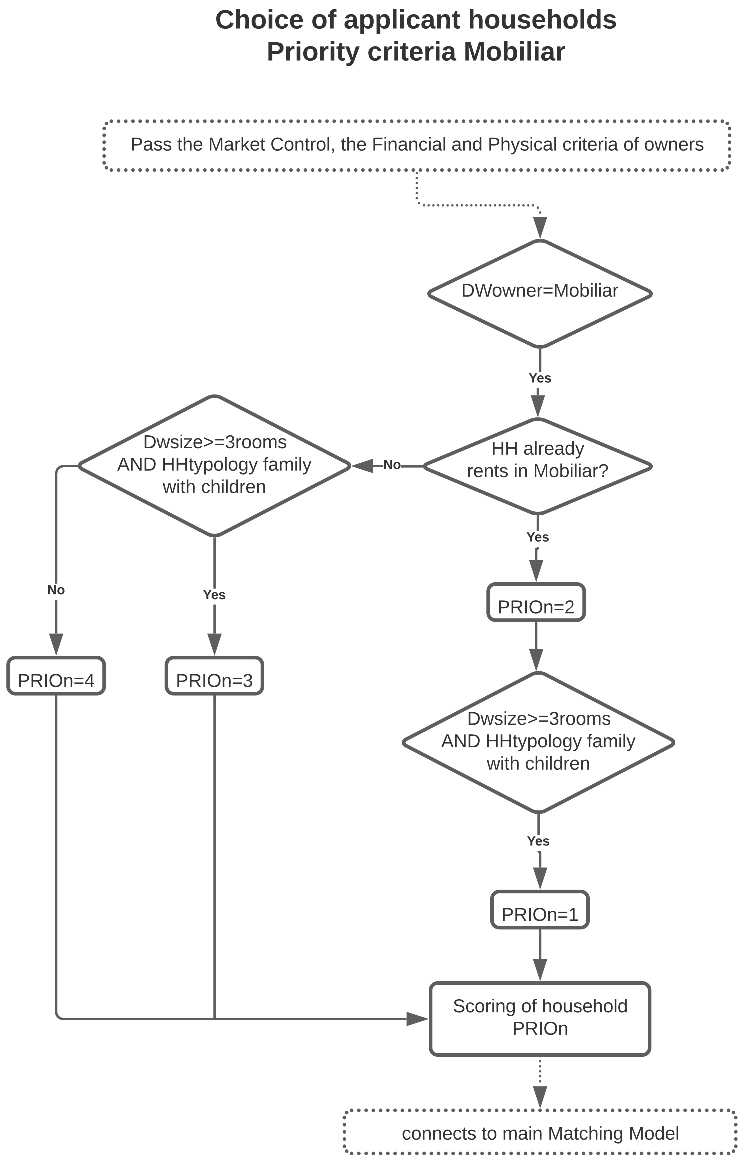


Figure B.10 – Model design - Matching model - Mobiliar priority criteria

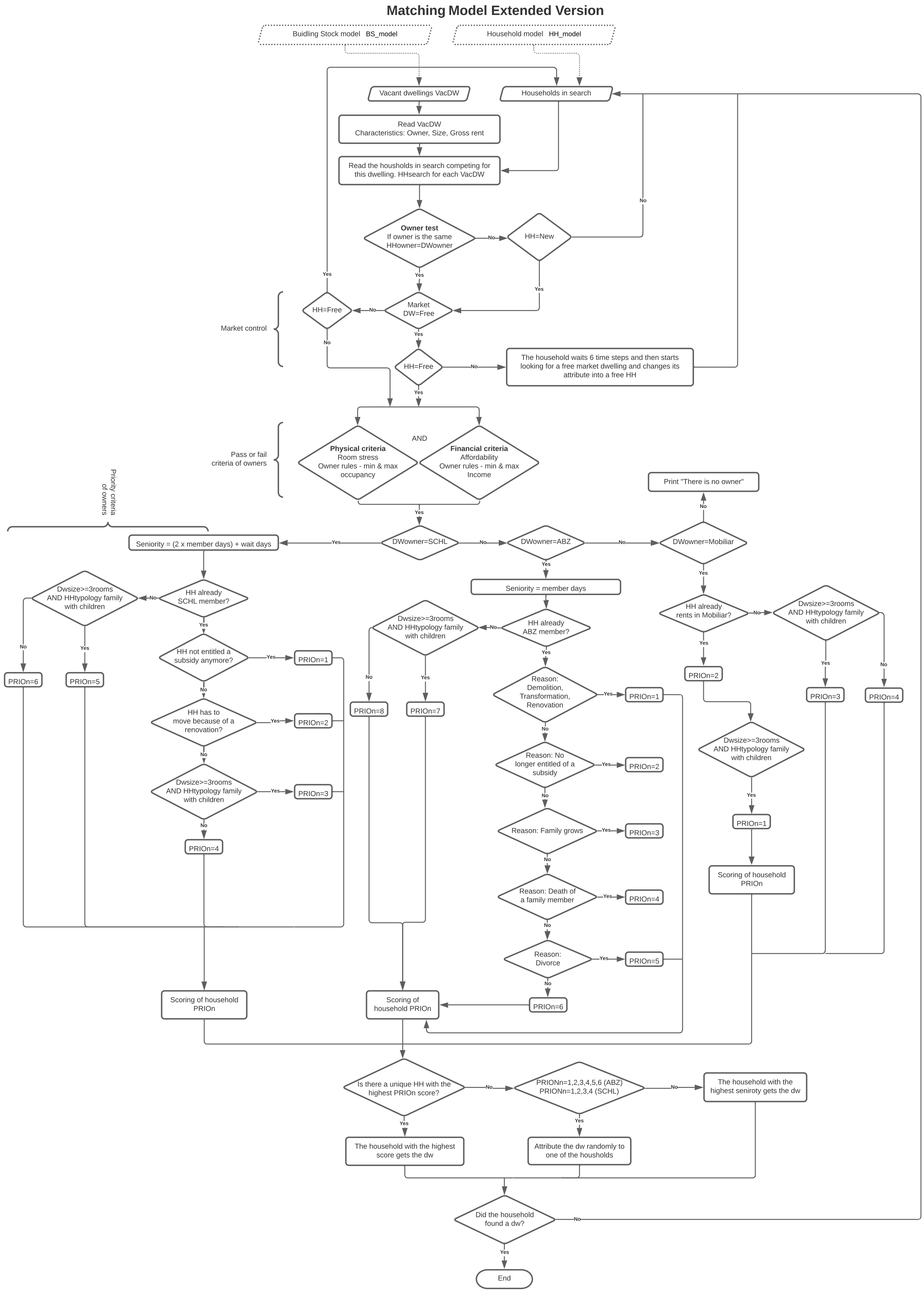


Figure B.11 – Model design - Matching model flowchart - extended version

C Owner Workshops

C.1 Owner Workshops: Questions

Overview of Workshop Questions

What are the decision-making processes regarding:

(A) The building stock

- Q1: What are the triggers and constraints for starting one of the following actions: renovation (heavy, light), transformation, demolition and reconstruction, new construction, purchasing or selling a building?
- Q2: What do you build, demolish, reconstruct (building, dwelling characteristics)?
- Q3: When do you start one of the above-mentioned actions?

(B) Funding, costs and rental income

- Q1: How do you fund the above?
- Q2: How do you calculate the rental income?

(C) Tenancy and allocation of dwellings to households

- Q1: How do you allocate / propose your dwellings to the households (criteria, priority)?
- Q2: How do you choose the tenant?

(D) Sustainability

- Q1: Measures to enhance the building energy performance?
- Q2: Measures to promote the sustainable behavior of the tenants?

Workshop Questions in Detail

(A) The building stock

Key points

- Strategy
- Triggers to build, to renovate, to transform, to demolish, to sell
- Factors that inhibit building, renovating, transforming, demolishing, selling

- Existing regulation for developing free market and subsidized buildings
- Estimation of the demand
- Design of the buildings (type of apartments, square meters, type of heating system, materials)
- Costs of construction and renovation

