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Material Flow Analysis of Extruded Aluminium in French Buildings

Opportunities and Challenges for the Implementation of a Window-to-Window System in France

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Abstract

As environmental considerations start playing a major role in consumers' choices, aluminium recycling becomes an increasingly important topic: indeed, remelting aluminium requires about 5 to 10 % of the energy used for primary production (Quinkert et al., 2001). However, scrap from wrought alloys is more and more used by refiners to produce secondary foundry alloys, which increases the share of primary aluminium in extrusion billets. Besides, a significant fraction of scrap is nowadays leaving Europe to developping countries, limiting the future potential for urban mining in the developed world.

Therefore, the W2W project is a pilot case to test in France the implementation of a different end of life management strategy, whose objective is to reuse building joinery scrap to make new extruded products. For this project to be successful, pre-sorting at the beginning of the collection process is paramount: otherwise, separating high quality wrought aluminium alloys from mixed scrap becomes a challenge.

The cycle of extruded aluminium in buildings and the current scrap availability in France have been studied using Material Flow Analysis (MFA). To build the model, data have been collected from Hydro internal sources and site visits. The scrap availability and the in-use stocks of extruded aluminium in buildings have been assessed using dynamic stock models based on historic production figures and assumptions on the average lifetime of products. Scenarios on the future production have been studied to estimate the future evolution of these figures.

The models predict yearly outputs of post-consumer scrap from aluminium joineries of about 30kt/year, among which 10 kt/year should be reusable for the production of new billets. These numbers have been examined using the tools of sensitivity and uncertainty analysis. Finally, the critical topics for a successful implantation of the W2W project are logistic issues, economic and technological feasibility and the consequences on the different stakeholders.

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1. Introduction

1.1 Background: the aluminium industry

1.1.1 Extruded aluminium

Since the beginning of the industrialisation of the aluminium production system one century ago, aluminium has become the second most processed metal in the world after iron. The primary production of aluminium is based on the extraction of bauxite which is processed into alumina through the Bayer process. Aluminium is then obtained from alumina through electrolysis, a highly energy intensive process (Schlesinger, 2007, p. 1). Nevertheless, contrarily to other materials, Aluminium presents the advantage to be indefinitely recyclable without any loss of its physical properties. For this reason, it is estimated that 75 % of the total aluminium ever produced is still in use today, (Martchek K. J., 2006), and that the recycling of aluminium reduces emissions by over 90 % compared to primary production (Martchek, 1997).

The figure 1 below presents a general flow chart of the aluminium industry.

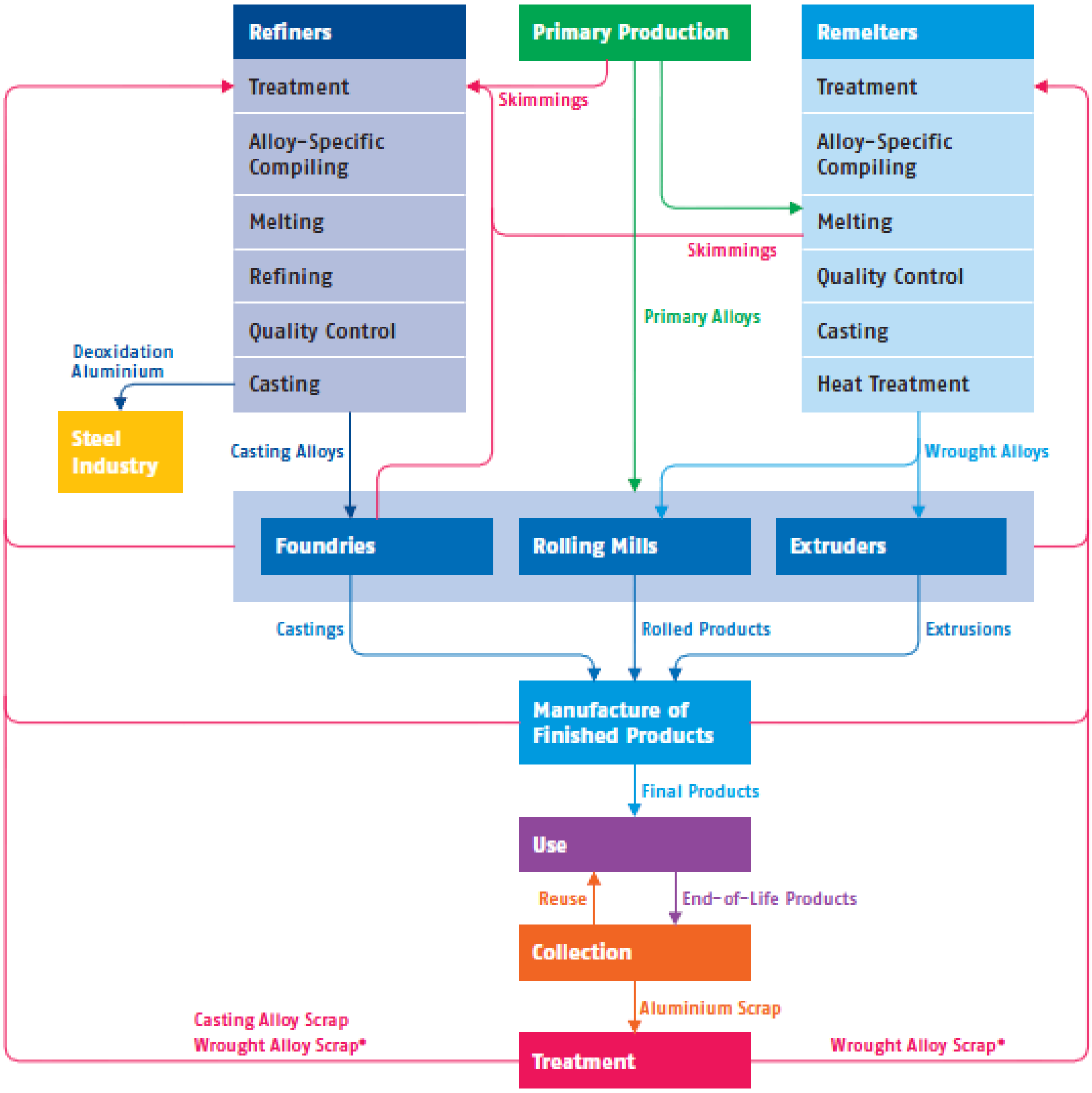

Figure 1: General aluminium flow chart (OEA, 2007)

Aluminium products are usually organised in three main categories: castings, rolled products and extruded products. They differ in their shapes, mechanical and chemical properties, production processes and material composition. Rolling and Extrusion use wrought alloys, which allow less alloying elements than casting alloys, and are then more challenging to recycle.

1.1.2 Aluminium joinery: the value chain

This study focuses on aluminium joineries. They are defined as building components made out of extruded aluminium, such as windows, doors, conservatories, curtain walls… Even if the project is called “Window-to-Window”, it includes all the joinery products. The figure 2 below introduces the main flows and processes in the value chain of aluminium joinery products.

