NTNU – Trondheim
Norwegian University of
Science and Technology

The Aluminium Stock in Non-Residential Buildings in Trondheim

A Bottom-Up Study Based on Building Type-Cohorts

Line Rude Jacobsen

Nanotechnology
Submission date: June 2014
Supervisor: Daniel Beat Mueller, EPT
Co-supervisor: Amund Nordli Løvik, EPT

Norwegian University of Science and Technology
Department of Energy and Process Engineering

Abstract

Aluminium scrap is a valuable commodity not only in a monetary sense, but also in the sense that its utilization is an important step in reducing greenhouse gas emissions. It is both beneficial and necessary that an increasing share of the world's aluminium demand is supplied by recycled aluminium. In order to prepare and optimize extraction of metal from the anthroposphere, decision makers must be informed on where, when, how much, and in what form the scrap flows will emerge. The building sector is frequently quoted as the largest repository of aluminium, however, little quantified information on the secondary resource reservoir in buildings currently exists.

This study use a bottom-up method to quantify the in-use stock of aluminium in non-residential buildings in the Norwegian city of Trondheim. 81 office and business (O&B) buildings and 12 university and college (U&C) buildings were investigated through a field study. Five components made up the inventory: windows, doors, HVAC, curtain walls and solar shading. The Al density of the individual buildings were calculated, and the mean Al densities of nine age-type building cohorts were found. The in-use aluminium stock of the non-residential buildings is 2.9 kt, or 16.2 kg/cap. Windows and curtain walls are the most significant building components, each constituting 41% of the in-use stock. The per-capita in-use stocks are 10.3 kg/cap in O&B buildings, and 1 kg/cap in U&C buildings, and the largest repositories are within buildings constructed in the 1980's and the 1990's for O&B and U&C, respectively. It was found that Al densities peaked in the 1990's for both building types – 1.06 kg Al/m^2 for O&B and 1.13 kg Al/m^2 for U&C.

Although the aluminium stock in non-residential buildings in Trondheim is small compared to other countries, it is proved to be a good reserve for the mining of secondary aluminium. An increase in future scrap flows is expected.

Sammendrag

Aluminiumskrap er verdifullt, ikke bare målt i kroner og øre, men også på den måten at resirkulering av aluminium er et viktig bidrag i kampen om å redusere klimagassutslipp. Det er både nødvendig og fordelaktig at en voksende andel av verdens aluminiumsbehov dekkes av resirkulert aluminium. For å tilrettelegge for, og optimalisere utvinningen av, aluminium fra antroposfæren må det finnes tilgjenglig informasjon om hvor, når, hvor mye, og i hvilken form aluminiumskrap vil oppstå. Selv om bygninger ofte blir omtalt som den sektoren som oppbevarer mest aluminium, finnes det lite kvantitativ kunnskap om aluminium i bygningsmassen.

Denne studien benytter en såkalt "bottom-up" metode for å kvantifisere mengden aluminium i næringsbygg og andre ikke-bebodde bygg. 81 kontor- og forretningsbygg (K&F) og 12 universitets- og høyskolebygg (U&H) i Trondheim ble undersøkt i en felstudie. Fem komponenter ble kartlagt i disse byggene: dører, vinduer, ventilasjonssystemer, utvendige persienner og fasadesystemer av glass. Aluminiumstettheten ble beregnet for hver bygning, og en gjennomsnittlig aluminiumstetthet for ni grupper av byggeår ble beregnet. Mengden aluminium i ikke-bebodde bygg ble funnet å være 2.9 kt, tilsvarende 16.2 kg per innbygger. Størsteparten av massen besto av vinduer og fasadesystemer, med henholdsvis 41% hver. Per innbygger var mengden aluminium i K&F- bygninger tilsammen 10.3 kg, og tilsammen 1 kg i U&H-bygninger. De største forekomstene finnes i bygninger fra henholdsvis 1980-tallet og 1990-tallet for K&F og U&H. Den høyeste aluminiumstettheten ble funnet for bygninger fra 1990-tallet, med en aluminiumstetthet på 1.06 kg/m^2 for K&F og 1.13 kg/m^2 for U&H.

Selv om mengden aluminium i ikke-bebodde bygg i Trondheim er relativt liten sammenlignet med andre land, så egner denne bygningsmassen seg godt for utvinning av resirkulerbart aluminium. Mengdene skrapmetall er også forventet å øke i årene som kommer.

Preface

This study was conducted during the spring of 2014 and conclude my five years of education in the Master's programme in Nanotechnology with Industrial Ecology at NTNU.

I would like to express my deepest gratitude to my supervisors Daniel Beat Müller and Amund Nordli Løvik, for their support and guidance throughout the research, and for giving me the opportunity to write my Master's thesis at Industrial Ecology. My sincere appreciation also is extended to Laila Sveen at Kartverket, Tor Inge Stensaas and is team at Riis Glass og Metall, and Professor John Sølve Tyssedal for for lending their time and expertise.

Special thanks to my friends Erlend, Ingrid, Marianne and Torstein for the heroic effort of correcting and commenting on my text, and to Elisabeth and Ingvild for mathematical discussions. Last, but not least, I would like to thank my parents for their enduring support through my academic pursuit.

Contents

1 Introduction **1**

2 Methodology **5**
2.1 System Definition 5
2.1.1 Selection of Building Types 6
2.1.2 Selection of Building Components 6
2.2 Methodological Approach 7
2.2.1 Aluminium Area Density 8
2.2.2 Sampling 8
2.2.3 Quantification of Aluminium Content in Component 9
2.2.4 The Cadastre 10
2.2.5 Upscaling to Include Other Non-Residential Building Types 11
2.3 Statistics 13
2.3.1 Correlation 13
2.3.2 Uncertainty Analysis 14
2.4 Building Components 16
2.4.1 Identifying Aluminium 16
2.4.2 Windows 16
2.4.3 Curtain Walls 19
2.4.4 Solar Shading, Doors and HVAC 21
2.5 The Non-Residential Building Stock of Trondheim 22

3 Results **25**
3.1 In-Use Stocks 25
3.2 Evolution of Al Density 27
3.3 Correlation of Building Size and Al density 31
3.4 Distribution and Correlation of Components 32

4 Discussion **35**
4.1 Uncertainties and Limitations of the Approach 35
4.2 In-Use Stock and Al Density Results 37
4.2.1 Comparison of Al Densities and In-Use Stock to Other Studies and Quantification of the In-Use Stock Error 37
4.2.2 Evaluation of the Contribution of Components to the Al Density and In-Use Stock 40
4.3 Analysis of the Application of Aluminium in Buildings 41
4.3.1 Correlation of Components and Building Size with Al Density 41

4.3.2 Drivers of Al Use in Buildings - A Brief Analysis of Aluminium Penetration in Terms of Building Type-Cohorts and Historic Construction Activity 41
4.4 Implications and Policy Relevance 44

Appendices **53**

A Calculations of the Al Content of Components **53**

B The Cadastre: Data Processing Steps **55**

C Field Study Data **56**

1 Introduction

In the almost 130 years that have passed after the Hall-Héroult process made commercial production possible, aluminium has become one of the most utilized metals in the world. Primary aluminium is mainly recovered from bauxite ores in a process using 3.5% of global electricity and causing 1% of global CO_2 emissions [Cullen and Allwood, 2013]. Aluminium is easily recycled and the recycling process requires as little as 5% of the energy used for primary production and emits only 5% of the greenhouse gases [Davis, 1993][IAI, 2009]. Recycled aluminium is referred to as secondary aluminium, and the stock of aluminium still in use make up what is called the secondary resource reservoir. Because of the expensive primary production process, aluminium scrap is a valuable commodity.

Secondary material is also valuable in the sense that its utilization is an important step in reducing greenhouse gas emissions. 51 years after Rachel Carson's *The Silent Spring* first put environmental concerns on the map and 26 years after Gro Harlem Brundtlands's report coined the term *sustainable development*, IPCC released a report stating with a 95% certainty that global warming is due to anthropogenic activities [Carson, 1962][WCED, 1987][IPCC, 2013]. The growing environmental concern, particularly over the last decade, prompt governments, industry and private citizens alike to change the ways of production and consumption. Utilization of the secondary resource reservoir is a prerequisite in the race of cutting emissions to prevent a potentially devastating climate change.

Parallel to the increased focus on sustainable development, demand for aluminium continue to grow. The rapid and sustained growth of the Chinese economy is reflected in a 10% annual average growth of per-capita Al stock [Wang and Graedel, 2010], and despite a more modest growth in the industrialized countries, no clear signs of saturation have yet been observed [Liu and B.Müller, 2013]. In fact, it is forecasted that by 2050, demand will reach 2-3 times today's levels [Cullen and Allwood, 2013]. However, this development cannot continue indefinitely. In a future of zero stock growth (the stock of which will multiple times larger than today's), the scrap supply can in theory be large enough to cover the material demand. About one-third of the aluminium produced in the world is now obtained from secondary sources, and the future metal supplies are expected – and required, from the environmental point of view – to have much higher shares of recycled Al [Schlesinger, 2006].

Historically, research has concentrated on the mapping and quantification of geogenic resources like bauxite, but in recent years some focus has been shifted to reservoirs of raw material in the anthroposphere. The fact that 75% of all aluminium ever produced is still in use – almost one billion metric tons – reflects the size of this reservoir and the potential for so-called urban mining [Schlesinger, 2006]. Mapping of the secondary resource reservoir is important to the process of forecasting developments in stock input (material demand) and output (scrap supply) – information that can prove crucial to decision makers. Such information will also be of value to the industry, as it can be used to identify possible areas of improvement and potentially unexploited markets. The current status, however, is that relatively little quantified information on the secondary resource reservoir exists.

Of the annual global aluminium consumption, the building and construction sector accounts for 24% [Allwood and Cullen, 2012], but these estimates varies on a regional basis: from 15.4% in the UK according to Schlesinger (2006), to 25% in Europe as reported by the European Aluminium Association [EAA, 2011]. In addition, definitions of the sector are varying, e.g. sometimes including infrastructure. It is clear, however, that the building sector constitutes the largest resource reservoirs because of the long lifetime of aluminium components in this sector [McMillan et al., 2010]. Studies on the in-use stocks in Connecticut and China suggest that 60% and 67% of the stock is allocated in the building sector [Recalde et al., 2008][Wang and Graedel, 2010]. On the other hand, dynamic top-down MFA employed by the International Aluminium Institute shows that this share is around 33% [IAI, 2014], still the largest single repository.

Aluminium is, because of the high strength-to-weight ratio and corrosion resistance, ideal for a number of building applications. However, information on material use in the building stock is scarce and incomplete. This concerns aluminium in particular, because it's use is often implemented for practical and aesthetic reasons rather than strict necessity. For this reason, aluminium content in buildings can differ widely, making it hard to draw general conclusions without an in-depth study. Indeed, aluminium stocks have not been as extensively studied as other metals, like copper and zinc [Recalde et al., 2008].

The stock of in-use material can be assessed either by a *top-down* or a *bottom-up* method. A top-down method calculates in-use stocks based on assumptions on product lifetimes and information on flows of material into use and out of use. The bottom-up approach involves estimation of the stock based on inventory statistics of products and their metal content [Wang and Graedel, 2010]. The bottom-up approach is superior to the top-down approach when it comes to assessing stocks on a regional level, because information on flows that the top-down approach bases the calculations on, is often rough estimates on national levels, or even derived from other national statistics where trade data is not to be found.

Three central bottom-up studies on in-use aluminium stocks are referred to in this work: A study on stocks in the State of Connecticut, USA, for the base year 2000 by Recalde *et. al* (2008), a study on China with base years 2000 and 2005 by Wang and Graedel (2010) and the work of Sundelin (2009) on assessing in-use stock in buildings in Trondheim. The studies by Recalde *et. al* (2008) and Wang and Graedel (2010) are the first of their kind to estimate aluminium in-use stocks on a regional and national level, respectively, and they both produce an estimate of the complete in-use stock of aluminium in all sectors. The study of Connecticut concluded on an in-use stock of 363 kg Al per capita, 97.7 kg of which was found in commercial buildings and 11.3 kg in industrial buildings. The study of China yielded an in-use stock of 37 kg Al per capita for 2005, with 11.5 kg of which in non-residential buildings. The differences between the developed and the developing country is evident.

Because these studies aimed at assessing the complete in-use stock, they do not go in-depth on the individual sectors. For calculation of the in-use stock in the building sector, both studies use estimates for the aluminium mass per floor area, or the *aluminium area density*, from other sources. These sources are somewhat obscure, and the estimates vague. It has also proved difficult to get a comprehensive understanding of the sources, partly because detailed references are lacking. Only three studies can be directly related to the investigation of buildings in respect to aluminium; one LCI study on a residential house in the north of Japan found an Al density of 0.5 kg/m^2, one LCA study on a building of Tsinghua University, China, found an Al density of 3.73 kg/m^2, and one study by TU Delft, on nine buildings in six European countries and commissioned by EAA, found recycling rates of 92%, on average [Nishioka et al., 2000][Zhang et al., 2006][EAA-Delft, 2004]. The buildings investigated in the latter study include Wembley Stadium in UK, one courthouse, one factory, one department store, two office buildings and three residential complexes. It is clear that the grounds on which estimates are made are rather weak, and in fact, Recalde *et al.* (2008) recommend future studies to focus specifically on the different categories.

The work of Sundelin (2009) is confined to assessing the Al stock within buildings on a regional level, with a focus on quantifying the Al mass per unit window area. Her study is probably the first to resolve the building stock in terms of construction year. Using three age categories and five building type categories, the study concluded on an in-use stock of Norway of 250 000 tons and an Al density of 0.8 kg Al/m^2 for non-residential buildings in general. In comparison, a top-down study conducted by Liu and Müller (2013) concluded on an in-use stock of 1.33 Mt in the building and construction sector, or 272.5 kg per capita [Liu, 2014][Liu and B.Müller, 2013]. However, this study focus on the evolution of the global in-use stock, and the numbers might be inaccurate on a country level. This number is therefore believed to be exaggerated.

Unlike the bottom-up studies described, this work calculates an area density for each sample building by the direct counting and size measurements of building components. The application of such a detailed component inventory ensure a more robust estimate of the in-use stocks and allows for more detailed statistics and analyses to be conducted. This study goes one step further than previous studies in assessing the in-use stocks by confining investigation to two building categories and applying a temporal resolution. A focus on two building categories enables an in-depth investigation that allows for a larger sample size, strengthening the reliability of the estimate. Applying a temporal resolution of the building stock allows for precise forecasting of future aluminium scrap flows. In addition, it will be a contribution towards developing a better understanding of material use in the building stock. It is perhaps the most detailed study on aluminium use in the non-residential building stock to date, and the hope is that findings in this study can be utilized and adapted to future studies on the use of aluminium in buildings.

The main focus of this work is to characterize the aluminium stock in buildings, by application of age-type building cohorts and a detailed inventory of components. More precisely, the scope of this work is to (i) estimate the in-use Al stock in the non-residential buildings in Trondheim, (ii) produce estimates for Al densities of different building type-cohorts, and (iii) analyze possible motivations for aluminium use in non-residential buildings. The extended analysis will include the application of building components, comparison between the building types investigated, and comparison to other studies. The motivation of this study is to provide information to decision makers on the amount of metal in use, as well as where, when, how much, and in which forms the supply is likely to be available.

This work is divided into four sections. Section 2 provide a description of the approach in question and exhaustive background information. Statistics relevant for the work is also presented, as well as a qualitative description of the building components and of the building stock in Trondheim. Results are presented categorically in Section 3, and a discussion on a number of different aspects in Section 4 is concluding the thesis.