Questions
New construction and Purchase

- What is your strategy?
- When do you decide to grow your building stock? (Always grow or study the demand)
- How do you estimate the demand? (Number of households and what type of households)
- How would you describe the current demand?
- Does current demand guide your future construction? (Dwelling size, rent, equipment, location)
- From your point of view, what are the main trends in construction nowadays? (Bigger dwellings, single-person dwellings)
- What are the biggest challenges and constraints, assuming you have the intention to add new dwellings to your building stock? (Scarcity of building land, bureaucracy, land cost, construction cost, access to funding, financial risk in case the dwelling remains empty)
- Do you prefer to build a new building (buying land and constructing) or to buy an existing one?
- How do you define the characteristics of a new building? (Rooms per apartment, number of 2-room, 3-room, 4-room apartments, square meters per apartment or per occupant)
- When building, do you have a typology or building norms regarding the square meters per room or per apartment?
- What is the percentage of subsidized dwellings you have? Do you have a target percentage of subsidized dwellings?
- When do you decide to construct a subsidized building?
- What are the challenges and constraints of adding a subsidized building to your building stock?

- Are there directives and constraints when building a subsidized apartment (in the design, typology of apartments, rooms per apartment, square meters, energy efficiency, cost)
- How do you calculate the future rent?

Sale and demolition

- When do you decide to sell a building?
- Why would you demolish? (In order to densify, to enhance living conditions, to increase rental income)
- Are there any criteria for demolishing a specific settlement?

Maintenance, Renovation and Refurbishment

- How do you keep an overview of your building stock? (Inventory, control, yearly report of state)
- Why do you renovate? (In order to maintain the quality of the existing building, to raise the rent, to enhance the energy performance of the building, to attract new tenants)
- How do you decide when to renovate or refurbish? (Is there a fixed frequency for renovations or refurbishments, according to a report of state, evaluation system e.g. STRATUS, direct request from the occupant's side)
- What kind of renovations do you do? (Full, building envelope, kitchen and bathroom, pipes, combination of the above)
- What types of renovations are most common e.g. painting, equipment, bathroom, kitchen etc.?
- Is there a standard duration for a heavy renovation? And for a light renovation?
- Is there an institutional framework or regulation guiding the construction and renovation phase?

(B) Funding, costs and rental income

Key points

- Funding
- Construction, maintenance and operation costs
- Rental income
- Renovations and future rent

Questions

- How do you fund a project? (Own capital, mortgage 1st, 2nd rank)
- How do you calculate the rental income for a new construction?
- How do you calculate rental income after a renovation?
- How do you calculate construction, renovation, demolition, maintenance and operation costs?
- Is there an upper limit of cost when starting a new construction (buying land and constructing)?
- Do you adapt rents to yearly changes? (Reference rate)
- In case of demolition, is the demolition cost taken into consideration for the future rent?

(C) Tenancy and allocation of dwellings to households

Key points

- Contract duration
- Occupancy rules
- Priority criteria
- Over or under-population penalties (contract termination or rent surplus)
- Minimum and maximum income
- Nationality, residence permit
- Rules for promoting housing and social mix
- Household with the highest demand
- Renovation and temporary housing for the tenants (cooperatives)

Questions

- What is the duration of a contract? (One year? Is it renewed automatically?)
- Do you have specific occupancy rules? (Room stress, size of dwelling, household size)
- Is there a rule for maximum or minimum occupancy, number of tenants per room? (E.g. number of rooms per dwelling = number of occupants + 1 etc.)
- Do you have priority rules to allocate the dwellings to specific types of households?

- According to what criteria do you choose your tenants or households? (Income of the tenant, income of all active members of the household taken into consideration, number of occupants, waiting lists, nationality, residence permit)
- Is there an occupancy condition related to the square meters per person?
- Is there a regulation promoting housing and social mix? If not, do you have a rule of your own? If yes, what is this rule?
- Do you perform any control later to check the actual number of the tenants in each apartment? (If occupancy conditions are met, over- or under-populated apartments)
- What type of household exhibits the highest demand in the waiting lists? (E.g. single person household, family with children, elderly)
- Do you prefer or promote a specific category of household?
- In case of a renovation, what do tenants do during the renovation? (Do you propose another transitional dwelling from your stock to them? Do they pay the same rent in the transitional apartment during the renovation?)
- How do tenants react to a renovation and the rent increase that follows? If they cannot afford the new rent, do you offer alternatives to them?

(D) Sustainability

Key points

- Design and sustainability
- Material choice
- Heating system choice
- Equipment choice
- Energy performance standards / labels
- Regulation related to environmental performance of building
- Waste management
- Measures to promote tenant's sustainable behavior

Questions

- Do you have specific guidelines for sustainable construction? (Design level)
- How important is energy efficiency of a building to you? And why?