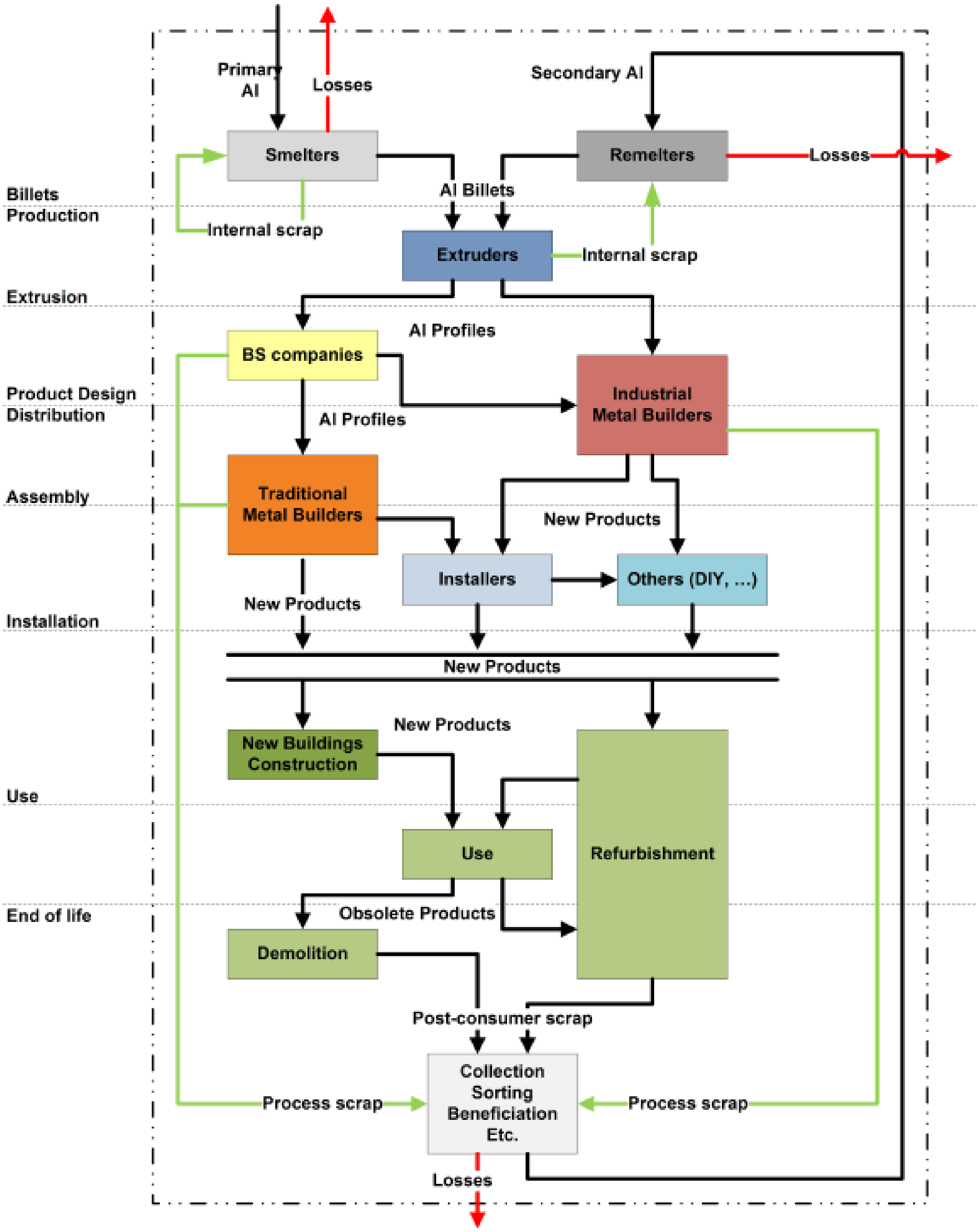

Figure 2: Simplified value chain of the use of extruded aluminium in buildings in France

Aluminium joinery products are almost all the time tailor-made to fit the exact dimensions of the buildings. This leads to a specific organisation of the value chain, with many different actors, and less industrialisation and vertical integration than one could expect for such products. Hence the Hydro group is involved in smelting, remelting, extrusion and building systems activities, but not in the more downstream processes, which is a challenge for the scrap collection.

1.1.3 Recycled content vs. end of life management

As environmental performance is regarded as an increasingly important issue, especially for buildings, there is currently a discussion inside the aluminium industry on how to refer to the recycling of aluminium for new products. Hence, some eco-labels require a given percentage of recycled aluminium in the composition of the products. This approach is called “recycled content”.

Nevertheless, even though this concept is very easy to understand and apply, it presents some weaknesses. The main problem is that different aluminium scrap qualities are not equal in terms of ease of recycling and environmental benefits provided. Indeed, today most of the process scrap is successfully recycled, because it does not present that much technical difficulties, the main one being the relative scarcity of high quality wrought alloys scrap on the market. Therefore, the aluminium companies who have an easy access to this scrap can boast a very high recycled content compared to the other ones. Contrarily, post-consumer scrap is currently very seldom used for remelting because of its lack of purity (Le Bouquin, 2012), even though it would provide higher environmental benefit.

On the other hand, the end of life management approach put the emphasis on the collection of obsolete products instead of the recycled content of the new products, and is currently the one defended by the majority of the aluminium industry (Sanchez, 2012).

Post-consumer vs. Process scrap

A major underlying problem in this discussion is the exact definition of internal (or in-house), process (or new) and post-consumer (or old) scrap. In this study, we will the definition generally accepted by the scientific community (from OEA 2007):

- Post-consumer (or old) scrap is defined as scrap from products that have reached their end user and have been discarded by him.
- Internal (or in-house) process scrap is defined as scrap that is recycled in the same company or integrated group where it has been generated. This is mostly the case for extrusion and smelting scrap.
- Process (or new) scrap is defined as scrap that arises during the production, the fabrication and manufacture of aluminium products up to the point where they are sold to the final consumer.

However, there has been some recent controversies as the European Aluminium Association (EAA) tends to favour a definition in which only the scrap generated during extrusion is considered as process scrap, while anything generated later in the value chain being labelled as post-consumer scrap, even if it has not reached its end user (Bjerkaas, 2012). If this definition makes sense for the manager of an extrusion plant, it does not fit with the usual terminology used in MFA and is not representative of the physical system. For these reasons, we will stick to the definitions presented above.

If this definition might make sense for aluminium extruders, it is not the most relevant when looking at the overall system. Hence, in this study the terms “old” and “post-consumer” scrap will refer only to products that have actually been used by the final consumer, while all the rest will be labelled “new”, “process” or “pre-consumer” scrap.

1.2 Previous Works

Several studies have already been conducted on topics close to this project. Rombach (2002) has studied the future availability of aluminium scrap in Germany and in Europe. Current availability and future projections were available for the different economic sectors, including buildings. Differentiation was also made between wrought and casting alloys, but without distinguishing rolled from extruded products. However, this model was based on partial data, and the main focus was not on France. Therefore, these estimations would need to be applied to the case of extruded aluminium in the building sector, transposed to France and actualised to the 2012 situation. Das et al. (2010) have also studied the availability os post-consumer scrap and started assessing the potential for urban mining. They stated that it should be possible to reuse post-consumer building scrap for wrought alloys production, as long as rolled and extruded products are separated on site. This should be feasible given their completely different shapes.

The work of Quinkertz & Rombach (2001) aimed at defining optimum recycling quotas. This approach takes into account the limits of the sorting processes as they also require energy to operate. Unfortunately, this study was focusing only on packaging industry, which makes it hard to transpose it to building profiles. The recycling quotas were used by Hoberg et al. (2003) to model the material flows in the collection subsystem in Germany. The question of the optimum in sorting quotas was also addressed by Li et al. (2011), but this time in terms of economic efficiency. The issues of scrap availabilty and optimum recycling quotas were also treated together by Rombach (2006).

Dynamics of the building stocks (mostly dwellings), as well as their lifetime distributions have been studied by several authors (Gleeson, 1985; Komatsu et al., 1992; Johnstone, 2001; Müller, 2005; Bergsdal et al., 2007; Sartori et al.,2008), but without addressing the particular case of aluminium joineries.

Several works exist on global and regional MFA models of aluminium flows. The GARC model (2009) is the first model of global aluminium flows, but it lacks refinement on a national scale in order to be used directly for the W2W project. Bertram, Martchek, & Rombach (2009) have proposed a more detailed model on the European scale, but the precision is still insufficient. In the same fashion, another European model based on mass balance was proposed (Boin & Bertram, 2005).

The economic aspects of secondary aluminium production have been treated by Blomberg & Söderholm (2009) in 4 European countries, including France. They concluded on a low own-price elasticity of secondary aluminium supply (0.21). Blomberg & Helmer (2000) have also built a scrap price and scrap generation model, but this was not focused on extrusion enough to apply to the W2W project. The aspects of reverse supply chain have been approached by Ferretti et al. (2006) and Logozar et al. (2006).

The study from TU Delft (2004) is the only one to monitor precisely the collection rates during demolition and refurbishment of old buildings in Europe. Nevertheless, no difference is made between extruded, rolled or castings products.