2 Methodology

2.1 System Definition

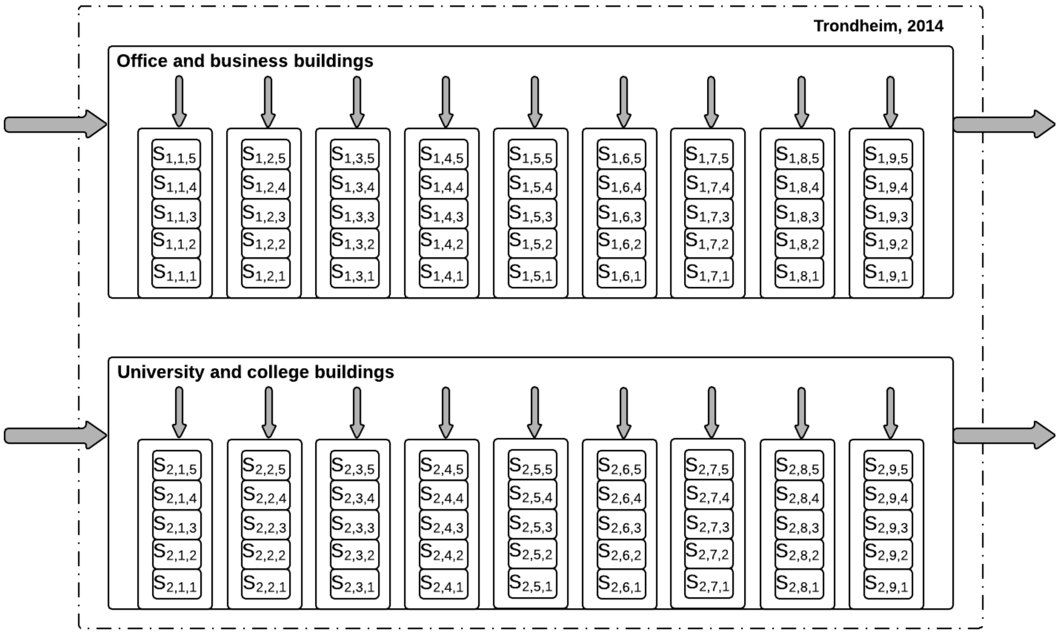

Figure 1: System boundaries defined as city of Trondheim in 2014 and office and business- and university and college buildings. Stocks $S_{t,h,c}$ characterized in terms of building type t, cohort h and building component c.

The scope of this work is to quantify the amount of aluminium for individual building types and cohorts, and find the in-use stock of aluminium in selected types of non-residential buildings in Trondheim.

Aluminium products flow into and out of use as illustrated by the horizontal arrows in Figure 1, accumulating as stock S in the use-phase for as long as they provide services. The system boundary in this work is the city of Trondheim in the year of 2014, and the non-residential building types "Office and Business" (O&B) and "University and College". The building stock is further divided into cohorts-types to enable investigation of historic aluminium use. As the name suggest, these are groups based on building type and year of construction.

The municipality of Trondheim has an area of 324 km^2. The registered population is 180 000, but the number of inhabitants swells beyond that during university semesters, as many of the town's students are registered residents of other municipalities in Norway. The city is defined by the geographical boundary of the municipality of Trondheim, and building components are taken as items fixed to, or being part of, the building structure itself.

Selected building components constitute a limited product inventory, and the stock of building components were classified in terms of the age-type building cohorts. The in-use aluminium stocks $S_{t,h,c}$ in Figure 1 are hence characterized in terms of building type t, cohort h and building component c. The inventory was quantified by a field study, involving visually inspection of pre-selected buildings in order to determine size and number of aluminium components. The inventory aluminium content was calculated in cooperation with producers.

2.1.1 Selection of Building Types

Two non-residential building types were investigated; "Office and Business" (O&B) and "University and College" (U&C), a sub-category of "Education, Culture and Research" (ECR). Types are classified according to the Norwegian cadastre as presented in Table 2 in Section 2.2.4. The decision is based on three factors: (i) the presumption that the O&B sector has higher amounts of aluminium is suggested by literature and is supported by the fact that this sector has higher turnover rates in terms of renovation, larger budgets for investments, and may contain more facilities and have larger facade areas, (ii) analysis of the building stock of Trondheim revealed that the O&B sector occupies the largest floor area, and (iii) the O&B sector is thought to be homogenous across cities (because the services and demands are constant regardless of location, unlike e.g. industrial buildings, which will vary according to the industry present in the area in question). U&C was selected on the same grounds as O&B, except that these buildings constitute a minor fraction of the floor area.

2.1.2 Selection of Building Components

Building components containing aluminium include roofing, facade cladding, flooring, window frames, ventilation grids, doors, industrial gates, isolation, lighting systems, solar shading, door handles, door hinges, signs, sinks, elevators, escalators, and a vast number of other applications.

The bulk of aluminium is found in the larger applications that weigh 10-100 kg apiece, like windows, doors and interior and exterior panels [EAA-Delft, 2004]. Although numerous, the aggregated weight of small objects does not come close to that of the larger objects. In order to determine which components have the most significant amounts of aluminium, literature studies were conducted. There seem to be a general agreement that windows and doors, curtain walls, ceilings and HVAC systems constitute the majority of aluminium-containing products [Wang and Graedel, 2010]. Worldwide, the consumption of aluminium in building applications are reported to be 37% for roofing and cladding, 27% for windows and doors and 18% for curtain walls, the remainder is categorized as the well-known "Other" [Allwood and Cullen, 2012]. In addition, an extensive study on 9 buildings in 6 countries by EAA and TU Delft concluded that most aluminium are found on the surface of buildings [EAA-Delft, 2004].

Five aluminium-containing building components were included in the field study investigations; windows, curtain walls, HVAC systems, solar shading and doors. A qualitative description on the components follows in Section 2.4. Three criteria were determining for the selection: (i) that components were externally visible and distinguishable, (ii) that they had significant amounts of aluminium, and (iii) that components were assumed to be frequently used in Norway.

2.2 Methodological Approach

The stock S of in-use aluminium in buildings of type t is measured in kg and can be expressed mathematically as

$$S_t = \sum_h \bar{\rho}_{t,h} Z_{t,h} \tag{1}$$

where $Z_{t,h}$ is the gross internal floor area of the building stock in cohort h and $\bar{\rho}$ is the mean aluminium area density of the cohort h. A field study was conducted to provide a basis for calculation of $\bar{\rho}$, of which the calculation steps are explained in the section to follow. $Z_{t,h}$ was acquired from official Norwegian statistics.

2.2.1 Aluminium Area Density

The aluminium area density is an expression of the average aluminium content in buildings whilst being independent on building size. It is a versatile measure that provide a common basis for comparison and is applicable e.g. for upscaling of results. For further reference, aluminium area density will be denoted Al density, and the unit is kg Al/m^2.

The Al density of an individual building is the sum of all aluminium-containing building components divided by the floor area of the building. Take M_c to be the mass of component c and $X_{h,b,c}$ to be the number of component c in building b. The aluminium mass of building b of cohort h, $M_{h,b}$, is then given as

$$M_{h,b} = \sum_c (M_c \cdot X_{h,b,c} \cdot F_c) \tag{2}$$

where F is a factor to correct for aluminium profile thicknesses. The Al density $\rho_{h,b}$ is equal to the mass of aluminium in the building divided by the floor area:

$$\rho_{h,b} = \frac{M_{h,b}}{A_{h,b}} \tag{3}$$

where $A_{h,b}$ is the floor area of building b.

The mean aluminium area density $\bar{\rho}_h$ of cohort h with n buildings is

$$\bar{\rho}_h = \frac{1}{n} \sum_{b=1}^{n} \rho_{h,b} \, . \tag{4}$$

2.2.2 Sampling

In order to select buildings for investigation, a stratified random sampling was carried out. The building stock were divided into age-type cohorts, and a random sample were chosen from each. This means that buildings without a building date (as explained in Appendix 2.2.4) were excluded from the sampling process altogether. The size of the samples from each cohort were set so that approximately 5% of the age-specified population were sampled, or about 2.5% of the building population at large, including buildings with unknown year of construction. The sample size was set arbitrarily, ensuring a large sample that at the same time were feasible to investigate.

Once a list of candidate buildings was constructed, buildings in remote or unaccessible areas were exchanged with buildings within the same age-type cohort in more accessible areas. The areas where buildings were situated were spread across the city, enforcing a tendency of excluding the residential areas and focusing on central areas with higher density of non-residential buildings. Because all buildings of these areas were inspected, some cohorts will have larger samples than required, some cohorts will only just have enough counts to satisfy the constraint of 2.5%.

2.2.3 Quantification of Aluminium Content in Component

Information on the aluminium content of the five building components were provided directly by different producers. The information were in the form of product specifications, technical drawings, technical reports, physical samples and custom-made spreadsheets. This enabled precise calculation of the aluminium content per component type and size, and the results are displayed in Table 1. Details on the calculations and parameters are provided in Appendix A.

Values for aluminium content in aluminium framed windows were calculated based on exact profile weights supplied by producer [Riis Glass og Metall, 2014b], as were values for doors. The aluminium content in aluminium cladded windows are informed estimates based on technical drawings and technical reports [Lian Trevarefabrikk, 2014][Tellnes, 2014a][Tellnes, 2014b]. Physical samples were provided by one producer to enable estimation of trim, cill and waterbar weights [NorDan, 2014]. Values for aluminium content in solar shading are based on custom-made spreadsheet supplied by one producer [Hunter Douglas, 2014], and the aluminium content for HVAC is supplied by one producer [Systemair Norge, 2014a]. A detailed description on each of the components are provided in Section 2.4.

Table 1: Aluminium content per component type and size. All values in kg except *.

Component		S ($1m^2$)	M ($2m^2$)	L ($5m^2$)
Plated doors	37.6			
Half-glazed doors	32.4			
Glazed doors	27.2			
Sliding doors	20.0			
HVAC	96.0			
Al trim windows		0.7	1.0	1.6
Al clad windows, fixed		2.4	3.2	4.6
Al clad windows, openable		4.1	5.5	7.8
Al profile windows, fixed		7.5	10.6	16.8
Al profile windows, openable		14.0	19.5	31.3
Curtain walls		12.0	16.9	26.8
Blinds		4.1	6.4	11.7
Correcting factor F^*	0.7 for small curtain wall areas			
	1.3 for large curtain wall areas			

2.2.4 The Cadastre

In order to design a field study, information on the building stock from the cadastre were used. The Norwegian Cadastre (*Matrikkelen*) is kept by the Norwegian Mapping and Cadastre Authority (*Kartverket*). The Cadastre is an extensive register of real estates, addresses and buildings, including information on year of construction, floor area and building type for buildings and their additions, extensions and reconstructions. It consists of 9 main building type categories, as seen in Table 2, with a total of 127 sub-categories [Kartverket, 2014a]. For buildings with combined functions, building types are assigned on basis of the function that occupy the largest amount of floor area. In the extreme case, a building with 51% floor area of type A and 49% floor area of type B would be categorizes as building type A.

Industry and Storage is an extensive category, ranging from factories, workshops and storages, to greenhouses and buildings connected to agricultural or fishing activities. Office and Business is more homogenous, including all types of pub-

Table 2: Main building types of the Norwegian cadastre with acronyms

	Building category	Acronym
1	Residential	
2	Industry and Storage	I&S
3	Office and Business	O&B
4	Infrastructure and Communication	I&C
5	Hotel and Resutaurant	H&R
6	Education, Culture and Research	ECR
7	Health	H
8	Prison and Readiness	P&R

lic administration and offices, businesses including department stores and malls, gas stations, banks and post offices. Cabins, hostels, hotels, restaurants, cafés, kiosks and canteens are collected in Hotel and Restaurant. Culture, Education and Research is an extensive category covering buildings for cultural, religious and educational activities, museums, sports arenas, kindergartens and libraries. Infrastructure and Communication and Prison and Readiness are negligible and will not be further discussed.

The cadastre in its present form was established in 1983, and buildings from before 1983 were mass registered in the 1990's [Kartverket, 2014b]. As a result, a number of these buildings lack information on floor area and year of construction, indicated as "Unknown" in the further building stock statistics. Values for $Z_{t,h}$ in Equation 1 were acquired through a number of data processing steps that were conducted to ensure that only existing buildings and relevant information were included. Details on the data processing is explained in Appendix B.

2.2.5 Upscaling to Include Other Non-Residential Building Types

An estimate of the complete in-use stock of Al in the non-residential building stock (NRBS) of Trondheim can be found by expanding the results from the office and business buildings investigations. Expansion is done by finding a reasonable ratio β_t of the mean Al area density of O&B, to the other building categories, and multiply this Al density share with the gross internal floor area $Z_{t,h}$ of the building category in question. The in-use stock of an investigated building type t is defined by Equation 1, and the expanded in-use stock $S_{t,exp}$ of building type t is expressed as:

$$S_{t,exp} = \sum_{h} (\beta_t \cdot \bar{\rho}_{O\&B,h}) \cdot Z_{t,h} \tag{5}$$

where $\bar{\rho}_{O\&B,h}$ is the mean Al area density of O&B as expressed in Equation 4. The complete aluminium in-use stock of the NRBS of Trondheim is then expressed as:

$$S_{NRBS} = \sum_{t} S_t \tag{6}$$

The product of Equation 6 is a purely theoretical estimate. The shares for Al density of the different categories are presented in Table 3, and the Al density of O&B is taken as 100%. The share β_t of the Al area density is assigned as follows of Table 3.

Table 3: Ratio β_t of the mean Al area density of O&B to other building categories

Building category (t)		Share of O&B Al density (β_t)
Industry and Storage	I&S	25% - medium
Infrastructure and Communication	I&C	25% - medium
Hotel and Resutaurant	H&R	70% - high
Education, Culture and Research	ECR	50% - medium/high
Health	H	50% - medium/high
Prison and Readiness	P&R	25% - medium

In their study, Recalde *et al.* (2008) argue a ratio of 1:4 of the Al density of commercial buildings to industrial buildings, because I&S buildings are generally low rise and have much less window and facade area. The same arguments apply for I&C, and a low share of aluminium are assigned to these categories. Similar to I&S, ECR is one of the most complex category. On one hand facilities with high al intensities, like sports arenas, research buildings and cinemas. On other hand some very low-intensity facilities like kindergartens, churches and museums are included, and an intermediate aluminium share is chosen. It is reasonable to assume that hotel and restaurant buildings subject to same factors as O&B (in terms of trends, higher investment, large buildings etc.), and thus have a high share of aluminium. Health buildings are classified as medium-high share because they are assumed to be a mix of high- and low rise institutional and public buildings.

2.3 Statistics

The theory presented in this section is based on *Statistics for Engineers and Scientists* by William Navidi [Navidi, 2008], and the reader is encouraged to consult this work for further details.

Generally, for two independent random variables X and Y, the variance of the sum $X+Y$ is

$$\sigma^2_{X+Y} = \sigma^2_X + \sigma^2_Y \tag{7}$$

where σ^2_X is the variance of X and σ^2_Y is the variance of Y. The variance of a linear combination on the form $c_1X + c_2Y$ is

$$\sigma^2_{c_1X+c_2Y} = c_1^2\sigma^2_X + c_2^2\sigma^2_Y. \tag{8}$$

2.3.1 Correlation

Correlation is a measure on the strength of the linear relationship between two variables, and is a number between -1 and 1. A positive correlation value is a result of two variables having a proportional relationship. If the correlation of two building components X and Y is positive and large, it means that a building with low amounts of component X generally has got low amounts of component Y, or that a building with high amounts of X has got high amounts of Y. A negative correlation signifies that the amounts of X and Y are inversely proportional. Correlation ϑ can be calculated according to Equation 9:

$$\vartheta_{X,Y} = \frac{Cov(X,Y)}{\sigma_X \sigma_Y} \tag{9}$$

where σ_X and σ_Y are the standard deviations of X and Y and the covariance of X and Y is expressed as:

$$Cov(X,Y) = \frac{1}{n}\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y}) \tag{10}$$

where the mean $\bar{X}$ and $\bar{Y}$ is the average value of all the samples n.