- Do you require that architects design the buildings more sustainable? (Insulation materials, thickness of walls, orientation of the building, inclination and materials of the roof, heating system, construction materials, floor)
- How are the different material choices done while building? How is sustainability taken into consideration?
- Do you have specific standards for the window paneling (Double glazed, etc.)
- How are decisions made for lighting and heating inside the building in terms of the location and orientation of the building, i.e. are the natural solutions taken into consideration? Or is it usually based on the location of land only?
- Are there any measures to minimize the equipment energy usage? (E.g. selection of appliances with A or B energy standards)
- How do you choose a heating source? (Fuel oil, gas, district heating, pellets) Is the decision made according to the region and the existing network or according to current market prices?
- Do you have criteria for including renewable sources of heating? (E.g. subsidies)
- Do you follow standards related to the energy performance of buildings for constructing new buildings or renovating? (Minergie, Passive house, CEN standards EPBD, ISO standards)
- If yes, which building standard have you chosen and why? (Affordable or easy to implement)
- What are the current certifications of your buildings? Any plans to improve or to change them?
- If no, what are the reasons not to apply for a certificate?
- What is the rate of change in switching to different standards, if any? (E.g. if there is a new policy, would you change the energy standard? If yes, how much time does it take?)
- Is there an institutional framework towards sustainability guiding the construction or renovation phase? (E.g. national, local policies)
- Have you ever renovated in order to change the number (transformation) of the apartments of an existing building?
- During the construction, how do you manage the waste? (Recycling and disposal)
- When renovating or demolishing, do you follow a procedure for the waste management?
- How do you promote the sustainable behavior of the occupants? E.g. is there any information campaign or control in the energy or water consumption from your part?

- Are there any measures you take so that the occupants reduce their:
  - Space usage
  - Heating usage
  - Electricity usage
  - Water usage
  - Waste generation

C.2 Owner Workshops: Summary

Discussion about owner determinants with the collaboration partners - Determinants for the quantitative decision-making model of property owners

Property owners, and in the case of this project the three collaboration partners (ABZ, SCHL, Mobiliar), make decisions about how to manage their building stock. These decisions include decisions about three main domains: (1) management and maintenance of their existing dwellings, (2) growth of their building stock, (3) allocation of the dwellings to the households. All these decisions affect directly or indirectly the environmental impact of housing. In order to better understand the decision-making processes and to study the determinants of their decisions, we organized three workshops, one with each partner. The workshops took place in person between February and May 2019 at the head-house of the partners (in Lausanne for SCHL, in Zurich for ABZ, in Bern for Mobiliar).
The participants of the workshops were the main researchers (from the project's side) and representatives of the direction, construction, energy and tenant departments (from the partner's side). Each workshop had a duration of two hours, and it was organized in form of thematic questions around four main subjects: building stock, costs and rental pricing, energy and environment, tenants and tenancy. The detailed workshop questions can be found above (see Appendix C.1).
Analyzing the qualitative and quantitative information given by the owners during the workshops allowed to better understand the decision-making processes of the owners, the similarities and differences in their approaches, which finally helped us building the decision-making model for each owner. Below can be found an overview of the workshops and the main determinants of the property owner's decisions. When we refer to the three project partners, we use the third-person plural, as we want to include the people that took decisions and keep deciding about the building stock and tenants.

ABZ

- ***Target***
  ABZ is a housing cooperative founded in 1916. Today, more than one hundred years after its foundation, it offers approximately 5,000 dwellings in the rental real estate market of Zurich (Zurich city and agglomeration). ABZ's main goal is to offer affordable and sustainable housing to people, to a broad diversity of households coming from various countries, belonging to different income and age groups.