1.3 Data gaps

Spatial boundaries

A first gap of knowledge is that if several authors have studied the flows of aluminium scrap globally, in Europe or in several countries, no literature was found on the availability of aluminium scrap in France alone. Most of the actual MFA models on aluminium, such as the GARC model, lack geographical refinement. It is not possible to extrapolate the availability of post-consumer scrap in France from these global or regional models, because the local particularities of each country are not taken into account. It is all the more difficult to predict these local differences than aluminium joineries are mostly sold locally by small companies or craftsmen (Dizel, 2012). Therefore, this study will need to address the local particularities of France by collecting the data at source.

Industrial sector

The scope of this project is also very restrictive: it was not possible to find any study focusing only on aluminium joineries. All the similar known works have been conducted on national production aggregated by main industrial sectors, or on buildings only (often put together with construction). The main issue is that aluminium joineries do not share the exact same characteristics with buildings, especially given the fact that their lifetime is usually shorter. Hence, it would be necessary in this project to address the issues of installation, refurbishment and demolition of aluminium joineries, to take into account the specificities of each product category and to derive values for the lifetime representative of this market.

Material

Another important gap of knowledge lies in the fact that many studies focus on aluminium in general, without being specific to wrought alloys and even less to extruded products. Therefore, it would be necessary to collect most of the data directly through extruders, building system companies and metal builders as it is not possible to transpose the data from the whole aluminium production.

In general, this study is more detailed and at a smaller scale than the existing literature, which makes necessary to collect more precise data at source.

1.4 Project aim

Environmental considerations play an increasing role for customers to select the window materials. Since the environmental profile of aluminium windows is mainly related to the high energy use in primary Al production, the energy consumption could be drastically reduced by increasing the share of post-consumer scrap in aluminium production. While the recycled content of aluminium windows is very low, most of the aluminium scrap from retired windows is recovered, however, usually not to produce new windows, but castings, while “the ideal is to recycle a specific alloy back to the identical alloy, as with beverage cans; the value of the alloy is maximized” (Das et al., 2010). This is all the more true for aluminium joinery that this industry uses some of the most expensive aluminium alloys. The potential of castings production to absorb post-consumer scrap is also expected to eventually reach its limitation, which will require finding other, non-casting applications. Besides, a surplus of casting scrap will have consequences for scrap prices, making it more attractive to sort post-consumer Al scrap. In this case, pre-sorting of scrap seems a key issue as “mixed scrap that requires extensive treatment […] is far less economically attractive” (Roy & Van Linden, 2007).

Consequently, a window-to-window recycling system could (i) significantly improve the environmental profile of windows (ii) offer an alternative to the increasingly tight castings market, and (iii) open up an attractive business opportunity. This is comforted by the fact that in Europe, the biggest increase of future scrap amounts can be expected for the transport sector followed by construction (Rombach, 2002). There is then a real opportunity to modernise in depth the European aluminium markets

Therefore, recycling is a strategically important topic for Hydro Building Systems (HBS) and is consequently a focus area. HBS is mainly one of the global leaders in primary aluminium production, but is currently having a pilot case in France where the overall objective is to increase the End of Life Recycling (ELR) rate of aluminium for the building industry. Collection of scrap from production of new windows and replacement of old windows from the customers of HBS is a key ingredient to increase the share of secondary aluminium in the building sector. In this context, HBS has also initiated an economic model of the scrap availability in France based on the profiles supplied to the French market. However, this model is not completed due to lack of reliable data from the French building industry.

Hence, the methodological tools of MFA and stock dynamics will be combined in order to be able to assess the availability of scrap from building profiles in France as well as the main logistic challenges to address before the implementation of the W2W project.

A static MFA model will be used to describe the current material flows in the production, use and collection subsystems of the French aluminium joinery life cycle. A dynamic model using stock behaviour will be used to quantify the current in-use stocks of aluminium joineries as well as the yearly outputs of post-consumer aluminium profiles scrap from buildings. This model will be built on the historic production of building profiles and assumptions on the lifetime of the different products. The dynamic modelling will also enable to make future projection for the potential available volumes of post-consumer scrap based on different growth scenarios.

Finally, sensitivity and uncertainty analyses would be performed in order to take advantage on the knowledge of the overall system to gain information on the behaviour of the most important flows, such as the availability of post-consumer scrap.

2. Methodology

2.1 System Definition

2.1.1 System boundaries

The goal of this case study is to assess the feasibility of a scrap collection system for the industry aluminium joinery products in France. Hence, it is important to be able to collect as much scrap as possible along the different processes in the value chain. Therefore, the system contains all the processes from aluminium remelting where aluminium billets are produced, to the use phase, end of life, collection and beneficiation of the scrap.

Following the end of life perspective chosen in this "Window-to-Window" project, only the extruded aluminium used in the building sector is considered. All the products who meet this definition are called "aluminium joinery" products. This excludes extruded aluminium products used in other sectors, such as automotive, industrial machinery, infrastructure, etc. Hence, these products from other sectors which leave or enter the system will be labelled as imports or exports. The differentiation between these different sectors is only made when the aluminium profiles are sold to the different industries. This means that it is very hard to make a difference between the different sectors at the remelting and extrusion plants. As result, the system includes all the extruded products for remelting and extrusion. Later in the value chain (in the aluminium profile market process), the products that are indeed used in the building sector will remain inside the system, while the rest will leave the system as "exports".

The spatial boundaries of the system are defined as the geographical boundaries of metropolitan France. Whenever possible, this model aims at describing all the yearly material flows and stocks in the physical system as they were during the year 2010, i.e. the yearly flows are calculated from January 1st to December 31st 2010. However, in cases when no recent figures were available, the results are based on older data sources and extrapolated for the year 2010.

2.1.2 System Overview: the different processes along the value chain

Subsystem 1: Production

Aluminium production, remelting (process 1) and billets market (market M1)

In France, the production of primary aluminium for extrusion is negligible. Hence, the aluminium billets are produced in remelting facilities, which amounts to approximately 40 % of the domestic demand (GLFA, 2010). There are three main plants in France; the biggest is in Lucé (owned by Hydro), located in central France with a capacity of 60 kt/yr. There are also two smaller plants, one near the Italian border with a capacity estimated between 15 and 20 kt/yr, and one near the Belgium border, producing between 4 and 5 kt/yr. Hence, the yearly production is about 80 kt/yr. The domestic billets consumption is about 200 kt/yr, and since the exports are negligible, the imports amount to about 120 kt/yr.

The main component of the remelting facility is a furnace, where aluminium scrap is melted and then casted into a mould to produce new billets. Contrary to casting refining, this requires monitoring very accurately the chemical composition of the scrap in order to produce high-quality alloys. Then, the billets are treated in a homogenisation oven.

Nowadays, only process scrap (pre-consumer) is used in French remelters, although some post-consumer scrap is already seldom used in other countries. 15 % of the furnace content is pure primary aluminium ingots, in order to decrease the concentration of impurities in the final alloys. The rest of the metal comes from extrusion scrap (50 %) and other process scrap (35 %). The extrusion scrap is mostly purchased through conversion agreements: a remelting company gets all the scrap produced by a given extrusion plant, which remains the owner of the scrap. The extruder is only charged a fixed “conversion price” per ton of scrap remelted into new billets. The rest of the scrap is bought on the new scrap market, mostly from major scrap dealers or traders, but also directly from some production plants.

During this process, the loss on ignition in the remelting furnace amounts to 3 % of the total input metal mass (Le Bouquin, 2012), which is in accordance with Martchek (2006), who states a melting recovery of 96 % for aluminium in the building sector (extrusion ingot remelting).

Extrusion of aluminium profiles (process 2) and aluminium profiles market (market M2)

The aluminium billets are then sent to extrusion plants. There, the billets are pressed through extrusion dice to produce profiles, and cut to the customer length of typically 6 m. If needed, a thermal break strip is also added in the profiles. The losses generated by this process are quite important: 20 % of the metal mass is lost, for several reasons. First, extrusion is not a continuous process and the scrap is mainly related to the start-up and end of each billet (butt-end, stretcher scrap, overlength). There are also some marginal losses due to mistakes during the extrusion process, the adding of the thermal break strips or the handling of the finished aluminium profiles.