2.3.2 Uncertainty Analysis

The reason to conduct a field study is to get information about the complete building stock, the *population* in statistical terms. The buildings investigated in the field study is a *sample* of the true building population. A sample will provide estimates for the true values of a population. The difference between the estimate and the true value is called the error in the measured value. When measurements or parameters are used for calculations, their errors will propagate to the calculated value and produce an error in the calculated value. An uncertainty analysis is an attempt to quantify the uncertainty in the final calculated value based on the given uncertainties (errors) in the parameters and measurements. The variance is a measure of spread, i.e. to which degree measurements deviate from the mean. In uncertainty analysis, the variance is taken as the error. Variance is denoted σ^2 for the population (true value), and s^2 for the sample (estimate).

Generally, for a sample $X_1, \ldots, X_n$ from a population with a true mean μ and sample mean $\bar{X}$, the sample variance is defined as

$$s^2 = \frac{1}{n-1} \sum_{i=1}^{n} (X_i - \bar{X})^2 \tag{11}$$

and the sample standard deviation, s, is defined as the square root of the sample variance. The variance of the sample mean $\bar{X}$ is

$$s_{\bar{X}} = \frac{s^2}{n} \,. \tag{12}$$

As explained in Section 2.1.1, stratified random sampling is used in order to ensure that the sample is representative for the population, meaning that the population is divided into subpopulations, and a simple random sample is drawn from each subpopulation. The subpopulations are cohorts with sample mean $\bar{\rho}_h$. From Equation 4, $\bar{\rho}_h$ is expressed as the mean of the individual densities ρ_{hb} of the n observed buildings. Two types of errors are associated with ρ_{hb}: an error ϵ_{hb} caused by the fact that a sampled building is unrepresentative, and an error v_{hb} caused by the imprecise calculation of aluminium content of the building components. If μ_h is the true mean value of the cohort, the Al density of individual buildings ρ_{hb} is defined as:

$$\rho_{hb} = \mu_h + \epsilon_{hb} + v_{hb} \tag{13}$$

and the variance of ρ_{hb} is

$$Var(\rho_{hb}) = \sigma^2_{h\epsilon} + \sigma^2_{hv} \,. \tag{14}$$

The variance of $\bar{\rho}_h$ from Equation 4 thus becomes

$$Var(\bar{\rho}_h) = \frac{\sigma^2_{h\epsilon}}{n} + \frac{\sigma^2_{hv}}{n} \,. \tag{15}$$

On the presumption that Var(v_{hb}) vary with b, σ^2_{hv} is calculated as

$$\sigma^2_{hv} = \frac{1}{n}\sum_{h=1}^{n} \sigma^2_{hbv} \,. \tag{16}$$

Because the true values σ^2 are unknown, they are estimated by s^2 as follows:

An estimate for Var($\bar{\rho}_h$) is given as S^2_h:

$$S^2_h = \frac{1}{n-1}\sum_{h=1}^{n} (\rho_{hb} - \bar{\rho}_h)^2 \,. \tag{17}$$

An estimate for σ^2_{hv} is given as S^2_{hv}:

$$\begin{aligned} S^2_{hv} &= \frac{1}{n}\sum_{h=1}^{n} S^2_{hb} \\ &= \frac{1}{n}\sum_{h=1}^{n}\left(\frac{1}{A^2_{hb}}\sum_{c} Var(M_c)\cdot X^2_{hbc}\right) \,. \end{aligned} \tag{18}$$

An estimate for $\sigma^2_{h\epsilon}$ is $S^2_{h\epsilon}$, and from Equation 14 it follows that

$$S^2_{h\epsilon} = S^2_h - S^2_{hv} \,. \tag{19}$$

The magnitude of the components S^2_h and S^2_{hv} provides insight on where the largest reduction in uncertainty can be achieved – either by calculating the aluminium content of components more precisely, or by having a larger sample. The uncertainty of the aluminium stock S_t of a building type (defined in Equation 1) is estimated by the variance S^2_t, and is expressed as

$$\begin{aligned} S^2_t &= \sum_h Var(\bar{\rho}_h)\cdot Z^2_h \\ &= \sum_h \left(\frac{\sigma^2_{h\epsilon}}{n} + \frac{1}{n^2}\sum_{h=1}^{n}\sigma^2_{hbv}\right)\cdot Z^2_h \end{aligned} \tag{20}$$

2.4 Building Components

2.4.1 Identifying Aluminium

One of the main challenges of a field study is the visual inspection, i.e. to be able to visually distinguish aluminium metal from other white metals. Based on appearance, aluminium can be confused with zinc and stainless steel, and they are applied for much the same purposes. In general, it is possible to distinguish white metals based on hardness, chemical-, magnetic-, reflective- or thermal properties. As white metals share some of the same properties – both zinc, some stainless steels and aluminium are non-magnetic – a combination of tests would be ideal. However, verification of these properties usually require close proximity to the object, which for a large part is not feasible in a field study. For instance, windows are usually situated above ground floor and cannot be closely inspected. For this reason, the most secure thing is to recognize areas of use and design of the components rather than the metal itself.

2.4.2 Windows

The frame of a window can be made out of wood, aluminium, steel or plastics, alone or in a combination. Wooden windows have traditionally been the dominant type of window frames in Norway, and it continues to be so to this day. While aluminium framed windows reportedly came into use in the UK as early as the 1930's [Lane, 1992], the commercial use of aluminium window frames in Trondheim started in the 1960's [Riis Glass og Metall, 2014a]. The first frames were made out of aluminium profiles, examples of which can be seen in Figure 2. In the 1980's, wooden windows were made with a cover of aluminium plates, the aluminium cladded windows, called Al clad (Figure 3). These frames combine the maintenance free properties of aluminium while keeping the costs down. The service life of an Al clad window is reportedly 60 years, as opposed to 40 years for timber frames [Tellnes, 2014a]. Conventional wooden frames can also be provided with single features of aluminium like window trim, sill and waterbar. The latter are referred to as aluminium window trim, or Al trim. In fact, one producer reports a standard fixed window without Al clad to hold an amount of more than 1 kg aluminium [Tellnes, 2014a].

For window frame materials other than wood, roughly 80% are expected to be aluminium [Schüco, 2014]. For this reason, whenever close inspection during the field

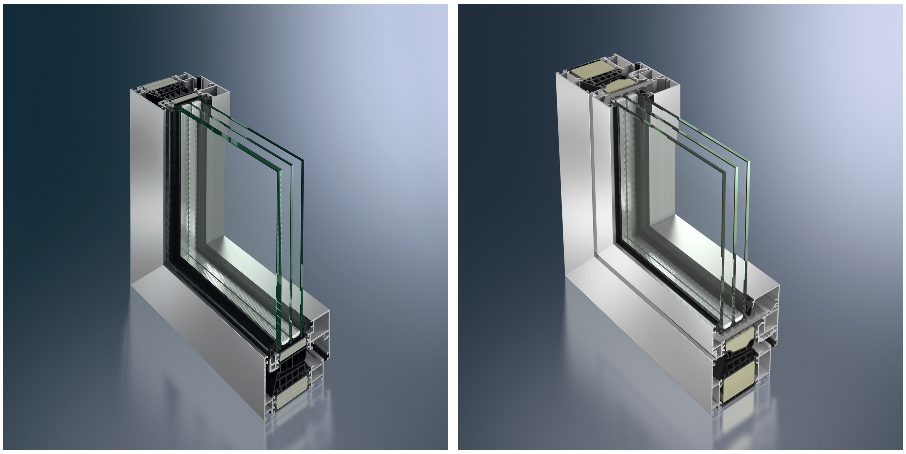

Figure 2: Two types of Al profile windows, the leftmost fixed and the rightmost openable [Schüco, 2012]

study was not possible, the material was assumed to be aluminium. A larger challenge than distinguishing the materials, was to visually distinguish profile frames from cladded frames. A close-up inspection will sometimes reveal an internal wooden frame. More evident, wooden frames tend to be thicker than the aluminium profiles. Cladded frames protrude more from the glazed areas, while aluminium frames can be almost in level with the glazing. In addition, aluminium cladded windows often have a slightly slanted sill as can be seen in Figure 3 (right), as opposed to aluminium frames where the sill is horizontal as in Figure 2. Skylight windows are exclusively made with aluminium cladding [NorDan, 2014]. Trim is easier to recognize - usually it is apparent that window frames are wooden, with a small metal trim on the glazing perimeter. Identification marks do not always apply, though, and individual evaluation is often required.

Figure 3: Two types of openable aluminium cladded windows [Lian Trevarefabrikk, 2014, MesterVindu, 2014]

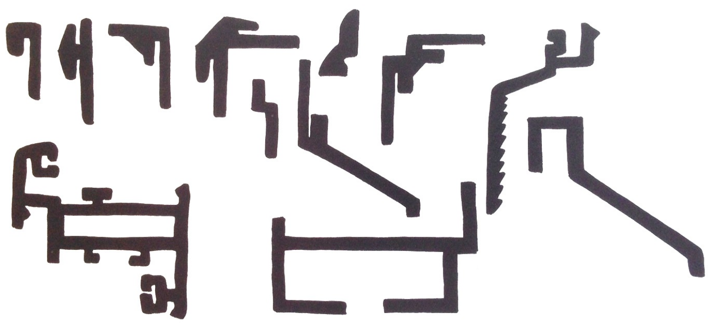

Figure 4: Examples of extruded aluminium profiles used for windows [Skanaluminium, 1972]

Because of the complex design of aluminium window features, they are almost exclusively of extruded aluminium. In fact, 45% of Al used for construction worldwide is in the form of extruded frames in windows, doors and curtain walls [Allwood and Cullen, 2012].

Figure 5: A1962 original building with different window types. The window area far left have original wooden frames, the middle area is probably a newer wooden Al clad frame with Al blinds, while the far right area consist of modern aluminium profile windows. It might also be that the middle and right areas are both Al profiles, but of different type, time or producer.

A building with a mix of original wooden windows and two types of aluminium-containing windows of newer date is shown in Figure 5. It is almost impossible to determine whether the aluminium frames are profile or clad from this distance without entering the building and inspecting the frames close-up. The rightmost windows are believed to be profiles as the frames do not protrude, while the windows in the middle part of the building are potentially aluminum clad. This building also serves to illustrate that building age has no correlation to component age – refurbishments are frequently done. This is especially true for windows, where new technology (e.g thermal breaks) has large a impact on the insulation performance of the windows, meaning that windows are likely to be replaced when new and better technology is produced.

2.4.3 Curtain Walls

Curtain walls are characterized by large, continuous glazed areas, often with the frame system barely visible from the outside as seen in Figure 6. Curtain walls contain a larger amount of aluminium per square meter window area, because of the vertical, load-bearing columns that are constructed to endure wind load. Curtain walls can have paneling of a number of materials, but glass is by far the most common. Dimensions range from 50 - 300 mm depth for the vertical profile [Riis Glass og Metall, 2014b], some examples of which can be seen in Figure 7. Because of the large variation in profile depths, a correcting factor F is applied in the calculation of aluminium mass in curtain walls, as displayed in Table 1 in Section 2.2.3.

Figure 6: Section of a curtain wall system [Building Design, 2008]

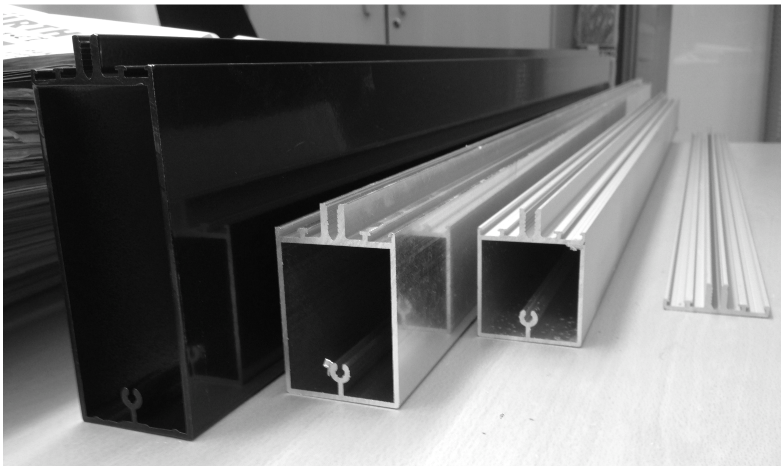

Figure 7: Various dimensions of profiles used for curtain walls, from a 155mm vertical profile bar (left) to a 5mm horizontal profile bar (right)

Curtain walls were first introduced in Trondheim in the 1970's [Riis Glass og Metall, 2014b]. They are not essential for most building structures, but rather applied for aesthetic reasons. Thus, they are subject to trends and architectural considerations. In very large vertical structures, steel is employed, but constructions of this sizes are not common in Norway. Recently, new technology make curtain walls very energy efficient, and ideal for e.g. passive houses [EAA, ndb].

2.4.4 Solar Shading, Doors and HVAC

Exterior blinds of aluminium is the most common aluminium-containing type of solar shading devices. Blinds for exterior use in Norway are almost exclusively made of aluminium [Hunter Douglas, 2014] because of the tough climate. Common dimensions range from slat depths of 50-80mm.

Figure 8: A typical glazed aluminium framed door (left) and illustration of automatic sliding doors (right) [Norfo, 2014][Norske Metallfasader, 2014]

Doors of metal are conventionally made of steel, iron or aluminium. Aluminium doors are often made of a combination of extruded profiles of 6xxx-series and rolled aluminium of a 3xxx or 5xxx alloy [Allwood and Cullen, 2012]. Doors are usually easily accessible and a magnet will suffice to determine if it is of industrial steel, iron or aluminium. Manual entrance doors and automatic sliding doors of aluminium are common features in commercial buildings, and examples of both types are shown in Figure 8. Fire doors are also large repositories of aluminium, but these are applied internally and are not included in this study. Strength and lightness is the most important properties for aluminium use in doors [Lane, 1992]. In this study, doors are divided into four categories based on aluminium content: plated doors, half-glazed doors, glazed doors and sliding doors. Half-glazed and plated doors have aluminium plates instead of glazings. In the field study, all doors are counted individually – e.g. one pair of sliding doors is counted as two individual.