- ***Construction activity (New construction, Renovation, Demolition, Transformation)***
  ABZ has the strategy to grow their building stock, densify and prolong the life of their buildings as much as possible, while maintaining the quality of their dwellings. Every year they do an evaluation of the state of their buildings in order to have a detailed case by case overview of the condition of their building stock. In parallel, they use Stratus, a software for valuation, investment, financial planning and estimation of the ideal time for repairs. The results of Stratus regarding the future interventions are mainly used as a comparative base and they consult it when they decide about renovations. There is a renovation budget, but the final amount dedicated to renovations is decided based on the evaluation of the stock and the specific needs of the stock. In addition, part of ABZ's strategy is a strategy called "Hold and maintain"; the goal is to maintain the building in a good condition, doing the necessary renovations and prolong the life of a building.
  ABZ has already planned the construction activity (new construction, demolition, renovation) for the next five (in detail) to ten years (in less detail). The main challenges for ABZ are to find buildable land at a price that allows them to construct affordable dwellings and to densify their existing building stock. Regarding the second point, they have been working intensively on that over the past years and there is not a lot of room for densification left, unless the city changes the terms for land use and allows them to construct more square meters. In that case there are some older buildings that could be densified. ABZ is convinced that the demand is high and that the market could absorb more dwellings. They do not worry having any vacancies. However, ABZ is small in size and cannot grow faster than 50 dwellings per year. Funding has proved not to be a problem; however, land scarcity is their biggest constraint and in order to solve this problem they try to find land by land leasing.
  As far as the size of their dwellings is concerned, the average living surface is 79 m^2 per dwelling and the average surface per room is 24 m^2. The majority of the dwellings are 3-room and 4-room apartments. Traditionally, family households were promoted and prioritized; construction followed this priority as well by building even more medium and large sized dwellings. However, ABZ has updated their strategy and they focus on accommodating tenants following the life-phases of the households. As a result, they

plan to build more smaller dwellings (1-room dwellings) and offer a higher dwelling size diversity. The system to construct subsidized dwellings is very complicated and that prevents them from further investing in the subsidized market. However, they do have a small number of subsidized dwellings from the past, in mixed settlements (i.e. settlements that have free-market and subsidized dwellings).
ABZ follows the "10, 20, 40, 80" rule for the life phases and interventions on a building; 10 years after its construction they do small scale maintenance works; at 20 years they do a light renovation, at 40 years they do a heavy, large-scale renovation and at 80 years they estimate the end of its life. However, practice shows that apart from this rule, the most important thing is the state of a building that defines the needed interventions. Based on their “Hold and maintain" strategy they try to prolong the building’s life, which also contributes in keeping the rents low. Before a proposed renovation, the current tenants vote in order to decide whether they accept the proposed renovation and the future augmentation in rents. After a heavy renovation, there is a rent augmentation of approximately 30-40%. During a heavy renovation, tenants have to leave their dwelling. ABZ proposes substitute dwellings, where the tenants can stay during the renovation and decide whether to move back to their old renovated apartment after the completion of works. On average, 50-60% of the tenants go back to their old but now renovated dwelling. The renovation, apart from enhancing the state of the building, is an opportunity for ABZ to densify because of the internal movement of tenants. ABZ doesn’t want to sell buildings. In the past, there were some cases of purchase when they sold some single-family houses. They decide to demolish when they cannot densify the existing settlement more or the state of the buildings is very poor.

- ***Funding and rental income***
  ABZ is funding their activities with own capital and the rental income is calculated in order to cover the costs (Kostenmiete, Mietzinsreglement); this calculation is not done for each settlement separately but for all the building stock by aggregating all the existing ABZ settlements. See formulas in respective chapters.

- ***Sustainability***
  ABZ aspires to reach net zero emissions by 2030. For that purpose, they replace the existing heating systems using oil by using more and more heat pumps and district heating. Their target is not to use any fossil fuel by 2025 and to augment the percentage of renewable energy sources. They also control on a yearly basis the energy and electricity consumption. They have a monitoring system to calculate the consumption; older buildings have counters per building while newer ones have counters per apartment. In addition, they try to allocate households to dwellings in order to avoid under-occupancy; for that reason, they have occupancy rules. However, it has been

proven to be challenging to monitor the number of occupants of their dwellings as time passes. For ABZ, constructing with energy labels is not a priority; they already have their own standards for construction, materials, grey energy, insulation, etc. Therefore, they do not prefer to use a building energy label, unless it is demanded by the state or city in the case of land leasing.

- ***Tenancy***
  The rent is calculated to cover the costs as explained above. The rent changes (increases or decreases) when the reference rate changes more than 0.5%. When a dwelling becomes vacant, there is a waiting list with members of the cooperative that are interested for the dwelling. There is an allocation system (point system) based on how old the member is, how long he or she has been waiting in the waiting list for an apartment, the number of household's occupants and the household's income. There are strict occupancy rules, check Table C.25. At the moment of a new tenancy agreement, the physical and financial occupancy rules are checked. Every five years, they ask their tenants to announce the number of occupants per household. However, they cannot be sure whether these numbers are correct or not. In the case of under-occupancy, ABZ proposes a new smaller dwelling, and the household is entitled to accept it or not.