Among the different extrusion presses in France, 5 of them are owned by Hydro in 4 different sites. The domestic production of aluminium profiles (all types of applications) is about 160 kt/yr, which is not enough to fulfil the domestic demand of 400 kt/yr. Thus, 240 kt/yr of aluminium profiles are imported (GLFA, 2010).

Design of building systems and surface treatment of the profiles (process 3)

Historically, aluminium joinery products have been designed by specialised companies, called Building Systems (BS) companies. They design their own aluminium profiles and buy them directly to extruders who have to follow their specifications.

Today, BS companies also take care of the surface treatment of the profiles, like coating or anodizing, but this is not always the case, and they tend to have more and more subcontractors for that. In addition to BS companies, some other actors have emerged during the last two decades. There are mostly industrial aluminium joinery producers, whose size and know-how which enables designing their own aluminium profiles and ordering them directly to extruders. Hence, they are direct competitors of BS companies. For the sake of simplicity, we will put together industrial windows producers, conservatories specialists and facades makers in a category called “industrial metal builders”. Today, these industrial metal builders are gaining more and more market shares at the expense of BS companies, and amount now for more than half of the total aluminium joinery market. In 2010, 58 % of the aluminium profiles in the building sector were used by industrial metal builders, the share of BS companies being only 42 % (EAA, 2009).

This process generates very little scrap. Indeed, the surface treatment and handling operations are the only physical processes happening here; the rate of loss is approximately 2 % (Negroni, 2012).

Product assembly (process 4)

Historically, the aluminium joinery products were assembled by traditional metal builders who bought profiles from BS companies. For instance, most of the aluminium windows used to be tailor-made, and if the product design was conceived by large companies, the final assembly was conducted by small craft businesses.

Nowadays, this organisation still holds for a bit less than half of the production, but the main part is now produced by the integrated industrial metal builders, who mainly design their profiles themselves, buy them directly from the extruders and assemble the products through a more industrialised process. Nevertheless, they still buy a small share of the profiles they use from BS companies, mostly when the design is complex.

The respective market share of traditional and industrial metal builders have been calculated by combining the market shares for the three main product segments (windows, curtain walls and conservatories) displayed in an internal study by Jean-Marc Dizel (2006).

Installation (process 5)

Three main actors are involved in the installation of new joinery products: traditional metal builders, industrial metal builders and installers. The distinction between traditional and industrial metal builders is somehow hard to define, as it tends to be different for each type of products. For instance, to be considered “industrial”, windows manufacturers should not install their windows themselves, but sell them to installers instead. On the other hand, for more specific products such as curtain walls and conservatories, it is more usual that the producer is also taking care of the installation, even if the size of the company and the optimisation of the production process make them “industrial” metal builders. For windows, there are also small assemblers who do not involve in installation, but the small size of their sales volumes and essentially manual production definitely define them as traditional metal builders.

Another distinction between industrial and traditional metal builders is their vertical integration. In some cases, industrial metal builders design their aluminium profiles themselves and order them directly from extruders, while traditional ones exclusively rely on building systems providers. In the beginning of the last decades, the rapid growth of industrial metal builders has pushed them to internalize the design process, but now that they have reached a more steady market share, they often have to face increasing costs and difficulties with design operations. Particularly, the increasing tightening of environmental regulations makes it necessary to continuously update the specifications of the products, which is hard to follow for non-specialists. Then, industrial producers rely again more and more on building systems companies, making the gap between traditional metal builders seem smaller (Dizel, 2012).

To simplify a process already complicated enough, the different distribution channels are not taken into account here. For instance, the brand Technal (part of HBSF) is distributing its profiles mostly through a network of more than 200 semi-franchised craftsmen called “Aluminiers”© Technal, slightly more involved in residential and renovation work, while the brand Wicona is selling directly to more industrialised customers, without the existence of an official network. Another HBS brand, ASKEY, is specialised in sales to industrial producers who would rebrand the products under their own name, making the flows more difficult to follow (Mourier, 2012).

While traditional metal builders either install their products themselves or sell them through craftsmen (joinery installers), industrial manufacturers might also sell their products through general contractors, wholesalers, consumer networks and home improvement retailers, including "Do It Yourself" networks.

Subsystem 2: Distribution, use and end of life

Distribution of new products

First, as there is no real physical change on the product at this stage, there is no process called "distribution" as such in the system. Moreover, the diversity of the products and distribution channels would have made necessary to separate between many different processes to represent the reality. This would have been at the expense of clarity, not to mention the challenge of the allocation of the flows to each of the processes. Thus, distribution is implied in the processes 5, 6 and 8, but not studied into details.

Distribution of new aluminium joinery products can occur through two different processes: when a new building is built, or when old joineries are replaced by new ones on an existing building (refurbishment). It is rather hard to estimate the importance of refurbishment compared to new construction. Different figures exist, but there are all inaccurate and give conflicting results. What is agreed on is that refurbishment is considerably steadier over time than new construction, which is more cyclic and directly related to the economic situation.

Aluminium products have a considerably higher share in the commercial than in the residential sector. This is explained by the predominance of aluminium windows (typically sliders) and curtain walls in non-residential buildings. For the window market, precise figures are available (see the graph below), which shows that housing renovation is the main market. Nevertheless, the market share of aluminium in France in 2010 was 66 % in the commercial sector compared to 16 % in housing (BATIETUDE, 2010), but due to the relative size of these two sectors (housing accounts for 87 % of the total market), the residential sector amounts for a little more than 60 % of the market.

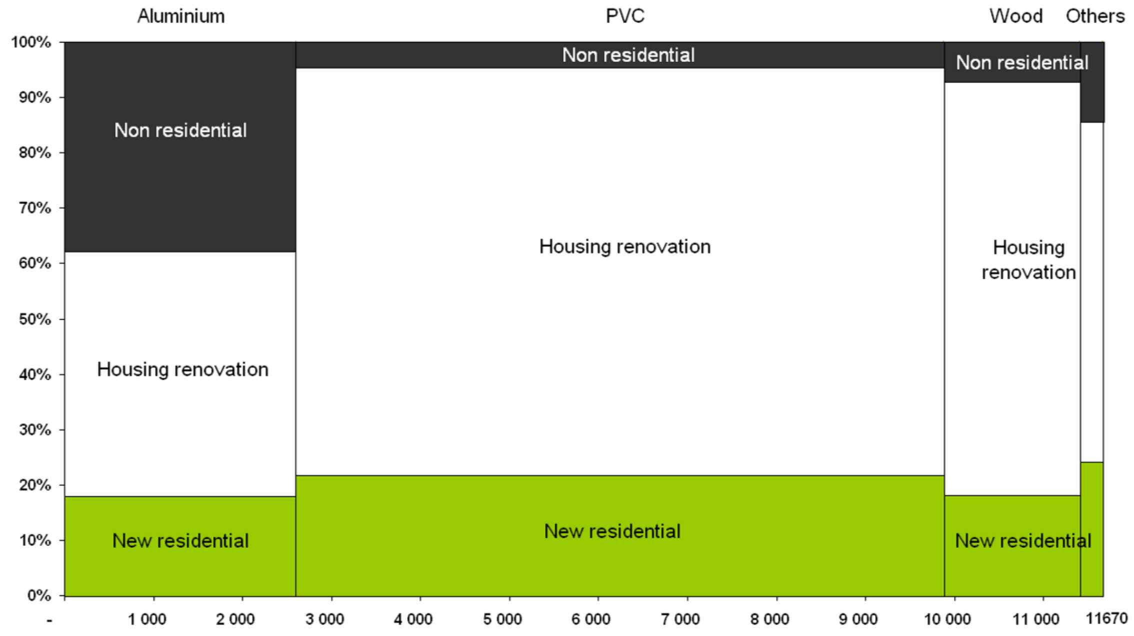

Figure 3: Market shares by material and sector for windows in France in 2010 (source Dizel from BATIETUDE, 2010)

However, this does not hold when one looks at the total aluminium joinery market. For instance, curtain walls are seen almost exclusively in the non-residential sector and should show a different behaviour. Moreover, some products such as conservatories have been introduced relatively recently compared to their lifetime, and the need for replacement is weaker than for windows (no regulations, no need for good insulation since a conservatory is seldom heated).