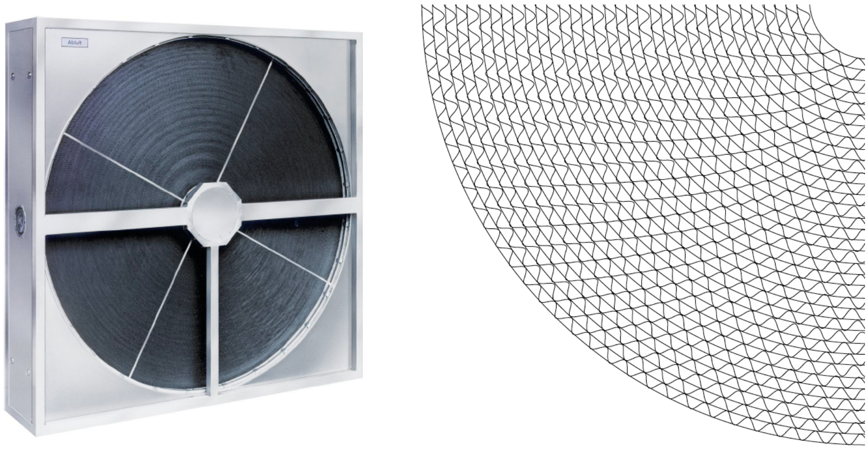

Figure 9: A rotary heat exchanger used for HVAC systems (left) and the wheel geometry (right) [Klingenburg GmbH, 2007]

Aluminium in **HVAC** (Heating, Ventilation and Air Conditioning) systems are mainly concentrated in one component: the rotary heat exchanger, a large porous wheel that extract heat from warm air leaving the ventilation system. The conductive properties of aluminium make the metal ideal for this purpose. The dimensions range from a diameter of 35 cm for residential buildings, up to a diameter of 4 m [Systemair Norge, 2014b] for commercial buildings. A diameter of 1.5 m is used as reference for the aluminium content. HVAC are identified in field study by the presence of large ventilation inlets etc. Rolled aluminium of the 8xxx series are frequently used for these HVAC heat exchangers [Hydro, 2012].

2.5 The Non-Residential Building Stock of Trondheim

The gross internal floor area of the non-residential building stock of Trondheim is represented in Figure 10, where it is categorized into building type and year of construction. Numbers are raw data from the Cadastre, meaning that no data processing steps have been taken.

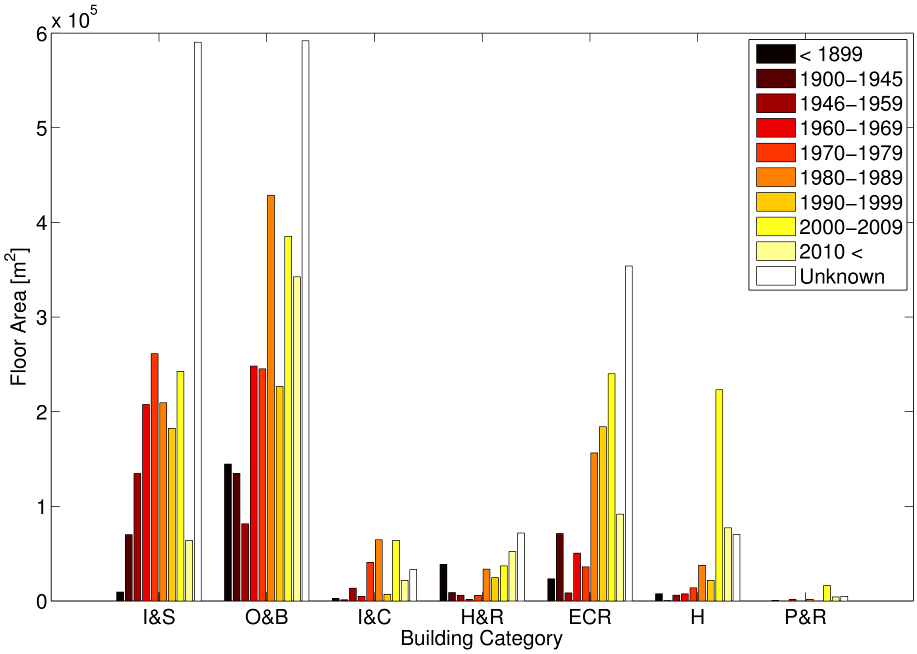

Figure 10: Gross internal floor area of the non-residential building stock of Trondheim, divided into ten groups of construction year and seven groups of building types. Data of buildings with unknown construction year is excluded.

Stocks of the pre-1945 buildings in O&B, H&R and ECR are larger than the subsequent post-1945 cohort. The fact that the stock of old buildings is large for these categories is not surprising, as the location of the historic city centre coincide with the present day centre and is an attractive location for offices, businesses, hotels, restaurants, cultural institutions and the likes. Old buildings can be subjected to severe restrictions like being listed as cultural heritage, which might explain the relatively large stock. A dip in building activity in the post-war period of the 1950's is prominent in the O&B, H&R and ECR categories, which might have exerted an increased demand on older buildings to be kept in use. The 1960's and 1970's see some stable, rising numbers in the stock size, as expected. A record high is reached in decade of 1980, in accordance with the economic boom of the 80's. This is also the decade when the Cadastre was established (as discussed in Section 2.2.4), leading to a complete registering of buildings in this and subsequent cohorts. A temporary decline of the building stock size in the 1990's is evident in all categories except ECR, coinciding with a recession as a result the economic contraction in the late 1980's [NOU, 2000]. A large boost in building stock of 2000 can be observed, which might prove to continue, especially the O&B.

Overall, the O&B has the largest stock size, the only match being I&S 1946-1959 cohort. I&S is in general a more complex category then O&B, as discussed in Section 2.2.4, and the fact that it is small compared to O&B reflects that Trondheim is not first and foremost an industrial municipality, but a university city. That being said, the amount of buildings with unknown floor area is the same in I&C and O&B, and it is plausible that significant a fraction of these should be allocated to the first two-three cohorts, yielding a higher floor area.

Table 4: Average floor area per building [m^2] of cohorts in building categories O&B and U&C, based on processed numbers from the Cadastre. *Data not available.

Cohort	**O&B**	**U&C**
<1899	1119	351
1900-1945	2585	3540
1946-1959	1935	- *
1960-1969	2982	3693
1970-1979	2912	1484
1980-1989	3514	7575
1990-1999	3782	4699
2000-2009	4282	31351
2010<	7445	17310

The average floor area per building is calculated based on processed information from the Cadastre, and the results are displayed in Table 4. Processing steps involve the distribution of buildings with unknown year of construction (as explained in Appendix B), to have a more correct representation.

3 Results

This section includes results from the field study and models of the building stock. First, calculated results on the in-use stock of aluminium in Trondheim will be presented. Results on both individual and mean Al area densities will be provided in the second section, which provides a basis for the discussion in Section 4.2.1. Next, a brief overview on the correlation of building size and Al density is provided, followed by a presentation of the correlations and distributions of the building components.

3.1 In-Use Stocks

The in-use aluminium stock of the office and business (O&B) buildings in Trondheim is calculated to be 1 845 700 ± 282 100 kg. The per-cohort stocks are displayed in Table 5, together with the total estimate. In the cohort model, the largest single contribution is from the 1980's building cohort, followed by the 1960's cohort. The lowest stock is in the cohort of pre-1899 buildings, as expected.

Table 5: Aluminium in-use stock [kg] per cohort in office and business (O&B) and university and college (U&C) buildings in Trondheim

Cohort	O&B	U&C
<1899	27 450	22
1900-1945	81 300	1 350
1946-1959	109 550	1 700
1960-1969	316 550	37 550
1970-1979	207 150	8 450
1980-1989	351 550	15 900
1990-1999	240 500	74 350
2000-2009	294 650	31 350
2010<	216 950	6 900
Total [kg]	**1 845 700**	**177 600**
Per capita	10.3 kg/cap	1 kg/cap

The in-use aluminium stock of the university and college (U&C) buildings is calculated to be 177 600. Due to the limited sample size (as seen in Table 7), no statistical uncertainty is calculated. The single largest stock is in the 1990's building cohorts, with almost twice the stock of the second largest, being the 1960's cohort.

The in-use aluminium stocks per component is displayed in Figure 11 and in Table 6. Of the components, the largest in-use aluminium stocks are found in windows and curtain walls, in almost equal amounts. Curtain walls has got a larger share of the aluminium stock in university and college buildings, while windows has got a larger share in office and business buildings. HVAC has got the smallest in-use stock for both building types – the aluminium stocks in windows and curtain walls are both more than nine times the size of the HVAC stock.

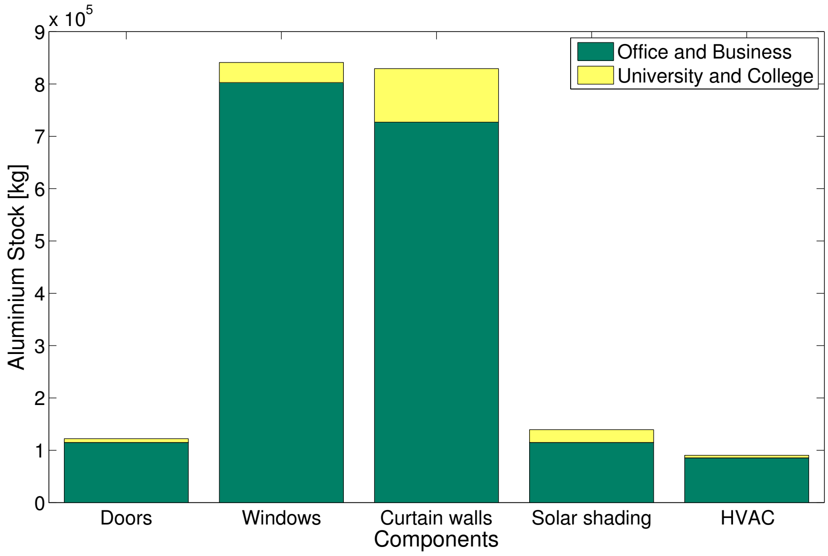

Figure 11: Aluminium in-use stock per component in office and business (O&B) and university and college (U&C) buildings in Trondheim

Table 6: Aluminium in-use stock [kg] per component in office and business (O&B) and university and college (U&C) buildings in Trondheim

Component	In-use stock	Fraction of in-use stock
Doors	122 000	6%
Al trim windows	19 000	< 1%
Al clad windows	199 000	10%
Al profile windows	623 000	31%
Curtain walls	829 000	41%
Solar shading	139 000	7%
HVAC	91 000	4%

The upscaling of the results for the complete non-residential building stock of Trondheim, according to the method explained in Section 2.2.5, yield an in-use stock of 2 904 150 kg, or 16.2 kg Al/cap.

3.2 Evolution of Al Density

A timeline based on year of construction of the 93 investigated buildings is presented in Figure 12. The bar heights reflects the Al area density. The width of each bar reflects the relative size of the building in question, and makes it possible to get a visual impression of the aluminium stock per building. The aluminium area density per investigated building is calculated according to Equation 3 in Section 2.2.1. The highest Al area density is 2.39 for a 1989 building (O&B) and 1.78 for a 1995 building (U&C), while the lowest is 0.02 for U&C (1910) and 13 buildings with zero aluminium for O&B – 9 of those in the pre-1899 cohort (detailed information is provided in Appendix C). In fact, 81% of the pre-1899 cohort have Al area densities below 10% of the maximum sample value of 2.39 kg/m^2. In other words, the distributions of the aluminium stock and Al densities are diverse.

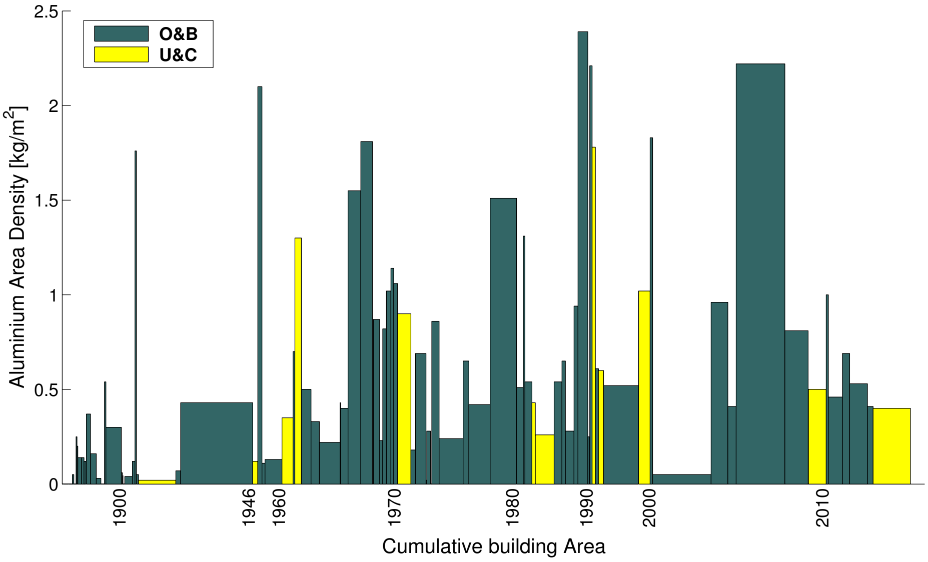

Figure 12: Al area density of investigated buildings, ordered after year of construction. Bar widths reflect relative size (gross internal floor area) per building.

The Al area densities of the investigated buildings in Figure 12 are presented per component in Figure 13, enabling analysis of the composition of the aluminium stock per building, and the temporal distribution of the building components. Solar shading, doors and HVAC have been aggregated, while windows have been split into Al profile, Al clad and Al trim windows.

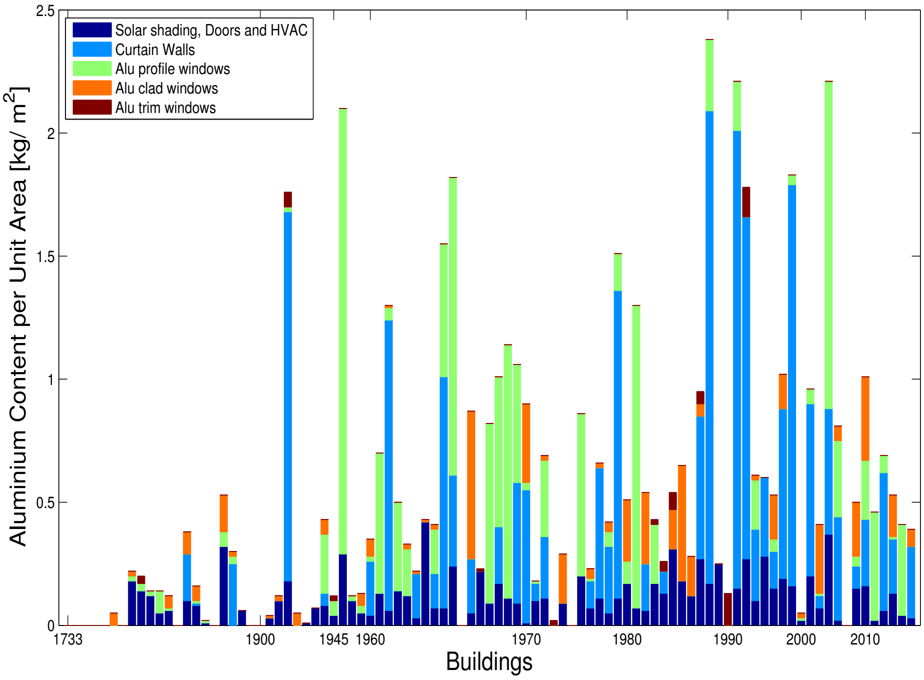

Figure 13: Al area density per component of investigated buildings, ordered after year of construction

The median of a sample is the value of the number n in the centre position when the samples are ordered from smallest to largest. The distribution of the sample values can be analyzed by comparing the median and the mean. The calculated median and mean per cohort for the investigated buildings are displayed in Table 7, together with the sample size.