- ***Main challenges***
  To summarize, the main challenges for ABZ are the scarcity of buildable land and the price of the land. Their main goal is to construct affordable housing and to densify their existing building stock as much as possible. If the settlement is under the state of heritage protection, it is very difficult to renovate and densify.

SCHL

- ***Target***
  SCHL is a housing cooperative founded in 1920; it is a non-profit investor whose main goal is to offer affordable housing to the rental market of Switzerland. They aim to grow their existing building stock, and the main constraint is to find land that is dedicated to housing construction at a price that allows to offer low rents. Vacancies are not an issue as their vacancy rate is almost zero.

- ***Construction activity (New construction, Renovation, Demolition, Transformation)***
  The strategy of SCHL is to grow their building stock, mainly by finding land and constructing new settlements. They are looking for opportunities of land either in the free market or by leasing it from the municipality. A settlement should have at least 25 dwellings. They avoid constructing small apartments because there is a high rotation rate; they aim to build more of larger dwellings (4-room plus dwellings). They

have specific detailed construction rules (square meters per room, square meters per dwelling size, height, materials, appliances, heating system) for new construction and renovations. They follow these standards for every constructed building, unless there are specific rules imposed by the municipality, for example in the case of a land lease. Given that SCHL's main goal is to offer affordable housing and that the construction cost is relatively fixed, land price is the biggest challenge. To construct affordable dwellings, the total cost per square meter should not exceed a specific amount (240 CHF/m^2).

Regarding the renovations and the necessary interventions, SCHL organizes a yearly diagnosis of its building stock to evaluate the state of the building. They have a limited renovation budget, and they do a five-year planning for renovations. The decisions are taken based on the needs and the state of the building. In the case of a new building, they realize the first light renovations between 20-25 years; between 40-50 years of age, they change the technical equipment and undertake heavy renovation.

SCHL has not yet demolished or transformed a lot of settlements. They are not particularly interested in selling their settlements; purchasing an existing building could be an option if the price allows to offer the dwellings for an affordable price in the rental market after renovation. However, competition is very hard, thus, purchase is very rare. Even if a building is expensive, they might buy it as long as it is profitable in long-term. They are owners of 330 subsidized dwellings, but they stopped constructing subsidized buildings. Pro Habitat Lausanne Foundation has taken over the construction of subsidized dwellings.

- ***Sustainability***

  Their main target is to replace the old fossil fuel heating systems with district heating. Building with energy labels is not a priority for SCHL, unless it is expected by the city (Minergie, or Minergie-P ECO). Allocation of households to dwellings is very important, and they have strict occupancy rules (see Table C.25). Based on the size of the dwelling an appropriate size of household is allocated. They are very interested in having an efficient use of living surface (m^2/person).

- ***Funding and rental income***

  SCHL has access to funding; the majority of the investment is covered by loans, 40% is covered by bank loans (first rank) at a low interest rate, another 40% is covered by CCL (second rank) and 20% is covered by own capital (Net Working Capital NWC). For further details, see the formulas in the respective chapters.

- ***Tenancy***

  The system is very similar to ABZ; there is a waiting list of households for all dwellings. At the moment when a dwelling becomes vacant, there is a prioritization system based on which the dwelling gets offered to the household that comes first. SCHL as well has limited control over the future occupancy of the dwellings.

- ***Main challenges***
  To summarize, the main challenge for SCHL is to find buildable land at a price that will allow them to construct affordable dwellings. Land scarcity and land price is the biggest constraint.

Mobiliar

- ***Target***
  Mobiliar is an insurance company, institutional profit-oriented investor that is interested in having a diversified portfolio. For that reason, Mobiliar has been investing and acquiring real estate assets; especially since 2000, real estate investments played an important role in the strategy of Mobiliar. According to the current strategy, Mobiliar will continue investing in real estate with the same interest.