Therefore, we should expect the importance of renovation to be smaller for the total joinery market than for windows alone. Indeed, these two activities are said to be on average on the same order of magnitude, but the building system sales specialists of the brand Wicona tend to agree on the fact that there is slightly more products sold for refurbishment than for new construction (Dizel, 2012). Erabuild (2008) states that in 2005 France, "for residential buildings, the cost of renovation represents a little more than half of the acquisitions of new housing". The best assumption is then that 55 % of the new products are installed through refurbishment projects. This information is extrapolated from Wicona sales in France figures, corrected to take into account the fact that this brand is historically more oriented towards non-residential customers. This is of course a simplification due to the lack of comprehensive data available, and might prove wrong in the future, especially if regulatory or economic factors change. For instance, incentives to improve the insulation of old buildings would result in an increased share of refurbishment since old wooden or aluminium products without thermal break should be replaced faster.

Considering the inherent difficulties of transporting assembled new windows, the relatively small size of the actors and their strong local implantation, no market is assumed for new joinery products, because international trade is considered negligible (< 5 % of the yearly installed volume).

New buildings construction (process 6)

According to interviews with local metal builders, the typical size of a project is significantly bigger (about ten times) for construction of new buildings than for refurbishment. Usually, metal builders do not deal directly with individuals for new construction. The joinery producer and installer are generally chosen by the architect or the general contractor.

Refurbishment (process 8a)

Statistics show that joinery products of a given material are not systematically replaced by the same material, which makes this process difficult to quantify. For instance, a study conducted on the French window market showed that 86 % of the windows replaced in France in 2010 were wooden windows, while the share of wood in new windows was only 14 %. 17 % of wooden windows, 13 % of PVC and 54 % of aluminium windows are replaced by new aluminium windows (BATIETUDE, 2010).

The "loyalty" to aluminium from customers is rather low, which creates difficulties when trying to build a logistic model for a window-to-window system: if a wooden window is replaced by an aluminium window (typical case), the window installer will have no use of the wooden frame. On the other hand, if an aluminium window is replaced by a PVC window, the aluminium frame will be most likely recovered by the PVC window installer, who has no direct commitment into closing the loop of the aluminium window cycle.

Renovation projects have different characteristics depending on their size. A partial renovation of a building typically results in 10 windows exchanged, while total refurbishment of a large building or even blocks generates considerably more scrap. The actors involved would also be different: small family owned metal builders are not able to take care of a large project, while more industrialised actors tend to avoid working directly with individuals.

Use phase (process 7)

Aluminium joinery products have typically a very long life time due to their mechanical and chemical properties. Most of the time, obsolescence occurs not because of the product being damaged or inefficient, but because of new regulations, environmental or aesthetic considerations, reorganisation or demolition of the building itself.

Hence, the stock in use is substantially larger than the yearly inputs, which are in turn larger than the outputs due to the overall growth of the market in the past decades. The figures for the in-use stock, as well as the yearly outputs will be taken from the results of the dynamic model. The numbers used in the static are those obtained with the long lifetime scenario, which is more pessimistic in terms of current availability of post-consumer scrap (see section 2.3. for more on the lifetime scenarios).

End of life

The collection rate in building demolition or refurbishment is assumed to be 95 % (Delft University of Technology, 2004). This number is an average for 9 different buildings, residential and commercial, located in 6 different countries, for which data has been closely monitored. This number can seem high, especially if compared with the 70 % given for the global collection rate in the building sector in 2000 by Martchek (2006). Besides, several factors could explain why this yield is so high. First, the simple fact to account closely for all the aluminium might push the demolition contractors to be more carefull when dealing with the aluminium waste. It is also stated in the study that the demolition companies were all of high standards, most of them operating in accordance with the norms ISO 9001 and 14001, and hence they are not necessarily representative of the average practice in the sector. And finally, this study was not totally independent as it was commissioned by the European Aluminium Association, which has a certain interest in boasting high collection rates.

However, it was decided that this number of 95 % would be more representative of the reality for different reasons. First, we might expect the recovery rate in Europe and in France to be higher than the global average, due to enhanced environmental standards. Moreover, even if considering the possible biais of the study conducted by TU Delft, it is also mentionned that the shape and size of the aluminium debris is directly linked to the collection rate, as it is shown in the figure 4 below.

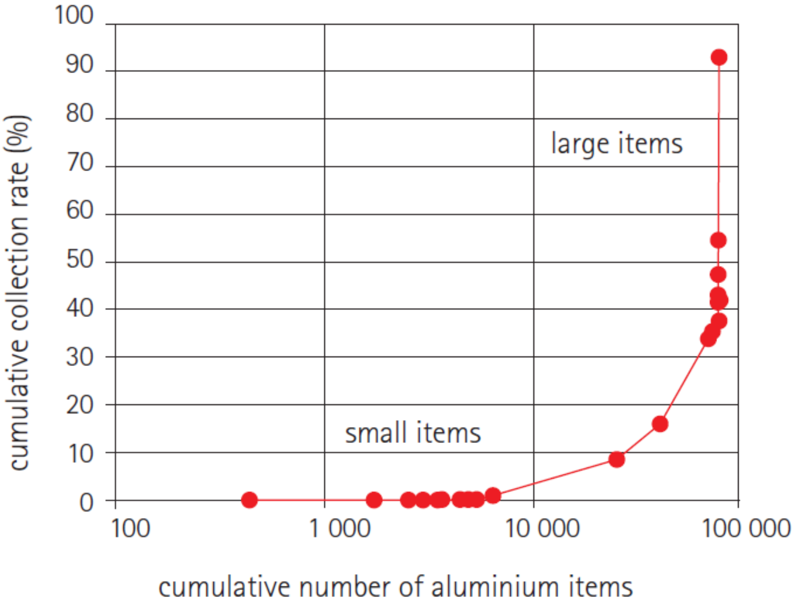

Figure 4: Influence of the size of aluminium debris in buildings on the collection rate (source TU Delft 2004)

This is of importance, because products made out of extruded aluminium profiles tend to be bigger than rolled or castings products. Thus, we can expect a higher collection rate for aluminium profiles, since they usually have long linear shapes and are quite easy to identify and sort. The collection rates were also smaller for residential buildings, because most of the aluminium content consisted of small parts, not made from extrusion, such as door handles and signs.

The repartition of the aluminium content depending on the type of building is also interesting to look at: the figure 5 below shows the concentration of aluminium in the building (on the vertical axis, in grams / tonne) and the weight of each aluminium object (on the horizontal axis, in grams / object).