The lowest mean Al area density is of the pre-1899 buildings, and the median indicate that half of the buildings have Al area densities below 0.05 kg/m^2. The highest Al area density is of the 1990's cohort. The median is the same as for the 2000's cohorts, while the means of the two cohorts are very different. By comparing the median and means of the 1990's and 2000's cohorts, it is evident that the 1990's value is affected by outliers - a minority of buildings with high area densities that greatly increase the mean value. The mean of the 2000's cohort is closer to the median, indicating that the sample values are more evenly distributed on the lower and the upper side of the mean. Generally, the differences in median and mean indicate that the samples have an overweight of buildings with lower Al

Table 7: Sample size and median and mean of Al density [kg/m^2] of investigated building categories

Cohort	Office and business buildings			University and college buildings	
	Sample size	Median	Mean $\bar{\rho}_h$	Sample size	Mean $\bar{\rho}_h$
<1899	21	0.05	0.11	-	-
1900-1945	7	0.07	0.35	1	0.02
1946-1959	3	0.13	0.78	1	0.12
1960-1969	15	0.70	0.74	2	0.83
1970-1979	10	0.35	0.49	1	0.90
1980-1989	9	0.54	0.82	2	0.35
1990-1999	5	0.61	1.06	3	1.13
2000-2009	6	0.61	0.74	1	0.50
2010<	5	0.53	0.62	1	0.40

area densities, and a minority of buildings with very high area densities. In fact, 34 of the 81 of the office and business buildings have Al area densities below 10% of the maximum sample value of 2.39 kg/m^2.

Because of the limited sample size of U&C in Table 7, this category is too small to be treated statistically. In this regard, the sampling of U&C first and foremost serves to investigate trends and feature in relation to O&B, and to investigate whether the two categories can be compared. As with O&B, the highest mean Al area density of U&C buildings is in the 1990's cohort, while the lowest Al area density is found in the 1900-1945 cohort.

The evolution of the mean Al area density of the O&B and U&C in Table 7 is illustrated in Figure 14 as a black dashed line and a solid blue line, respectively. The mean Al area densities of three of the largest subcategories of O&B – "Other offices", "Store and Business" and "Other businesses" – are also included, which allow for a more thorough analysis. The Al area densities of the pre-1899 cohort are almost identical, and increase from this point until a dip around 1970's is experienced by all categories except store and business buildings. A peak in the 1990's is also evident for all except one category. From the 2000's onwards, all categories exhibits the same tendency of a modest decline in Al area density. The evolution of U&C have general similarities to the evolution of O&B, and it can be argued that U&C exhibits a delayed evolution in respect to O&B, from 1899 until both reach the peak in the 1990's. In addition, magnitudes and growth rates are somewhat different.

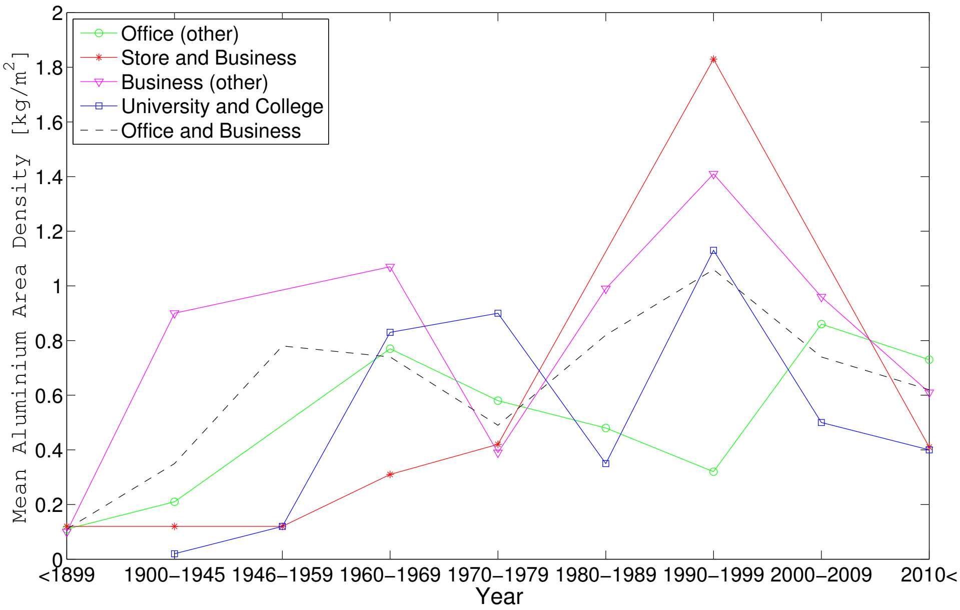

Figure 14: Evolution of mean Al area densities of U&C, O&B and three of its subcategories

3.3 Correlation of Building Size and Al density

Figure 15 illustrate the individual relationships between Al density and floor area per building of buildings investigated in the field study. Numerically, the correlation coefficient was found to be 0.1.

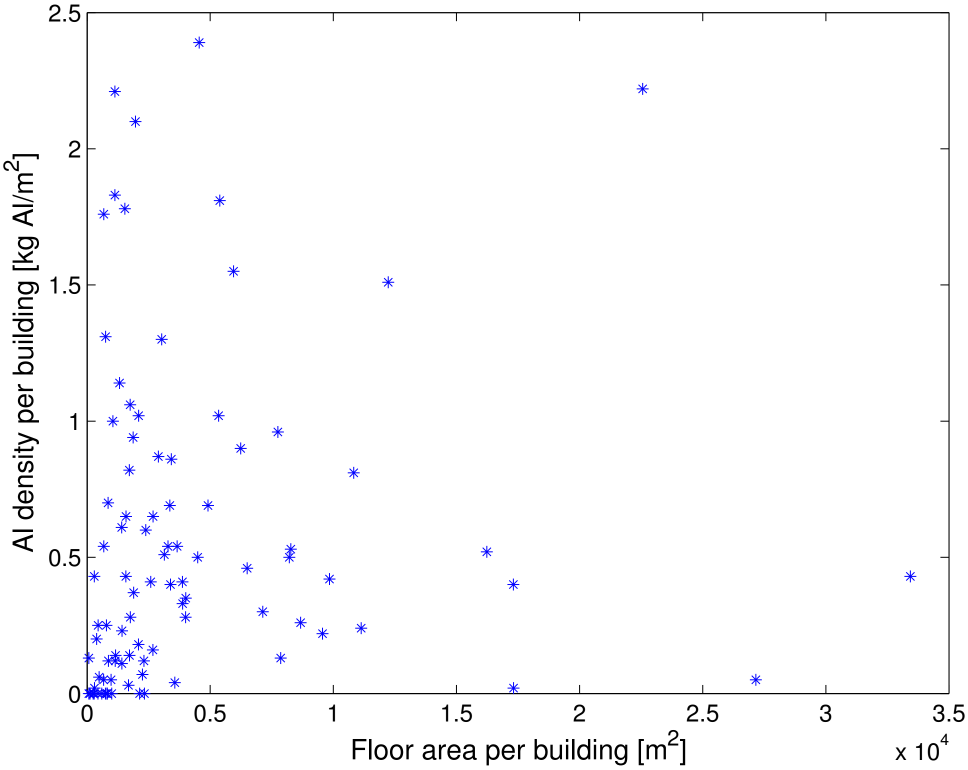

Figure 15: The 93 investigated buildings plotted in terms of Al density and floor area per building

3.4 Distribution and Correlation of Components

The distribution of building components per building is visualized in Figure 16, with the height of the bars corresponding to the Al area density of the individual investigated buildings. It gives an indication on the penetration of the components, i.e. the share of buildings where a component is present in significant amounts, and the distribution of the components, i.e. how the amount of a given component varies from one building to another.

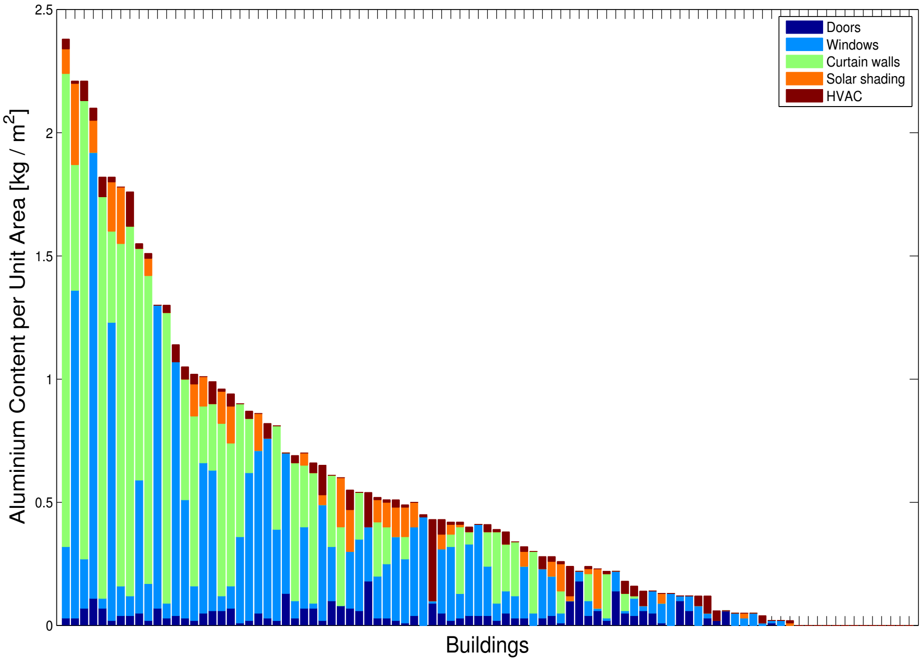

Figure 16: Al area density of sampled buildings in sinking order, divided into area density per component

Correlation coefficients of each component to the collective of the other components were calculated, and results are shown in the upper part of Table 8. Coefficients of the correlation of components are individually included in the lower part of the table. The fact that no correlations are negative, except HVAC and solar shading, means that other components are found to some extent whenever one is present. Solar shading has the highest calculated correlation with the other components, meaning that if a building employs aluminium blinds, the probability of finding aluminium in another component is relatively high. Naturally, solar shading has a high correlation with windows and curtain walls. On the other end, curtain walls has got a low correlation with the other building components, indicating that application of curtain walls to a large degree is independent of other components.

Table 8: Correlation of the investigated building components. * Correlation of the component in question to the sum of all other components.

Component	Correlation*
Solar shading	0.48
Doors	0.19
HVAC	0.16
Windows	0.09
Curtain Walls	0.08
	Specific Correlation
Windows - solar shading	0.38
Doors - HVAC	0.32
Curtain walls - solar shading	0.20
Doors - Windows	0.19
Curtain walls - HVAC	0.16
Doors - Solar shading	0.08
Doors - Curtain walls	0.07
Windows - HVAC	0.04
Windows - Curtain walls	0.02
Solar shading - HVAC	-0.07

4 Discussion

The following discussion is divided into three main parts: First, a discussion on the chosen approach, its weaknesses and its sources of error. Second, Al densities, the results on the in-use Al stock and the significance of components will be discussed, and an analysis of the application of Al in buildings use will be provided. Finally, implications of the results in terms of policy relevance will be presented.

4.1 Uncertainties and Limitations of the Approach

Three elements are needed for a bottom-up study: (i) a product inventory, (ii) aluminium content of products and (iii) the stock of products. Uncertainty, variability and restricted access to information, or lack of information, are connected to all three factors.

For a bottom-up study, it is not feasible to include a complete product inventory – door handles and peep holes, small ventilation grid and strips, closers and hinges and the likes will have to be neglected for practical purposes. In addition, this work confined the inventory to exterior applications, and only included five of the exterior applications in the investigations. As examples, roofing, facade cladding and building signage are quoted amongst the most significant building components [Jan van Houwelingen, 2004], but are not included in the inventory of this study. However, as the largest share of aluminium is found on the surface of buildings, and the chosen components are representative for what is believed to be the most used building applications in Norway, this study should provide a reasonable estimate of the in-use stock. The selection of building components are explained in more detail in Section 2.1.2.

The aluminium content of the building components were calculated based on information from producers. For accuracy, some of the components were divided into size categories. Still, only a rough estimate of the contents is achieved, because large uncertainties and generalizations apply. This can be illustrated with windows as an example: even though the content estimate is acquired by detailed calculations and exact data, the estimate only holds for one window type of one producer. Other windows can vary in profile dimensions, window size and technology. However, the uncertainty analysis (described in Section 2.3.2) shows that the uncertainty connected with the calculation of the Al content is rather small. Compared to the larger uncertainty associated with the sampling, the contribution of uncertainty for the calculation of component content can in fact be deemed negligible.

The perhaps largest uncertainties in this study are connected to quantification of the stock of products. In this work, a field study was chosen for the purpose of quantifying the inventory stock. Previous bottom-up studies emphasize that few experts (architect, contractors etc.) are informed on the amount of aluminium in buildings [Wang and Graedel, 2010]. A field study is not dependent on knowledge and goodwill of others, and is therefore considered more reliable. Still, a field study introduce uncertainties: access to buildings can be fully or partly restricted, and a large probability of human error is connected to the assessment of component type and size by visual inspection. These include both systematic and random errors and can be compensated by careful design of the study and by education on the component's design.

Other sources of errors are connected with the sampling of buildings: the errors of having a too small sample size or an unrepresentative building sample, in addition to errors related to background data that cannot be avoided (e.g. errors in the Cadastre). Regarding the error of a too small sample size, statistics on U&B in Table 7 illustrate that the sample size should be a minimum of three to be able to conduct reasonable statistics. Uncertainty analysis can also shred some light on whether the sample size is sufficient. In order to provide a representative building sample, buildings from different districts should be investigated, and the selection should be as randomized as possible. The sample of the 1990's cohort serve as a possible example of this error, as few buildings were sampled – perhaps as a result of the "wrong" district being investigated. Because of the very low correlation between the building size and Al density, it is of less importance if the sample is representative in terms of building sizes.

Results of the uncertainty analysis show that the largest error in this work is associated with the sampling; meaning that the difference in building samples is more prominent than the error in the aluminium calculations. This reflects that the building stock is very heterogenous and that a large sample is required. However, the calculated error is not more than 15% of the in-use stock estimate, and it can thus be concluded that the estimate is reliable.

4.2 In-Use Stock and Al Density Results

4.2.1 Comparison of Al Densities and In-Use Stock to Other Studies and Quantification of the In-Use Stock Error

To provide a basis for comparison, kg per capita is used as measure for in the in-use stocks. The calculated stock in non-residential buildings in Trondheim of 16.2 kg/cap is very low compared to the other studies referred in Table 9. In fact, it is one order of magnitude lower than the in-use stock reported for Europe, and although this estimate is for all sectors, it illustrate that the stock of this study is comparably small. The aluminium stock in Trondheim non-residential buildings is on level with those in China – a country that is very different from Norway in a number of ways, not least terms of economy – supporting the observation that the stock of this study is rather modest.

Table 9: Comparison of in-use aluminium stock determinations

Region/year	Method	Stock per capita (kg)	Description	Reference
CT, USA, 2000	Bottom-up	97.7	Commercial buildings	[1]
		11.3	Industrial buildings	
China, 2005	Bottom-up	11.5	Non-residential buildings	[2]
USA, 2003	Top-down	410.0	All sectors	[3]
Europe, 2003	Top-down	160.0	All sectors	[3]
World, 2010	Top-down	99	All sectors	[4]
Norway, 2010	Top-down	272.5	Building and construction	[5]
TRD, NOR, 2014	Bottom-up	11.0	Office and business buildings	This study
		16.2	Non-residential buildings	

[1]:[Recalde et al., 2008] [2]:[Wang and Graedel, 2010] [3]:[Hatayama et al., 2009] [4]: [IAI, 2011] [5]: [Liu and B.Müller, 2013]

The in-use stock per capita for Norway was calculated in a top-down study conducted by Liu and Müller (2013) for the entire building and construction sector, and is almost 17 times larger than the in-use stock of the NRBS, which arguably should contain 97% of the in-use aluminium stock [EAA-Delft, 2004]. If 33% of the stock is assumed to be within the building and construction sector, this would correspond to 90 kg/cap of the top-down estimate for Norway [IAI, 2014]. In comparison, the top-down study of US by Hatayama *et al.* (2009) is only 24% above the bottom-up value for Connecticut found by Recalde *et al.* (2008). However, the study of Liu and Müller focus on the evolution of the global in-use stock, and the numbers might be inaccurate on a country level. In addition, the definition of the building and construction sector involves infrastructure. This number is therefore assumed to be greatly exaggerated.