- ***Construction activity (New construction, Renovation, Demolition, Transformation)***
  Although selling and buying existing buildings is of high interest to Mobiliar, their main focus is buying land and constructing new buildings. They conduct a very thorough analysis of the Swiss real estate market (with market data from external collaborators e.g. Wüest Partner), which allows them to estimate the potential rental income of a building. They use discounted cash-flow analysis (DCF) for the valuation of real estate assets. They are interested in acquiring profitable dwellings that guarantee high rental income and high rate of return. In order to maximize the rental income, the building should be in a place or in a state that allows high rents and guarantees that vacancies will be zero or limited. Mobiliar aims to maximize the rate of return of each settlement; they do an evaluation of their building stock based on financial returns and the potential to increase these returns. Based on that, they decide about whether to sell, renovate, demolish and reconstruct a settlement.
  In general, they prefer land and buildings situated in central locations, for example next to a train station or close to the lake of the city. However, it is very difficult to find land or buildings in such locations. Demand is higher for small and medium sized dwellings; 1-room dwellings are very easy to rent at a good rental price and 3-room and 4-room dwellings are the most financially performing. New construction is more profitable than purchasing an existing building. However, if they had the option to purchase or construct a settlement with the same (satisfying) return rate, they would prefer to purchase it.
  Regarding the renovations, they conduct a yearly control of the state of their buildings,

and they have reports about the state of the building and its potential. They have a three-year renovation bottom-up plan based on which they decide for renovations. The target is to reach the market rent. Whenever the rents are lower than the market rent and they see the potential, they invest in renovations in order to reach the market rent. Demolitions and reconstructions take place often, because there are opportunities for centrally located old buildings that need deep renovations and are sold for a relatively good price.

- ***Sustainability***
  Mobiliar is interested in having a modern energy performing building stock; they are interested in building energy labels. That way the dwellings are more attractive to the Swiss households and thus more competitive in the Swiss market.

- ***Funding and rental income***
  Mobiliar is covering 100% of their investments with own capital; the rental income is not calculated based on the cost but instead based on the market potential. They set a lower return rate limit and depending on the market potential and the vacancies they adjust the rents. In addition, the first 10 years of life of a building, it is probable that the rents will be low; after the first years the rent reaches the potential market rent.

- ***Tenancy***
  Mobiliar is not directly involved in the choice of the tenants; the management of the dwellings is given to real-estate agencies all over the country. The respective Mobiliar department is communicating with these agencies to maintain the overview of the tenants, the vacancies and rent collection. The agencies in collaboration with Mobiliar give priority to families when it comes to renting a 3-room plus dwelling. Apart from that, they have no specific occupancy rules; the main underlying rule is the financial ability of the household to cover the rent.

- ***Main challenges***
  Mobiliar is facing as well the challenge of land scarcity and high land costs. Mobiliar is very interested in maximizing the financial returns of the settlements, minimizing the cost or maximizing the rental income by having, for example, dwellings in an excellent location that guarantee high rental income.

Table C.25 – Workshop - Owner occupancy and income rules

Owner's occupancy rules						
	ABZ		SCHL		Mobiliar	
Number of rooms	Number of occupants					
	Min >=	Max <=	Min >=	Max <=	Min >=	Max <=
Physical criteria - Owner's min & max occupancy						
Free market & subsidized market						
1-1.5room	1	2	1	2	1	2
2-2.5room	1	4	1	3	1	3
3-3.5room	2	5	2	4	1	4
4-4.5room	3	6	3	5	2	5
5-5.5room	4	7	4	6	3	6
6-6.5room	5	8	5	7	4	7
7-7.5room	6	9	6	8	4	8
Financial criteria - Owner's income rules						
Free market						
	Household's Income					
	Min >=	Max <=	Min >=	Max <=	Min >=	Max <=
	3 x gross rent	15 x gross	3 x gross rent	15 x gross	3 x gross rent	
Subsidized						
	Fixed by the state					
Source: Workshops with the project's collaboration partners, own analysis						

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Wüest Partner (2021*b*), 'Du chauffage au refroidissement des bâtimens', *Immo-Monitoring 2021/2* . Zürich. [49]

Wüest Partner (2021*c*), 'Habitat: prévisions 2021', *Immo-Monitoring 2021/2* . Zürich. [48, 49]

Wüest Partner (2021*d*), 'Interactions sur le marché immobilier', *Immo-Monitoring 2021/2* . Zürich. [14]