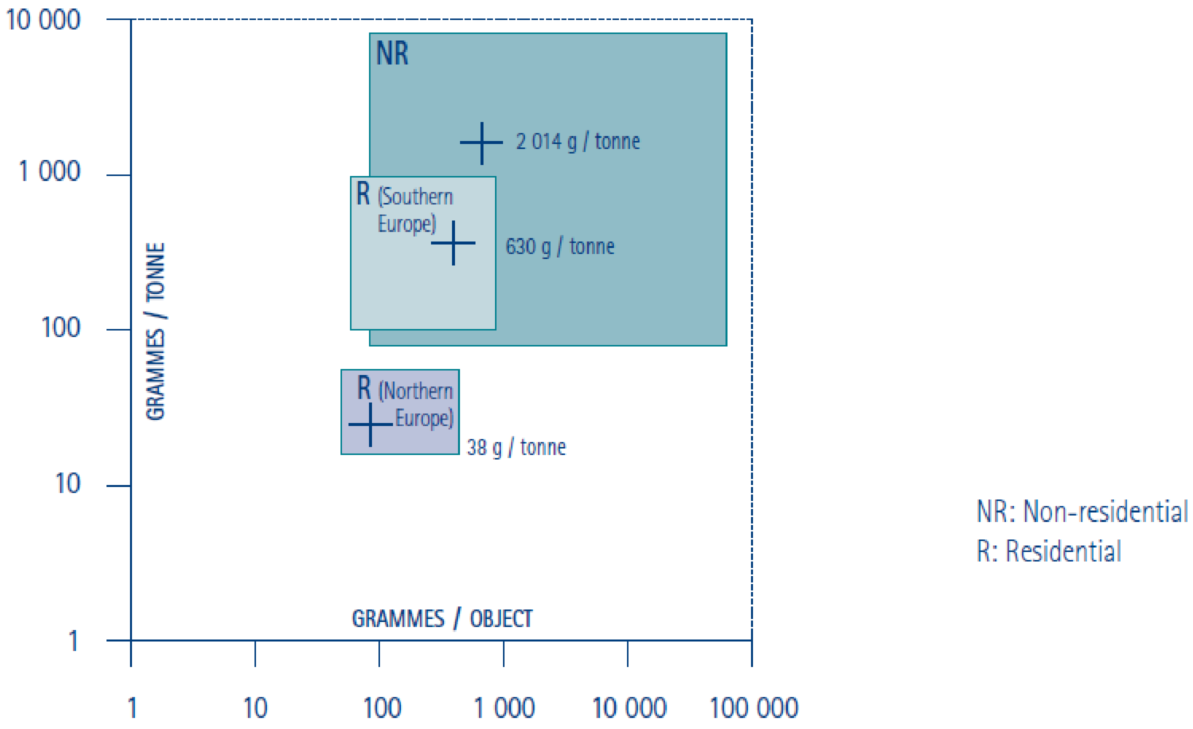

Figure 5: Aluminium content of buildings in Europe (Source TU Delft 2004)

By comparing the two previous figures, we can expect the collection rate to be higher in non-residential buildings. We see also a geographical difference for residential buildings: the aluminium concentration and the average size of the aluminium items tend to be higher in Southern than in Northern Europe. The case of France is a bit trickier: originally a Latin country, it is also located at a crossroads between Latin, Germanic and British civilisations. This appears clearly in the building stock, which exhibits highly variable patterns in the different geographical regions of France. In general, the Western and Southern parts of France share the characteristics of the Southern Europe, while the concentration of aluminium in buildings in the Nordic and Eastern regions is much smaller (Dizel, 2012).

However, keeping these particularities in mind, it was decided to keep with the share of 95 % percent proposed by TU Delft (2004), since there was no easy way to define a better estimate. This number is also partly confirmed by Rombach (2002), who gives estimates of the collection rates in Germany of 85 % in 1998, 90 % in 2010 and 95 % in 2020. These numbers are smaller by 5 %, but they take into account the whole building and construction sector, where we could expect the losses to be higher than in buildings only.

Refurbishment (process 8b)

There was no precise information available on the provenance of building scrap, and no easy way to tell which share of the building profiles come from demolition and which one from refurbishment. Since it was assumed that a building will be in average completely renovated once during its whole lifetime, the share of post-consumer aluminium scrap coming from refurbishment was set to 50 %. Interviews with scrap dealers and metal builders tend to confirm the order of magnitude of this figure, but the uncertainty remains high on this point.

The interviews with metal builders (customers of HBSF) have shown that during refurbishment, the installer or metal builder in charge of the installation of the new products is most of the time taking care of the scrap coming from the obsolete products. However, as it has already been mentioned before, the old products are not so often made out of aluminium. This is still interesting from a value chain perspective, because it should be easier for a building system company to get hold of this scrap through its distribution networks, all the more that selling this scrap is not the core business of the installers.

Demolition (process 9)

The demolition of buildings is usually conducted by general demolition contractors, but since the aluminium parts are among the only materials profitable to collect, the dismantling and sorting of aluminium scrap (especially extruded profiles) is usually well organised (TU Delft, 2004). However, the scrap coming form demoltion is considered less interesting in the frame of the W2W scrap coolection project. Indeed, the scrap is never collected by windows installers or metal builders, which make it harder to collect by companies such as Hydro, because It ends up further away from its core activities in the value chain. Moreover, the demolition companies are usually in charge of all the building waste, and aluminium is a lucrative material, so it is very unlikely that it would be possible to collect it without the rest of the waste which are of no interest for the project.

Furthermore, in terms of scrap quality, the risk is also higher to have aluminium profiles mixed with other aluminium products, and even other materials. This would make necessary to process to several advanced sorting operations before using this scrap for remelting.

Subsystem 3: Collection and beneficiation

First, it is essential to specify that the way this subsystem was modelled is a mix between the current situation of aluminium recycling in France and a more ideal system if a Window-to-Window collection system would be implemented. Indeed, today there is very limited post-consumer scrap being reused in remelters for the production of new billets in France. Hence, the only current outlets are secondary foundries and exports. Therefore, in order to model the current situation it would have been sufficient to describe only these flows. However, differences still exist in the scrap quality and in the collection channels. Even if they are used in the same applications in the end, scrap from building profiles is purer and thus more expensive than mixed scrap from vehicles and households.

When doing the modelling, the goal was then to model these different channels, and to try to identify which fraction of the total outputs of post-consumer scrap is likely to be reused for the production of building profiles. This is equivalent to finding which fraction of the aluminium building scrap is contaminated with other materials or aluminium alloys in the beginning of the collection process, and which one remains clean enough during the whole beneficiation phase.

Obsolete products market (market M3)

The obsolete aluminium joinery market is mostly dominated by scrap dealers and demolition contractors. It becomes difficult to track the flows of materials at this stage, because many actors are involved, and an important part of the trade is not official.

There are four main sources of supply for metal scrap:

- Individuals and households that have to get rid of small quantities of scrap, or know that metal scrap has value and thus collect it from their friends, neighbours… They sell it afterwards either to large scrap dealers if they have dedicated collection points, or to small unofficial scrap dealers.
- Craftsmen like metal builders that have cut-offs during their production.
- Larger industrial producers, who generally have regular contracts with large scrap dealing companies.
- Unofficial scrap dealers, thievery, and underground economy. A network of very small, mostly underground scrap dealers and thieves remains very active and efficient in France. They either collect the scrap directly from individuals or small craftsmen or steal it from construction yards, electric cables, collection sites, etc. and sell it to larger scrap dealers afterwards.

The market is then more or less organised in 3 layers between the generation of the scrap and the sorting by the main actors of the markets. The figure 6 below shows this simplified organisation in 3 layers.