The per capita in-use stocks have two variables; floor area per capita and Al density. The magnitudes of the in-use stocks per capita do not reflect this nuance. A comparison of Al densities is therefore of interest whenever the application of aluminium is in question. An overview of Al densities from different studies is presented in Table 10.

Table 10: Al densities of different bottom-up studies

Region/year	Al density [kg/m^2]	Building category	Source	Reference
Japan, 2000	0.50	Residential	LCI calculations	[1]
Delft, NL, 2004	-		Field study	[2]
Tsinghua, China, 2006	3.73	Office building	Case study	[3]
Connecticut, 2000	0.50	Residential	Basis: [1],[2]	[4]
	4.00	Commercial		
	1.00	Industrial		
China, 2005	1.95	Urban non-residential	Basis: [1],[2], [3], other	[5]
Vienna, Austria	0.14 - 2.30		Field study	[6]
TRD,NOR 2009:	0.80	Non-residential	Field Study	[7]
TRD,NOR 2014:	0.11 - 1.06	Office and business	Field study	This study

[1]: [Nishioka et al., 2000] [2]: [EAA-Delft, 2004] [3]: [Recalde et al., 2008]
[4]: [Zhang et al., 2006] [5]: [Wang and Graedel, 2010] [6]: [Kleemannn, 2014]
[7]: [Sundelin, 2009]

The Al densities exhibit large differences between the studies. As emphasized in Section 1, the bases for choices of the Al densities in other bottom-up studies are somewhat unclear, and it seems unlikely that building age is regarded in other studies except that by Sundelin (2009).

Of the studies presented in Tables 9 and 10, conditions in Connecticut are most similar to Trondheim, both being developed countries in a semi-tempered climate. As no studies thus far have demonstrated a significant difference in Al use of commercial buildings in different countries [EAA-Delft, 2004], it is reasonable to believe that numbers for Connecticut and Trondheim should be similar. However, it is to expect that numbers for aluminium use in Norway are less than for US, as aluminium is more utilized in buildings in US than in Norway. Norway is a large producer of aluminium, but traditionally, wood has been – and continue to be – amongst the most important building materials. In other words, the difference can be explained largely in terms of architectural style and building tradition.

The numbers from TU Vienna are results from an ongoing project on "Evaluating the Material Composition of Buildings in Vienna" at Institute for Water Quality, Resource and Waste Management of the Vienna University of Technology. The project include field studies to investigate the complete inventory of selected buildings in Vienna. The approach is very thorough, including exterior and interior components of all sizes, and the results are very much in line with the numbers found in this study which lie between 0 and 2.39 kg Al/m^2 for individual buildings. Further results from this project might give a perspective on whether internal components are significant or not, and possibly shred some light on the reason for the differences in Al densities observed between the studies.

As discussed in Section 4.1, this study does not operate with a complete building inventory. Because of the obvious lack of information, it is challenging to establish a number for the underestimate caused by this. Recalde *et al.* (2008) use a 10 % underestimate to account for incomplete information on aluminium applications, the aluminium content and stock of components. The uncertainty analysis of this work (explained in Section 2.3.2) shows a 15% uncertainty that arises from calculation of components and variation in building stocks alone. In addition, minor applications are believed to constitute about 5% of the total aluminium stocks [Recalde et al., 2008]. In sum, an underestimate of 30% could apply. If this underestimate was applied to the results of this study, the in-use stocks of non-residential buildings in Trondheim would scale to 21.1 kg Al/m^2, and the results should therefore be considered as a lowest estimate.

The phrase "lowest estimate" can be viewed in terms of the definitions used for primary mineral reservoirs: "resource" is a legal description, and "reserve" is an economical description. A resource is in such a form and amount that it is considered potentially valuable to extract, while "reserves" is the part of the resource where extraction is economically and technically feasible [U.S. Geological Survey, 1980]. The estimated in-use stock of aluminium of this work is available and easily extractable and can therefore be considered a reserve.

4.2.2 Evaluation of the Contribution of Components to the Al Density and In-Use Stock

Of the in-use stock presented in Figure 11, both windows and curtain walls have a share of 41%, together constituting more than 80% of the stock. Closer inspection of the contribution from different window types presented in Table 6, reveal that the share of Al trim windows are negligible. Al clad windows are seen in Figure 13 to be somewhat unevenly distributed, but have a significant share of 10% of the in-use stock. A previous bottom-up study on the in-use Al stock in Trondheim [Sundelin, 2009] found that 76% of aluminium in windows was in the form of Al clad, a larger share than proved in this study. However, it is plausible that for the building stock as a whole, the Al trim and Al clad windows have a substantially larger share as these types to a greater extent are used in residential buildings. In this respect, the in-use stock is sensitive to changes in mass per window of these two types – a slight change in aluminium mass per component will have a great effect of the aluminium mass of the aggregated components.

The aluminium profile windows contribute to 31% of the in-use stock, exhibiting large individual variations in Al density per building. Because both aluminium profile windows and curtain walls are very Al intensive, the in-use stock is sensitive to changes in the number of these components. The correlation between curtain walls and other aluminium-containing building applications are generally low, indicating that the use of curtain walls are disconnected from other considerations.

Solar shading, doors and HVAC make up the rest of the inventory and together they make up 18% of the in-use stock. As can be seen in Figure 16, solar shading has a somewhat uneven distribution on individual buildings. The large correlation with the other components, especially with windows and curtain walls, suggests that buildings with low amounts of Al components have low amounts of blinds and vice versa – in this sense it can serve as an indicator for aluminium repositories. The contribution of doors to the in-use stock and Al area density are rather insignificant. In terms of the the low number of HVACs (depending on the building size, usually one per building, if any) this category constitute a rather substantial 2% of the in-use stock. Although a small share of the total stock, it consists entirely of rolled products, and in terms of recycling it should not be disregarded.

4.3 Analysis of the Application of Aluminium in Buildings

4.3.1 Correlation of Components and Building Size with Al Density

The aluminium content in buildings is very diverse, and calculations on correlation were conducted in order to verify or disprove the hypothesis that if Al is present in one building component, there is a higher probability of finding other components of Al. The result of the correlation calculations are displayed in Table 8, and the generally low correlation values suggest that aluminium components are distributed on many buildings rather than gathered in a few, selected buildings. The low correlation value between building size and Al density, displayed in Figure 15, also emphasizes that the employment of aluminum in buildings seems more or less random. Still, the correlation value could be analyzed in more detail. In the case of windows and curtain walls, a negative correlation in numbers (regardless of material) could be expected, as curtain walls and windows provide the same services – bringing daylight to the occupants while providing protection against the outside climate. Interestingly, the negative correlation between aluminium windows and curtain walls was not found, implying that the use of aluminium in these components correlate to such an extent that it compensate for the expected negative number correlation – i.e. if curtain walls of aluminium are used, chances are that aluminium features in window frames and vice versa.

4.3.2 Drivers of Al Use in Buildings - A Brief Analysis of Aluminium Penetration in Terms of Building Type-Cohorts and Historic Construction Activity

This section will focus on the question of what motivates use of aluminium in non-residential buildings, and the following discussion is based on observations and results of the O&B buildings. Potential factors that influence the demand for aluminium are: (i) the general economical situation in society, (ii) architectural motivations (iii) new technology and solutions (e.g. thermal breaks), and (iv) government incentives or regulations. The calculations of correlation in Section 3.3 established that aluminium use, in terms of Al density, is largely detached from building size. The building sector is closely influenced by the economic development [Wells, 1985][Veidekke, 2014]. Although the aluminium use can be seen as independent on building sizes, and of the building stock as such, it is interesting to view the evolution of Al density in light of the historic construction activity because the historic construction activity serve as an indication of the overall willingness and ability to invest in buildings. In other words, comparison to the construction activity will provide indications of the role of economic growth as a driver for aluminium use in non-residential buildings.

Pre 1960: Aluminium was first introduced in buildings in Trondheim in the 1960's [Riis Glass og Metall, 2014b], but results from the field study prove that it penetrate in pre-1960 buildings. Aluminium can be introduced in older buildings either through building additions and extensions of a newer date, or through replacement of components in the original building. According to Figure 13, retrofitted solar shading, doors and HVAC (not distinguished in the figure) together maintain the largest contributions to the aluminium stock of the pre-1945 buildings, with Al clad windows as second largest. Observations in the field study revealed Al clad skylight windows, as seen in Figure 17, to be a common way of introducing aluminium. Curtain walls and storefront systems are also observed in older buildings. Usually these components are parts of modern extension, like the building in Figure 17 (left) illustrate.

Figure 17: An original 1904 building with curtain walls as an extension connecting it to the neighbouring building (left) and old skylight windows in an original 1830 building (right)

The observations from the field study show that the implementation of Al components transcends the construction year of buildings – original building components are readily exchanged while the building structure is preserved. The reason might be that components have shorter lifetimes than the building structure, and/or that the Al components provide better services than components of other material would. Unfortunately, the age of components could not be assessed in this study. Differences in design of components of different ages are minute, and takes an expert eye to identify [Riis Glass og Metall, 2014b]. The complexity of the problem in determining component lifetime is illustrated in Figure 5, showing one building with three different window sets of different types and ages. Lifetimes of aluminium building components are generally reported to be 35-70 years [McMillan et al., 2010], but this depends on trends for refurbishments and the rate of technology development (e.g. older windows are replaced by windows with thermal break) rather than the technical lifetime itself (i.e. how long the producer say it will last).

Generally, Al densities of the pre-1960 cohorts are very low, as seen in Figure 14. In fact, 81% of the samples in the pre-1899 cohort has Al densities lower than 10 percent of the observed maximum value of 2.39 kg/m^2. This illustrate that components are retrofitted only to a limited degree.

Post 1960: The low correlation of building size and Al density is supported by the Al densities of the 1960's and 1970's: Despite having the same amount of gross internal floor area (seen in Figure 10) and the same average building size of just about 3000 m^2 (from Table 4), the mean Al density of the 60's is 50% higher than that of the 70's. The difference can be assigned to architectural trends, or it could be that the novelty value of aluminium in building components wore off, but this will only be speculations without deeper knowledge on these subjects.

Building stock statistics show that the floor area stock increase during the 1980's, in accordance with an economic boom. There is an apparent correlation between the development in building stock area, economic boom and Al density - the Al density is seen in Figure 14 to increase in all subcategories of O&B.However, the Al density of both U&C buildings and O&B buildings peak at record high in the 1990's, coinciding with the economic depression that occurred during this period [NOU, 2000]. It is interesting to note that aluminium intensive curtain walls had the highest shares in this period – an indication that architectural motives are driving the observed development, detached from economic considerations.

In terms of implementation of new technology and solutions, it is clear that this has an influence on the Al use. Window Al cladding were introduced in the end of the 1980's [Riis Glass og Metall, 2014b], and indications of this can be seen in Figure 13 in the form of high shares of the Al density in this decade. Aluminium cladding serve as an illustration of new solutions that have a direct effect on the aluminium demand – Al clad windows are less aluminium intensive, and take a market share from Al profile windows because they offer the same services [Riis

Glass og Metall, 2014b]. The result of this isolated case is a decrease in Al density.

It is now in its place to address the significance of governmental regulations on the aluminium use in non-residential buildings. A report on energy efficiency state that 20% of the Norwegian energy consumption can be saved by upgrading to and investing in modern technology, the largest potential savings being within the building stock [Bellona and Siemens, 2007]. Actions for improving energy efficiency in buildings include replacing windows and doors with a lower U-value (better insulating properties). However, critics claim that Norwegian legislation on energy efficiency in buildings is too liberal, and that it is generally not followed by the construction industry [Bellona and Siemens, 2008]. From this it can be deduced that the largest impact of such regulations has yet to be seen in Norway. Reports point at the role of aluminium as a key part in the construction of sustainable, energy-efficient buildings [EAA, ndb]. It is probable that an increase in Al density will result as focus is shifted to energy-efficient buildings and stronger regulations demand the replacements of doors and windows by those of lower U-values, amongst other actions.

As expected, the use of aluminium in buildings is not easy to characterized in any rigorous way. This analysis suggests that it is not exclusively economical growth that are driving the use of Al in buildings, but that the development must be seen in a larger picture, including aspects like retrofitting, architectural trends, development of new technology and solutions and governmental regulations.

4.4 Implications and Policy Relevance

The in-use aluminium stock contained in all non-residential buildings in Trondheim was found to be 16.2 kg Al/cap as a lowest estimate. Hypothetically, if the entire stock were to exit the use phase within the next 30 years, this would result in an average annual output flow of 0.5 kg Al/cap. In comparison, the apparent aluminium consumption in Norway for the year 2010 was reported to be 8.7 kg/cap, and the old scrap generation was reported to be 13.4 kg/cap [EAA, nda]. In the outlined scenario, the output flow from non-residential buildings corresponds to just about 4% of the reported old scrap generation. This serves to illustrate that the current in-use stock of 16.2 kg/cap is small compared to overall aluminium flows. The comparisons of per-capita aluminium stocks as described in Section 4.2.1 also demonstrated the large differences in stocks of this study to the stocks of other regions – e.g. stocks in Connecticut being tenfold larger than those estimated for Trondheim. There is reason to believe that the per-capita aluminium in-use stock in other sectors does not exhibit such large, regional variations as does the aluminium stock in buildings, i.e. that the stock in buildings is less significant in Trondheim than in other regions. Without more detailed knowledge, however, this is not straightforward to assess.

In general, building applications of aluminium are of newer date in Norway, and if lifetime is taken as 30-75 years [McMillan et al., 2010], most aluminium contained in buildings have not exited the use phase yet. When the majority of the first generations of aluminium components reach the end-of-life, the outputs from the building sector will be much more significant than it is at the moment. A dynamic material flow analysis (MFA) should be applied to forecast long-term trends, but an MFA snapshot like the one provided in this study gives valuable insight in the current state of the stock, and allows for assumptions on future scrap flows to be made.

From the results of this study, it is clear that the largest repositories of aluminium are found within O&B buildings constructed in the 1980's and U&C buildings constructed in the 1990's. This aluminium can be expected to exit the use phase within the next 40 years, depending on the lifetime of components. The better part of this will be in the form of extruded aluminium from windows and curtain walls. In terms of Al density, the 1990's cohort is the most significant for both building types. In order to produce 1 ton of aluminium scrap, 950 square meters of a 1990's O&B building must be demolished. This equals one-quarter of a building of this cohort, on average. Compared to the cohort with the lowest Al density, the pre-1899 cohort, 9100 square meters must be demolished to produce the same amount of aluminium scrap, equal to a little more than 8 buildings of this cohort on average. This is an illustrative example of how the scrap flows are expected to increase.

Changes in Al density can be expected whenever a new generation of technology is applied, or governmental incentives and regulations enforce upgrading of the building stock. It is reasonable to assume that buildings of newer date employ higher standards in terms of energy efficiency, and that such regulations will have the largest effect on pre-1980 buildings. As modern aluminium components are high-tech and e.g. are incorporated in passive houses [EAA, ndb], it gives reason to believe they will replace a share of old, non-aluminium components. If so, stronger governmental regulations will first and foremost have the effect of increasing the Al density of the building stock.