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Curriculum Vitae

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Research interests

Housing economics, Construction sector, Environmental impact, Sustainable development, Housing policy, Computational design, Agent-based modelling, Statistics, Data analysis

Education

PhD Candidate *since 2017*
Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland
Laboratory of Environmental and Urban Economics (LEURE)
Specialisation: Housing economics, Sustainable development, Statistics, Data analysis, Agent-based modelling
Dissertation: *Towards sufficiency in housing: Agent-based model and transition scenarios*
Research project: "Shrinking Housing's Environmental Footprint (SHEF)" funded by the Swiss National Science Foundation (SNSF), National Research Program (NRP 73) "Sustainable Economy"

Master M1 & M2, "Urban and Regional Planning" *2016*
National Technical University of Athens (NTUA), Greece
School of Architecture, Department of Urbanism and Spatial Planning
Specialisation: Tourism, Cultural Management, Data Analysis, Urban & Regional Planning
Master Thesis: *Cultural Tourism - Museums and Archaeological Sites in Athens*

Master M1, "Urban and Regional Planning" *2013*
School for Advanced Studies in the Social Sciences (EHESS, Paris), France
Department of Social Sciences, Urban Space and Development
Specialisation: Urban Sociology, Urban Geography
Master Thesis: *The Economic and Real Estate Crisis in Athens and its Impact on the Urban Space*

Dipl.-Ing., BSc, MSc / Diploma in Civil Engineering *2012*
National Technical University of Athens (NTUA), Greece
School of Civil Engineering, Department of Transportation Planning and Engineering
Master Thesis: *Urban Planning - Industrial Heritage Sites in Transformation*

Skills and Personal Traits

Language skills: Greek (native), English (C2), French (C2), German (C2), Spanish (C2), Italian (B1), Chinese (elementary)

Computer literacy: LaTeX, MS Office, SPSS, R, Python, Pandas, NumPy, GitHub, AutoCad, Adobe Photoshop, InDesign

Academic and Professional Experience

Laboratory of Environmental and Urban Economics (LEURE) *Oct. 2017 - Present*
EPFL, Lausanne, Switzerland
Doctoral Assistant

- Dissertation under the supervision of Prof. Ph. Thalmann
- Project *Shrinking Housing's Environmental Footprint*, working on an interdisciplinary project, collaboration of three laboratories in EPFL and ETHZ
- Collaborated with three large-scale real estate owners in Switzerland (ABZ, SCHL, die Mobiliar), data gathering, interviews, owner workshops, tenant's survey
- Statistical analysis of real-estate data (SPSS, R, Python) and Writing Data Management Plan (DMP) EPFL
- Analysed the decision-making processes of large-scale real estate owners about their building stock (new construction, demolition-reconstruction, renovation, transformation) and the attribution of their dwellings to households
- Developed an agent-based model (ABM) describing the housing market
- Co-supervised the ENAC Week -Design Together "Sustainable development - Reducing the square meters of housing, Supervised student semester projects

Freelance Civil Engineer *2015 - 2017*
Athens, Greece

Civil Engineer in Pleias Architects Ltd. and Akrokeramon Ltd. *2013 - 2015*
Athens, Greece

RESEARCH

PROJECT REPORTS

- SHEF Deliverable 1.B "Description of the building stock and occupants"
- SHEF Deliverable 2.A.2 "Dynamic accounting-type models"
- SHEF Deliverable 2.B.1 "Correlation between owner actions and environmental impact"
- SHEF Deliverable 2.D "Discussion of owner determinants with collaboration partners"
- SHEF Deliverable 3.A.2 "Definition of owner agents"
- SHEF Deliverable 3.B "Model"
- SHEF Deliverable 4.B "ABM emphasis on owners"
- SHEF Deliverable 4.D "Main results and lessons"
- SHEF Deliverable 4.E "Policy recommendations"

COURSES ATTENDED (Selection)

Environmental Economics, Prof. Thalmann P., Dr. Vöhringer F., Dr. Vielle M., EPFL
Climate Economics for Engineers, Prof. Thalmann P., Dr. Vöhringer F., Dr. Vielle M., EPFL
Models for applied Environmental Economics , Dr. Vöhringer Frank, EPFL

EXTRACURRICULAR ACTIVITIES AND INTERESTS

Field hockey, Tennis, Foreign languages, Piano