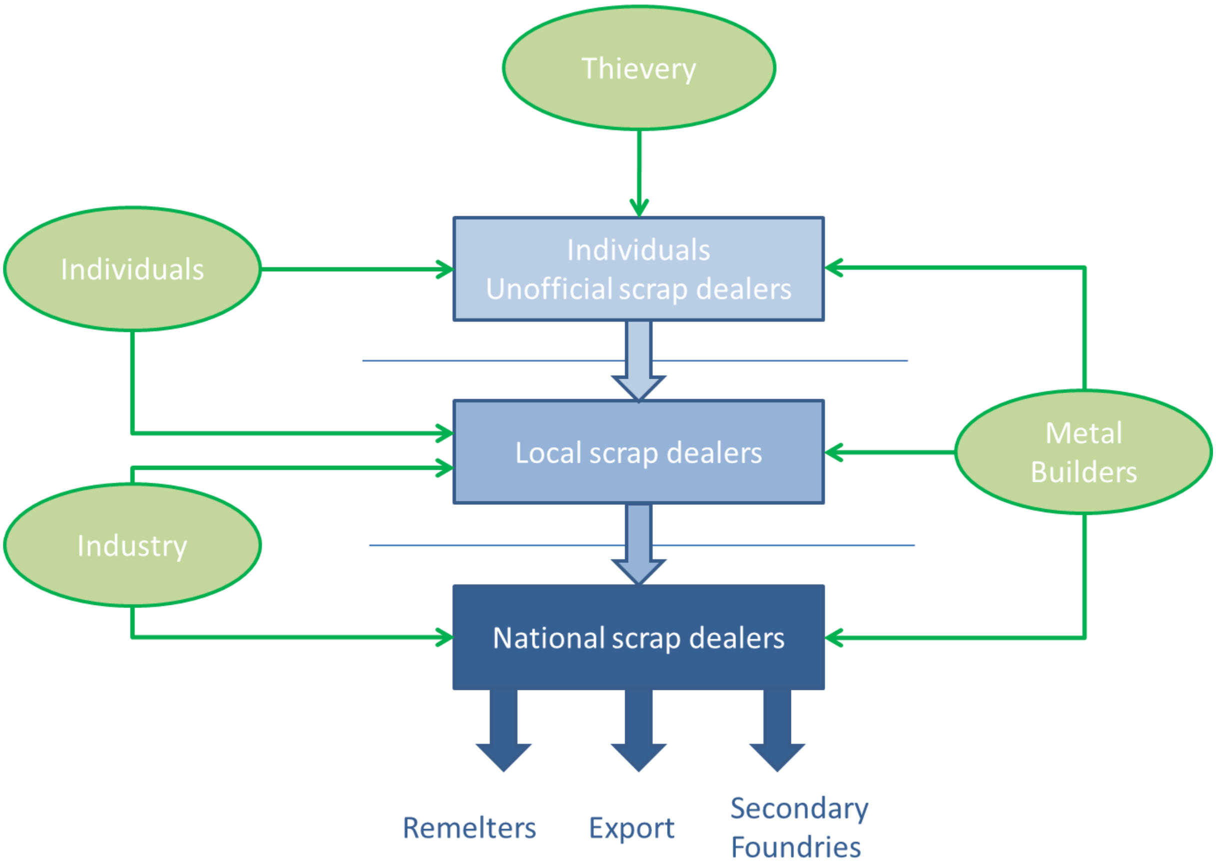

Figure 6: Simplified organisation of the scrap dealing market in France – Scrap flows

Scrap generated by the industry, or large metal building companies will be collected either by local scrap dealers or directly by the main players. There is also a scale effect in the sense that companies larger than about 20 employees have legal difficulties to get rid of their scrap through illegal ways. Thus, if not stolen in the meantime (the skips in the courtyards of metal builders are regularly emptied by thieves), the scrap from large companies will reach the official scrap dealers directly.

On the other hand, for small companies it is easier and more interesting for them to get rid of their scrap illegally: if the transaction is not recorded, they do not pay taxes on it and they can use the black money they get from the scrap for other discreet operations. So, when not coming directly from the industry, the scrap is usually first collected by individuals, or unofficial small scrap dealers. According to scrap dealers (Guilloteau, 2012; de Foucauld, 2012), this unofficial supply amounts for about 40 % of the total scrap collected. This fraction is currently slowly decreasing due to reinforced regulations on scrap and cash payments in France. Since 2011, it is forbidden to buy scrap with cash, and scrap dealers have to record each transaction with the identity of the seller. As a consequence, the size of the underground scrap economy in France is decreasing , but since the regulations are less restrictive in the neighbouring countries, there is also more scrap leaving France.

Then, because of the tough regulations, it is difficult for them to sell the scrap in France directly to the biggest scrap dealers, so the scrap is usually travelling through medium-size scrap dealers in order to make it look legal enough to reach the main actors of the market. This scale and regulation effects explain the organisation in three different layers.

The main actors in the market were identified through the website of the French trade union of the recycling industry (FEDEREC , 2012). Here, all the collection and sorting sites are listed by type of waste processed. A difficulty is that no company or site is specialised in aluminium only: some will deal with all types of materials, while some will be specialised in metals only. If the iron and steel scrap is recorded separately, the most precise category that includes aluminium is “non-ferrous metals”. The main components are copper, aluminium, lead, zinc and tin. It is therefore almost impossible to record the flows of aluminium only, but a unit that is handling non-ferrous metals will necessarily process aluminium.

Therefore, to have an overview of the aluminium scrap market, the different companies involved were sorted by the number of collection sites for non-ferrous metals that they own. This is of course a simplification, as the size of the sites is not taken into account, as well as their relative specialisation in aluminium. The share of aluminium in the total collected scrap can vary because of a strategic choice from the company or because of the presence of large aluminium processing industries in the surrounding area.

However, the number of sites owned by a single company remains a good measurement, because the scrap is mostly collected locally. In general, the relatively low value of the scrap prevents it for travelling over long distances, and the companies have knowledge of the different sources of supply in their local area. Each collection site usually extends its influence in a radius of about 50 km (Guilloteau, 2012), so there is no need for very large collection sites, because their capacity will quickly exceeds the local supplies. Hence, in order to gain more market shares, a large scrap dealing company will have to increase its number of sites to expand geographically its collection network. In that sense, the number of sites a given company owns is a good measure of its influence on the national market.

The figure 7 below illustrates the split of the market between the different scrap dealers.

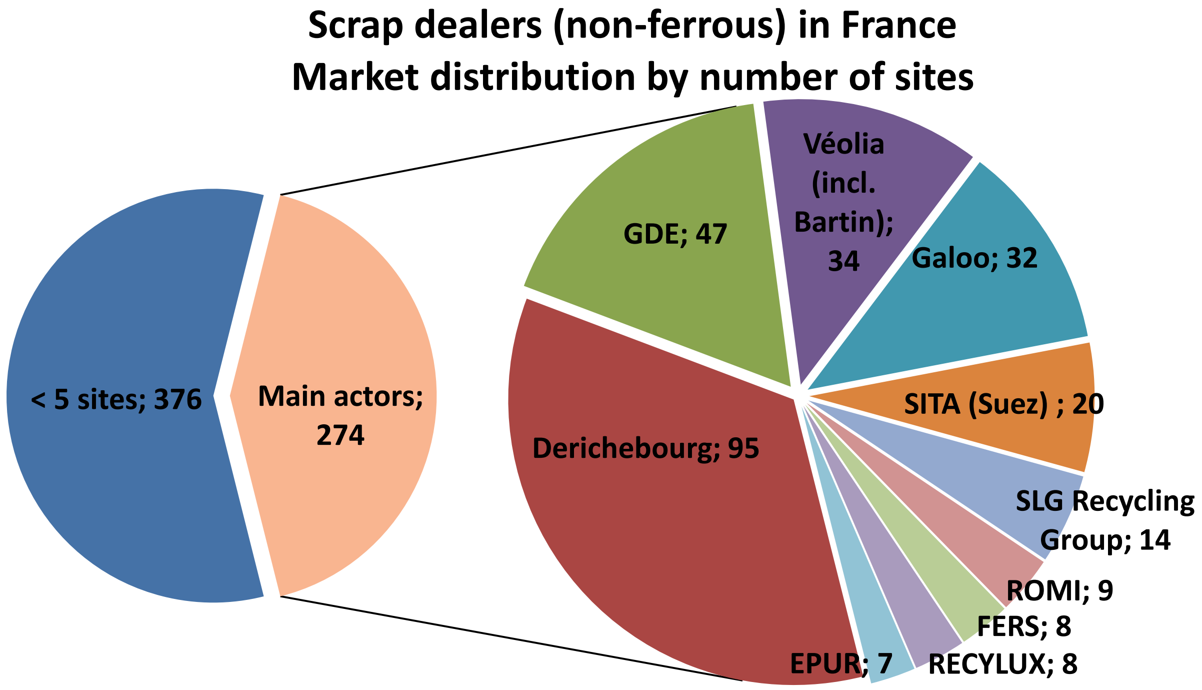

Figure 7: Scrap Dealers in France: market distribution among the main actors (source FEDEREC 2012).

First, we see that the main actors represent less than half of the sites implanted in France. However, their share in the total aluminium scrap inputs are supposed to be consequently higher, for two reasons. First, in general they will tend to have slightly bigger collection sites in average. And more importantly, a lot of scrap transiting first to local scrap dealers will be sold afterwards to the main actors, so in the end the share of scrap transiting throuh the main players is supposed to be higher than the 40 % represented on the figure 7.

About the relative importance of the different actors, we notice that Derichebourg has a dominant position. The four next followers, GDE, Véolia, Galoo and SITA are also important players at a national level. The five other groups identified are too small to really be implanted over the whole French territory, and would be better described as big regional scrap dealers. A conclusion from this graph is that even if the market is very complex at a low scale, there are very few main actors at the national level. Hence, most of the scrap will be collected right after it is generated through small companies and individuals, but it will later transit through the very few companies that are large enough to handle the large infrastructure and logistic needed to treat large volumes of scrap over a wide area. In this sense, the market is not very competitive, especially since there are usually officious agreements between the scrap dealers in order to decrease the competition and hence secure the supply and maintain low prices for the buying of scrap.