The fact that only a fraction of the produced aluminium in building components has returned as scrap illustrates the need for government and industry to prepare for larger quanta of Al scrap in the future. Both infrastructure, waste processing facilities and recycling plants should be scaled to handle future waste flows. Today, recycled aluminium is used for a limited number of alloys and applications, mainly in the automotive industry [Løvik et al., 2014]. In order to prevent scrap from accumulating in the automotive industry and result in a future scrap surplus, closed-loop recycling of building components is a solution. Closed-loop recycling is feasible for building components; this study shows that a few alloys make up the largest fraction of the total stock – extruded 6xxx alloys from doors, windows and curtain walls, for the most parts [Allwood and Cullen, 2012], with a minor fraction of rolled products like 8xxx alloy in heat exchanger that need to be separated. For future closed-loop recycling to be feasible, equipment, technology and infrastructure are required.

The goal of this work was to contribute to an enhanced understanding of aluminium use in the building stock, and provide decision makers with the information needed to optimize the recycling effort. Hopefully, it is a small step in the direction of making production and development more sustainable. About one-third of the aluminium produced in the world is now obtained from secondary sources, and the future metal supplies are expected – and required, from the environmental point of view – to have much higher shares of recycled aluminium. If the right means are implemented, most of the aluminium in the buildings that surround us today will re-emerge as new, service-providing goods for generations to come.

References

[Allwood and Cullen, 2012] Allwood, J. M. and Cullen, J. M. (2012). *Sustainable Materials - With Both Eyes Open.* UIT Cambridge Ltd.

[Bellona and Siemens, 2007] Bellona and Siemens (2007). The Bellona Foundation and Siemens AS. report. *Energieffektivisering* [Energy Efficiency Improvement]. Available in Norwegian at https://w3.siemens.no/home/no/no/campaign/Energieffektivisering/ Documents/Energieffektiviseringsrapp[accessed June 2014].

[Bellona and Siemens, 2008] Bellona and Siemens (2008). The Bellona Foundation and Siemens AS. report. *Barrierestudiet* [The Barrier Study]. Available in Norwegian at http://www.bellona.no/filearchive/fil_Barrierestudie.pdf [accessed June 2014].

[Building Design, 2008] Building Design (2008). Schüco curtain walling. Available at http://www.bdonline.co.uk/schüco-curtain-walling/3108865.article [accessed June 2014].

[Carson, 1962] Carson, R. L. (1962). *Silent Spring.* Houghton Mifflin, Boston.

[Cullen and Allwood, 2013] Cullen, J. M. and Allwood, J. M. (2013). Mapping the global flow of aluminum: From liquid aluminum to end-use goods. *Environmental Science & Technology*, 47:3057–3064.

[Davis, 1993] Davis, J., editor (1993). *Aluminium and Aluminium Alloys.* ASM International, 2nd edition.

[EAA, 2011] EAA (2011). European Aluminium Association. publication: Activity report 2011. Available at http://www.alueurope.eu/wp-content/uploads/2012/03/EAA-Activity-Report-2011-HI-RES_V1_FINAL.pdf [accessed June 2014].

[EAA, nda] EAA (n.d.a). European Aluminium Association. publication: Aluminium use in europe – country profiles 2007-2010. Available at http://www.alueurope.eu/pdf/Aluminium_use___in_Europe_by_country.pdf [accessed June 2014].

[EAA, ndb] EAA (n.d.b). European Aluminium Association. publication. sustainability of aluminium in buildings. Available at http://www.alueurope.eu/publications-building/ [accessed June 2014].

[EAA-Delft, 2004] EAA-Delft (2004). European Aluminium Association and Delft University of Technology. Collection of aluminium from buildings in Europe. Available at: http://greenbuilding.world-aluminium.org/uploads/media/1256563698Delft_Brochure_and_TU_Delft_Report.pdf [accessed June 2014].

[Hatayama et al., 2009] Hatayama, H., Daigo, I., Matsuno, Y., and Adachi, Y. (2009). Assessment of the recycling potential of aluminum in japan, the united states, europe and china. *Materials transactions*, 50(3):650–656.

[Hunter Douglas, 2014] Hunter Douglas (2014). March 2014. Personal Communication: Company Representative Odd Stensbøl.

[Hydro, 2012] Hydro (2012). Hydro Aluminium Rolled Products. Inspection Certificate. RMH 106422-1. Unpublished.

[IAI, 2009] IAI (2009). International Aluminium Institute. Publication. Global Aluminum Recycling: A Cornerstone of Sustainable Development. Available at http://www.world-aluminium.org/publications/#846 [accessed June 2014].

[IAI, 2011] IAI (2011). International Aluminium Institute. Publication. Global Aluminium Industry Sustainability Performance 2010. Available at http://www.world-aluminium.org/media/filer_public/2013/01/15/2011_-_for_iai_website.pdf [accessed June 2014].

[IAI, 2014] IAI (2014). International Aluminium Institute. Publication. Global Mass Flow Model - 2012 (2014). Available at http://www.world-aluminium.org/publications/#846 [accessed June 2014].

[IPCC, 2013] IPCC (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom.

[Jan van Houwelingen, 2004] Jan van Houwelingen, Udo Boin, M. R. (2004). Aluminium in Buildings – inventory and collection during demolition. In *International RILEM Conference on the Use of Recycled Materials in Buildings and*

Structures, volume 1, pages 193–200.

[Kartverket, 2014a] Kartverket (2014a). *Føringsinstruks for matrikkelen* (Instructions for cadastre keeping). Available at http://www.statkart.no/Eiendom-og-areal/Matrikkelen/veiledning-for-lokal-matrikkelmyndighet/foringsinstruks-for-matrikkelen/ [accessed May 2014].

[Kartverket, 2014b] Kartverket (2014b). *Kurs i matrikkelføring - Den norske eiendomsregistreringens historie* (History of the Norwegian cadastre). Available at http://kartverket.no/Documents/Matrikkel/kurs/forkurs/pdf/2-Den-norske-eiendomsregistrerings-historie-v1-2.pdf [accessed May 2014].

[Kleemannn, 2014] Kleemannn, F. (2014). March 2041. Personal Communication: PhD cand. Fritz Kleemann of Vienna University of Technology.

[Klingenburg GmbH, 2007] Klingenburg GmbH (2007). Regenerative heat recovery with rotary heat exchangers. Available at http://www.klingenburg.de/en/pdf/RWT_K01E.pdf [accessed May 2014].

[Lane, 1992] Lane, J. (1992). *Aluminium in Buildings.* Ashgate.

[Lian Trevarefabrikk, 2014] Lian Trevarefabrikk (2014). Homepage. Available at http://www.lian.no/ [accessed June 2014].

[Liu, 2014] Liu, G. (2014). May 2014. Personal Communication: PhD cand. Gang Liu of the Norwegian University of Science and Technology.

[Liu and B.Müller, 2013] Liu, G. and B.Müller, D. (2013). Centennial Evolution of Aluminium In-Use Stocks on Our Aluminized Planet. *Environmental Science & Technology*, 47(9).

[Løvik et al., 2014] Løvik, A. N., Modaresi, R., and Müller, D. B. (2014). Long-Term Strategies for Increased Recycling of Automotive Aluminium and its Alloying Elements. *Environmental Science & Technology.*

[McMillan et al., 2010] McMillan, C. A., Moore, M. R., Keoleian, G. A., and Bulkley, J. W. (2010). Quantifying u.s. aluminum in-use stocks and their relationship with economic output. *Ecological Economics*, 69(12):2606 – 2613.

[MesterVindu, 2014] MesterVindu (2014). Aluminiumsbekledning. Available at http://mestervindu.no/tilbehor/aluminiumsbekledning/ [accessed June 2014].

[Navidi, 2008] Navidi, W. (2008). *Statistics for Engineers and Scientists*. McGraw-Hill, second edition edition.

[Nishioka et al., 2000] Nishioka, Y., Yanagisawa, Y., and Spengler, J. D. (2000). Saving enegy versus saving materials - life-cycle inventory analysis of housing in a cold-climate region of japan. *Journal of Industrial Ecology*, 4(1).

[NorDan, 2014] NorDan (2014). April 2014. Personal Communication: Company Representative Arnt Ove Surdal.

[Norfo, 2014] Norfo (2014). Aluminiumsdører. Available at http://www.norfo.no/produkter/dorer/spesialdorer/aluminiumsdorer/ [accessed June 2014].

[Norske Metallfasader, 2014] Norske Metallfasader (2014). Automatiske dører. Available at http://metallfasader.no/produkter/automatiske_d_rer/ [accessed June 2014].

[NOU, 2000] NOU (2000). Norwegian Ministry of Finance: *En strategi for sysselsetting og verdiskaping* (A strategy on employment and value creation). *Norsk Offentlig Utredning (NOU) 2000:21* (Official Norwegian Report 2000:21). Available at: http://www.regjeringen.no/nb/dep/fin/dok/nouer/.

[Recalde et al., 2008] Recalde, K., Wang, J., and Graedel, T. (2008). Aluminium in-use stocks in the state of Connecticut. *Resources, Conservation and Recycling*, 52(11):1271 – 1282.

[Riis Glass og Metall, 2014a] Riis Glass og Metall (2014a). March 2014. Personal Communication: Company Representative Jan Erik Langø.

[Riis Glass og Metall, 2014b] Riis Glass og Metall (2014b). March 2014. Personal Communication: Company Representative Tore Staverløkk.

[Schlesinger, 2006] Schlesinger, M. E. (2006). *Aluminium Recycling*. CRC Press.

[Schüco, 2012] Schüco (2012). Press Release. Schüco Window AWS 90.SI+. Available at http://www.schueco.com/web/in/company/press/produkte/aluminium/AWS_90 [accessed June 2014].

[Schüco, 2014] Schüco (2014). March 2014. Personal Communication: Company Representative Samim Azimi.

[Skanaluminium, 1972] Skanaluminium (1972). Skandinavisk Organ for Aluminiumindustrien. *Aluminium i bygg - Skandinavia 1973* (aluminium in buildings - scandinavia 1973). Ingeniørforlaget.

[Sundelin, 2009] Sundelin, K. E. (2009). Aluminium recycling of the norwegian building stock system. Master's thesis, NTNU - Norwegian University of Science and Technology.

[Systemair Norge, 2014a] Systemair Norge (2014a). April 2014. Personal Communication: Company Representative Øystein Amdal.

[Systemair Norge, 2014b] Systemair Norge (2014b). March 2014. Personal Communication: Company Representative Sturla Ingebrigtsen.

[Tellnes, 2014a] Tellnes, L. G. F. (2014a). NorDan NTech Fixed window 105. Technical Report NEPD 00245E, The Norwegian EPD Foundation.

[Tellnes, 2014b] Tellnes, L. G. F. (2014b). NorDan NTech Inward opening tilt & turn window 105/80. Technical Report NEPD 00176E Rev.1, The Norwegian EPD Foundation.

[U.S. Geological Survey, 1980] U.S. Geological Survey (1980). USGS Circular: 831. Principles of a Resource/Reserve Classification For Minerals. Available at http://pubs.usgs.gov/circ/1980/0831/report.pdf [accessed June 2014].

[Veidekke, 2014] Veidekke (2014). Veidekke's Economic Activity Report: Growth outlook for building and construction. Available at http://en.veidekke.com/news-and-media/press-room/article87792.ece [accessed June 2014].

[Wang and Graedel, 2010] Wang, J. and Graedel, T. E. (2010). Aluminium in-use stocks in China: a bottom-up study. *Journal of Material Cycles and Waste Management*.

[WCED, 1987] WCED (1987). United Nations World Commission on Environment and Development. Report. Our Common future. Available at http://www.un-documents.net/our-common-future.pdf [accessed June 2014].

[Wells, 1985] Wells, J. (1985). The role of construction in economic growth and development. *Habitat International*, 9(1):55 – 70.

[Zhang et al., 2006] Zhang, Z., Wu, X., Yang, X., and Zhu, Y. (2006). Bepas—a life cycle building environmental performance assessment model. *Building and Environment*, 41(5):669 – 675.

Appendices

A Calculations of the Al Content of Components

Table 11 display the parameters used for calculations of the window aluminium content, and Table 12 include the complete set of formulas used for calculating the aluminium content in the building components investigated in the field study.

Table 11: Parameters used for calculations of window aluminium content

Parameter	Value [kg/m]	Source
Aluminium density ρ_{Al}	2.70 g/cm^3	
Alu-trim windows		
Trim profile W_{tr}	0.21	Physical sample
Top board W_{tp}	0.33	Physical sample
Bottom board W_{tp}	0.57	Physical sample
Alu-clad windows		
Fixed profiles	0.243	Technical drawings
Openable profiles	0.445	Technical drawings
Alu-framed windows		
Fixed profiles W_{fi}	3.50	Weight of profile supplied by producer
Openable profiles W_{op}	1.86	Weight of profile supplied by producer

Table 12: Formulas for calculations of the aluminium mass, M_c, of the respective components c. Variables highlighted in red denotes measured or estimated values, while blue denotes fixed parameters.

Component	M_c	Variables and Parameters
Doors		d_1, d_2 - Door frame height and width
Plated	$W_d(2d_1 + 2d_2) + 4\rho_{Al}\, p_1\, p_2\, p_3$	W_d - Door profile [kg/m]
Half-glazed	$W_d(2d_1 + 2d_2) + 2\rho_{Al}\, p_1\, p_2\, p_3$	ρ_{Al} - Density of aluminium
Glazed	$W_d(2d_1 + 2d_2)$	p_1, p_2, p_3 - thickness, height and
		width of aluminium plate
Alu-trim windows		a_1, a_2 - Window frame height and width
	$W_{tr}(2a_1 + 2a_2) + a_2(W_{tp} + W_{bt})$	W_{tr} - Trim profile [kg/m]
Alu-clad windows		W_{tp}, W_{bt} - Top and bottom board [kg/m]
Fixed	$\rho_{Al}\, t_1\, t_2\, (2a_1 + 2a_2)$	t_1, t_2 - thickness, depth of fixed alu-clad
Openable	$\rho_{Al}\, d_1\, d_2\, (2a_1 + 2a_2)$	d_1, d_2 - thickness, depth of opeable alu-clad
Alu-framed windows		W_{fi} - Fixed profiles [kg/m]
Fixed	$W_{fi}(2a_1 + 2a_2)$	W_{op} - Openable profiles [kg/m]
Openable	$W_{op}(2a_1 + 2a_2)$	C- Factor correcting for material shared
Curtain walls		between adjacent frames
	$C(2a_1 W_{vr} + 2a_2 W_{hz})$	W_{vr} - Vertical curtain wall profiles [kg/m]
		W_{hz} - Horizontal curtain wall profiles [kg/m]
Solar shading		$\bar{M}_{sc}$ - Blinds - mean of three weight classes
	$(\bar{M}_{sc}\, /\, s_1\, s_2) \times b_1\, b_2$	s_1, s_2 - Height and width of blinds
		b_1, b_2 - Blind height and width

B The Cadastre: Data Processing Steps

As explained in Section 2.2.4, the values for $Z_{t,h}$ in Equation 1 were acquired through a number of data processing steps that were conducted to ensure that only existing buildings and relevant information were included.

Cadastre data were provided in the form of spreadsheets that amongst other included the following information: Building ID, construction/demolition date, building status, building type, gross internal floor area of residential sections, gross internal floor area of non-residential sections, building modification and address. All residential buildings and buildings with invalid statuses (e.g. demolished buildings) were removed prior to the data processing. After filtering to remove all duplicate entries, the resulting list only included relevant buildings. For Trondheim, 50% of all buildings lack a construction date, and 15% lack information on floor area. It is assumed that all these buildings dates from before the Cadastre was established in 1983.

For buildings with unknown construction date, data processing was done by taking the number of buildings in the "pre-Cadastre" cohorts 1899-1979 as 100%, and calculating the fractions that the individual cohorts hold. The buildings with unknown date were then distributed on the pre-Cadastre cohorts in amounts that correspond to the fraction that the cohort in question was found to constitute. This is perhaps best illustrated by an example: the sum of buildings of I&S from 1899-1979 is 356 buildings. 12 buildings are registered in the pre-1899 cohort, constituting 3.37% of the building stock of the pre-Cadastre years. 1811 buildings are registered without a building date, and 3.37% of this equals 61 buildings. Thus, 61 buildings are re-distributed to the pre-1899 cohort, yielding a total of 73 buildings.

For buildings with unknown floor area, the following procedure were conducted. An estimate for the total floor area for Trondheim were made based on existing information. Buildings lacking both floor area and building date were distributed on the pre-Cadastre cohorts based on already existing numbers for 1899-1979 (as described in the paragraph above). An estimate for the average area per building for each cohort was found by taking the number of buildings with an area entry and divide the total area on this number. The average floor area per building for each cohort were multiplied by the number of buildings with unknown floor area within each cohort. the sum of the assigned floor area and the known floor area make up the total stock of floor area, $Z_{t,h}$ within each cohort. The results are displayed in Table 13

Table 13: Cumulative floor area [1000 m^2] of non-residential buildings in Trondheim

Cohort, Bld.categ.	**>1899**	**1900-1945**	**1946-1959**	**1960-1969**	**1970-1979**	**1980-1989**	**1990-1999**	**2000-2009**	**2010<**
I&S	23	192	336	509	651	214	194	297	66
O&B	249	232	140	428	423	429	227	398	350
I&C	5	2	25	9	74	65	7	137	34
H&R	87	20	14	4	13	34	25	40	52
ECR	87	261	35	191	132	158	189	251	92
H	24	2	0	5	0	2	1	19	4
P&R	0	5	0	11	0	2	0	16	4

It is only an assumption that all buildings with unknown date entries date from the pre-Cadastre years, and that these buildings should be distributed according to the size of the cohorts. Therefore, it is not granted that the resulting model is a representative one. Regarding the buildings lacking area, it is a possibility that a large fraction of these are small (insignificant) buildings, and that the calculated average floor area per building is too large for this reason.

C Field Study Data

The data acquired though the field study is displayed in tables 14 and 15 for the office and business buildings, and in table 16 for the university and college buildings. Abbreviations: Bld No:building Number, Year of constr:year of construction, Plt: plated, Hf-glz: half- glazed, Glz: glazed, Sld: Sliding, S: small, M: medium, L: large, FS: fixed small, FM:fixed medium, FL:fixed large, OS:openable small, OM:openable medium, OL:openable large, F: curtain wall correcting factor. Number entries indicate number of components, except F.

Table 14: Data from the field study – Office and business buildings

Bld No	Year of constr.	Cate-gory	Area	Doors Plt	Hf-glz	Glz	Sld	Alu trim S	M	L	Alu clad windows FS	FM	FL	OS	OM	OL	Alu profile windows FS	FM	FL	OS	OM	OL	Curtain walls S	M	L	*F*	Solar sh S	M	L	HVAC	Al dens
1	1733	319	805	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.00
2	1740	329	2328	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.00
3	1772	319	745	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.00
4	1807	329	73	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.00
5	1814	329	812	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.00
6	1830	319	672	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.05
7	1840	319	1000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.00
8	1841	319	1725	1	1	0	2	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	1	0	0	0	1	0.14
9	1841	322	1154	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	5	0	0	0	0	0	0	1	0	0	0	0	0.14
10	1841	322	451	0	0	3	0	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0.22
11	1841	322	385	0	0	2	0	15	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0.20
12	1844	319	869	0	0	2	0	0	0	0	0	0	0	6	3	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0.12
13	1847	319	243	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.00
14	1852	319	2672	0	0	4	0	0	0	0	0	0	24	12	0	0	0	0	1	0	0	0	0	2	0	1	0	2	0	1	0.16
15	1852	319	1890	0	1	2	0	0	0	0	0	0	0	12	21	0	0	0	0	0	0	0	2	16	0	1.3	0	0	0	1	0.34
16	1857	322	2130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.00
17	1857	322	1683	0	0	1	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	1	0	0	0	0	0.03
18	1872	329	680	0	0	3	2	0	0	0	0	0	0	0	19	0	0	4	0	0	0	0	0	0	0	1	0	0	0	1	0.54
19	1882	319	7135	0	0	0	0	0	0	0	11	34	0	0	0	0	7	14	0	0	0	0	2	21	43	1.3	0	0	0	0	0.26
20	1895	329	492	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.06
21	1897	329	285	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.00
22	1900	319	820	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.00
23	1902	329	3561	0	0	0	0	0	0	0	0	0	0	6	2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0.04
24	1903	322	1142	0	2	2	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.12
25	1904	329	675	0	0	1	0	60	0	0	0	0	0	0	0	0	0	1	0	0	0	0	29	31	0	1.3	0	0	0	1	1.55
26	1906	311	972	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.05
27	1921	311	2249	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0.07
28	1940	319	33434	2	8	9	12	0	0	0	120	254	0	244	0	0	585	61	0	205	9	0	62	34	0	1.3	74	159	8	3	0.42
29	1955	311	1968	0	4	3	0	0	0	0	0	0	0	0	0	0	15	195	0	0	71	0	0	0	0	1	0	41	0	1	2.10
30	1955	322	1412	0	0	0	2	7	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	1	0.11
31	1959	322	7863	0	1	1	2	0	0	0	4	0	0	78	5	0	5	12	0	0	4	0	0	0	0	1	75	1	0	0	0.13
32	1961	311	854	0	0	4	0	0	0	0	0	0	0	0	0	0	4	12	0	0	17	0	0	0	0	1	0	0	0	0	0.70
33	1962	329	4490	0	2	2	2	0	0	0	4	0	0	0	0	0	7	38	0	1	59	0	0	0	0	1	0	71	0	0	0.50
34	1962	322	3880	0	2	2	0	0	0	0	20	5	0	1	0	0	67	22	0	1	0	0	0	0	0	1	50	5	0	1	0.33
35	1962	322	9558	0	0	4	4	0	0	0	14	2	0	8	0	0	0	0	0	0	0	0	8	31	31	1.3	0	0	0	1	0.19
36	1964	329	292	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0.43
37	1964	322	3388	0	1	2	2	0	0	0	0	10	0	5	0	0	27	28	0	8	0	0	22	6	0	1.3	0	0	0	1	0.37
38	1965	329	5949	0	0	12	0	0	0	0	0	6	0	0	0	0	0	132	0	129	0	0	129	166	0	1	0	0	0	1	1.34
39	1965	329	5389	0	2	2	0	0	0	0	0	0	0	0	0	0	617	120	0	45	0	0	164	0	0	1.3	0	15	83	1	1.81
40	1965	319	440	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.00

Table 15: Data from the field study – Office and business buildings continued

Bld	Year of	Cate-	Area	Doors				Alu trim			Alu clad windows						Alu profile windows						Curtain walls				Solar sh			HVAC	Al dens
No	constr.	gory		Plt	Hf-glz	Glz	Sld	S	M	L	FS	FM	FL	OS	OM	OL	FS	FM	FL	OS	OM	OL	S	M	L	*F*	S	M	L		
41	1966	319	2892	0	0	2	0	0	0	0	118	57	0	311	1	0	0	0	0	0	0	0	5	25	0	1.3	0	0	0	1	0.82
42	1967	311	1420	0	0	3	0	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	56	0	0	0	0.23
43	1967	319	1716	0	1	1	0	0	0	0	0	0	0	0	0	0	135	0	2	15	0	0	0	0	0	1	0	0	0	1	0.82
44	1968	319	2094	0	0	4	0	0	0	0	0	0	0	0	0	0	9	54	1	13	23	0	0	24	3	1	0	1	21	0	1.02
45	1969	319	1320	0	0	2	0	0	0	0	0	0	0	0	0	0	65	51	0	0	17	0	0	0	0	1	0	0	0	1	1.14
46	1969	329	1750	0	0	2	0	0	0	0	0	0	0	0	0	0	55	8	9	11	2	0	0	20	15	1.3	0	0	0	1	0.99
47	1971	322	2089	0	0	1	4	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	4	3	1	0	0	0	1	0.18
48	1972	321	4910	0	0	9	4	0	0	0	23	1	0	5	1	0	69	77	0	15	0	0	42	42	0	1	1	20	8	0	0.69
49	1973	329	303	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.02
50	1973	329	1757	0	0	2	0	0	0	0	38	48	0	25	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0.28
51	1975	319	595	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.00
52	1977	329	3418	0	0	6	0	0	0	0	0	0	0	0	0	0	83	4	0	0	81	0	0	0	0	1	0	81	0	0	0.86
53	1977	319	11130	0	3	8	4	0	0	0	84	0	0	70	0	0	1	14	0	0	0	0	35	34	9	1	62	0	0	1	0.24
54	1977	322	2678	1	1	0	6	0	0	0	0	16	0	0	0	0	0	0	0	0	0	0	0	60	6	1.3	0	0	0	1	0.56
55	1978	322	9843	0	0	6	6	0	0	0	12	104	0	0	0	0	4	22	21	0	0	0	23	5	54	1.3	0	21	0	1	0.34
56	1979	319	12231	0	0	8	2	0	0	0	0	0	0	0	0	0	84	50	0	46	0	0	206	600	0	1.3	110	62	0	2	1.28
57	1980	329	3137	0	0	2	0	0	0	0	59	21	0	140	0	0	26	8	0	0	0	0	0	0	0	1	84	0	4	1	0.51
58	1981	329	754	0	0	2	0	0	0	0	0	0	0	0	0	0	73	1	0	21	4	0	0	0	0	1	0	0	0	0	1.31
59	1982	319	3284	0	0	7	0	0	0	0	71	58	0	75	53	0	0	0	0	0	0	0	6	24	0	1.3	0	0	0	0	0.49
60	1986	329	3654	0	7	1	0	356	0	0	154	19	0	46	0	0	0	0	0	0	0	0	0	0	0	1	22	81	0	3	0.55
61	1987	319	1580	0	0	1	0	0	0	0	307	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5	7	0	2	0.65
62	1988	329	4000	2	0	2	1	0	0	0	169	0	0	57	0	0	0	0	0	0	0	0	0	0	0	1	4	32	0	1	0.28
63	1989	329	1870	0	0	5	0	123	0	0	0	0	0	0	0	0	0	8	0	0	0	0	13	54	0	1	18	32	0	1	0.94
64	1989	329	4555	0	0	5	0	0	0	0	0	0	0	0	0	0	22	24	0	48	12	0	265	174	8	1.3	0	72	0	2	1.85
65	1989	319	787	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3	0	1	0.25
66	1991	319	72	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.13
67	1994	329	1130	0	0	2	1	0	0	0	0	0	0	0	0	0	4	8	0	2	4	0	25	38	28	1.3	0	0	0	1	1.84
68	1995	329	1405	1	0	1	4	0	0	0	0	0	0	4	2	0	13	17	0	0	0	0	10	12	0	1.3	0	0	0	0	0.55
69	1997	319	16236	0	1	16	4	0	0	0	85	123	0	148	301	0	46	40	0	0	0	0	9	92	5	1.3	20	217	18	2	0.48
70	1998	322	1130	0	0	0	4	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	93	0	1.3	0	0	0	1	1.58
71	2000	311	27159	0	0	1	4	0	0	0	0	33	0	99	0	0	8	13	5	0	5	0	0	0	0	1	27	57	0	0	0.05
72	2001	329	7747	0	0	16	2	0	0	0	0	0	0	0	0	0	8	36	0	0	2	0	21	280	2	1.3	0	158	0	1	0.92
73	2001	319	3875	0	0	6	0	0	0	0	32	125	0	92	45	0	0	2	0	0	0	0	0	0	6	1.3	0	0	0	1	0.40
74	2002	319	22563	1	0	26	2	0	0	0	0	0	0	0	0	0	1053	1222	0	583	52	0	360	400	10	1	1587.5	1232.5	0	2	2.52
75	2003	319	10830	0	0	7	3	0	0	0	86	0	0	0	86	0	97	112	0	0	72	0	23	176	16	1.3	0	0	0	0	0.73
76	2003	319	120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.00
77	2011	319	1050	0	0	1	2	0	0	0	84	10	0	29	0	0	4	17	0	0	2	0	15	9	0	1	0	0	0	1	1.04
78	2011	319	6502	0	0	1	0	0	0	0	0	0	0	0	0	0	0	268	0	0	0	0	0	0	0	1	0	0	0	1	0.46
79	2012	329	3360	3	0	0	0	0	0	0	0	0	0	0	0	0	16	11	0	0	0	0	16	62	18	1.3	0	0	0	1	0.65
80	2012	329	8270	0	0	6	4	0	0	0	241	252	0	0	0	0	0	4	0	0	1	0	78	32	8	1.3	0	116	0	1	0.51
81	2012	322	2588	0	0	1	4	0	0	0	0	0	0	0	0	0	10	9	23	0	20	0	0	0	0	1	0	0	0	0	0.41

Table 16: Data from the field study – University and college buildings

Bld	Year of	Cate-	Area	Doors				Alu trim			Alu clad windows						Alu profile windows						Curtain walls				Solar sh			HVAC	Al dens
No	constr.	gory		Plt	Hf-glz	Glz	Sld	S	M	L	FS	FM	FL	OS	OM	OL	FS	FM	FL	OS	OM	OL	S	M	L	*F*	S	M	L		
82	1910	619	17319.55	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	1	0	0	11	1	0.02
83	1951	629	2308.61	0	0	0	0	76	0	0	0	0	0	0	0	0	0	3	0	0	5	0	0	0	0	1	0	0	0	1	0.12
84	1960	629	5112	0	1	5	0	0	0	0	37	44	0	28	2	0	11	3	0	0	0	0	2	52	0	1.3	0	0	2	0	0.31
85	1962	621	3030.46	0	0	0	4	0	0	0	0	0	0	5	0	0	24	0	0	0	0	0	295	0	0	1	0	0	0	1	1.29
86	1971	619	6238.04	0	0	1	2	0	0	0	32	27	0	382	44	0	14	8	0	0	0	0	0	150	0	1.3	0	0	0	0	0.76
87	1984	621	8671	0	1	2	0	527	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	30	0	1	226	0	0	1	0.26
88	1984	621	1572	0	0	0	4	43	0	0	0	0	0	0	0	0	40	7	0	0	0	0	0	0	0	1	24	0	0	1	0.43
89	1995	629	1534	0	0	1	2	150	74	0	0	0	0	0	0	0	0	0	0	0	0	0	70	70	0	1	0	45	5	0	1.71
90	1996	621	2385	2	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	13	1.3	33	52	0	0	0.55
91	1998	621	5341	0	0	2	2	0	0	0	72	0	0	144	0	0	0	1	0	0	0	0	180	54	5	1.3	4	87	12	2	0.93
92	2003	621	8214	0	0	4	0	0	0	0	112	262	0	168	4	0	0	31	0	0	0	0	0	41	0	1	0	127	18	1	0.50
93	2013	621	17310	0	0	8	10	0	0	0	6	338	0	0	20	0	0	8	0	0	0	0	31	148	45	1.3	0	0	0	1	0.34