It is also assumed that a small share of the obsolete products is directly reused as such. For instance, old windows from demolition of buildings can be reused if they are in good shape, for instance through exports in Eastern Europe (TU Delft, 2004). Unfortunately, no quantitative numbers were provided in this study, so this flow (suposedly small) was assumed to be 3 % of the total. It was also assumed that 10 % of the products collected are lost or used for other applications: no specific reference exists for this number, but it seems to be the best estimate compared to the usual yields of such collection processes.

Solid Waste Treatment (process 10)

This process represents the processing of aluminium scrap when it is mixed with other metals and waste. Today, this is the main outlet for obsolete products. Since they are usually not sorted in the upstream processes, they reach the collection sites mixed with other materials. Then, it is not profitable enough to specifically sort aluminium profiles. The standard treatment consists of shredding all the scrap together in large rotary shredders (Weignein, 2012). Scrap inputs usually include non-ferrous metals, iron and steel, ELV, WEEE and other materials. The shredding process generates losses under the form of small particles, called dust or shredding residues.

At the output of the shredder, the debris is generally up to 20 cm long (Guilloteau, 2012). Some magnets are disposed on top of the conveyor belt, so the iron containing materials are separated that way. Then, the rest is entering into several vertical columns with a strong air flow going upwards inside of them. The denser objects will remain at the bottom of the column, which enables to sort the different materials by density. Three or more different fractions are differentiated: the heaviest one includes the heaviest metals and minerals, and the lightest one consists mostly of plastics and inert materials. The aluminium is contained in the medium fraction with the other non-ferrous metals. The difficulty is to choose the right range for each category. For instance, if the upper limit for the lightest fraction is too high, some aluminium will go with the plastics and inert materials and will be lost, but if it is too low there will be more impurities in the non-ferrous metals fraction.

More sorting operations can take place afterwards. To separate the different materials contained in the non-ferrous metals fraction, three main types of sorting are used:

- *Eddy-current sorting*: the different metals will react differently to magnetic fields given their intrinsic electronic properties. It is therefore possible to separate the metals from non-conductive materials (which will not react at all to the eddy-current), and to a certain extent the different metals or alloys. The drawbacks of this technique are the difficulties that arise when the scrap does not have homogeneous sizes and shapes (this will affect the reaction to the eddy-current) and when pieces are made of an assembly of different materials. Therefore, it is mostly use to separate the non-ferrous metals from the rest, or copper from aluminium, but not to discriminate between metals of similar characteristics (Schlesinger, 2007, CH5, *Beneficiation Technology*,p.70)
- *A sink-and-float method*, generally applied in two stages. First, the shredded scrap is put into water. The lower density fraction (containing plastics, inert materials…) will float, while all the other metals will sink. Then, aluminium can be separated from copper and other non-ferrous metals using a heavy media separation (HMS) process. This consists of using the same sorting technique, but in a solution with a higher density than water, such as ferro silicates and magnetite solutions. The lighter metals, with densities lower than 3 g.cm^{-3}, such as magnesium and aluminium will float, while the rest (copper, zinc, tin, lead…), with densities higher than 5 kg.m^{-3} will sink (Guilloteau, 2012; Recylux, 2012).
- *X-ray sorting* is also used when more refinement is needed. This enables to separate between the different metals and even alloys to a certain extent by analysing their electronic structure. The scrap enters the sorting unit on a conveyor belt, where the metal is analysed and the position on the conveyor belt is recorded. Then, at the outlet of the machine, the scrap falls from the conveyor belt, and compressed air blades will push the pieces of scrap in different boxes depending on their material composition. This is currently the most precise sorting technique, but also the most expensive and time-consuming (Guilloteau, 2012).

The general mass yield of the shredding and sorting processes is around 80 % for mixed waste (Derichebourg, 2012). Slightly more than half of the losses occur during the shredding process (dust and very small shredding residues), while the rest is lost during the sorting operations. There is always a trade-off between the purity of the treated scrap targeted and the acceptable amounts of losses: a more discriminant sorting process will result in a cleaner final product, but more low quality scrap would have to be discarded.

Today, the main outlet from treated mixed aluminium scrap in France is secondary foundries or export, with relatively low specifications on scrap purity. The major scrap dealers have generally non interest in sorting to well the aluminium scrap. Especially since the beginning of the economic crisis in 2008, there has been large cut-offs in jobs in the recycling industry in France, and an increased speculation on raw materials. Therefore, it is less risky for the main players to treat as much scrap as they can, as fast as possible, at the possible expense of quality. It has both the advantages of decreasing the need for labour and avoiding owning too much stocks of scrap for a long time while facing the risk of a drop in prices due to speculation or quick changes in the economic situation (Derichebourg, 2012). It also means that when the aluminium profiles are mixed upstream in the value chain, they will normally not be reused for the remelting of extrusion billets, which shows the importance of preliminary on-site sorting for a Window-to-Window project to be successful.

Landfilling (process 11)

The landfilling process is not studied into details in this system. It simply represents the final destination of scrap lost during the collection or sorting processes. Due to the high collection rates for aluminium and the effective sorting technique, only relatively low volumes are landfilled each year. Most of the aluminium landfilled is under forms that cannot be beneficiated, for instance when the shredding residues are too small to be collected, or when the aluminium fraction in some products is either too small to make recycling profitable, or too deeply entwined with other materials.

Separation of the different product parts (process 12)

The aluminium parts of the products are most of the time summarily separated from the inert or organic material. For instance, in the case of aluminium windows, the craftsmen who get the obsolete windows (generally installers or metal builders for refurbishment, demolition contractors otherwise) will remove the glazing and the non-aluminium parts that are easy to remove. This process usually takes place spontaneously because of the large scrap price difference: whole windows with glazing (containing approximately 50 % of aluminium mass) are usually worth 200 to 300 €/ton, compared to 1000 €/ton without the glazing (Guilloteau, 2012). It is then profitable to remove the glazing for the craftsmen since they will earn more money with the scrap and for the scrap dealers because they want to avoid spending time on these operations.

If the aluminium profiles after separation are clean from other materials, they can be remelted directly. This is usually the case with profiles without thermal break (the polyurethane strips are very hard to remove) and without Zamak (this zinc alloy is used inside the corners of the windows, curtain walls etc. to hold the profiles together, and are hard to remove). As a consequence, for products without thermal break it is possible to obtain clean profiles simply by cutting off the corners, which is sometimes done. However, in most cases, the parts with impurities remaining will be shredded, and then sorted again depending on the expected final use. Even clean aluminium profiles are usually sheared at scrap dealers' plants in order to maximize the mass carried by truck: whole length profiles (1 m or more) take so much space that it is impossible to fill in more than 5 tons per truck, while with parts after shearing being approximately 40 cm long it is possible to load trucks of about 23 tons, which is almost the legal limit in France (de Foucauld, 2012).

Shredding of aluminium scrap (process 13)

The scrap with impurities is cut into smaller pieces (approximately 20 cm long) by large rotary shredders. A first sorting is realised at the output of the shredder. Some magnets will remove the materials containing iron and steel, and then the rest of the shredded parts will be sorted by ventilation.

The yield of the shredder is about 92 % in aluminium mass; the rest ends up together with as shredding residues (dust which is definitely lost or small aluminium parts mixed with other waste and can be recovered to a certain extent). This yield is higher than for the mixed scrap treatment process, because the inputs consist of cleaner aluminium scrap. Therefore, less shredding is needed, there is less risk to see aluminium mixed with other materials, the scrap is more homogeneous, and the different settings can be adjusted more precisely.

Sorting of shredded scrap (process 14)

The different sorting techniques have already been described in the part on mixed scrap treatment (process 10). The sorting processes are basically the same, but as the inputs of scrap are cleaner, a better quality of the final product can be achieved more easily.

It is assume that some scrap from other sectors is entering the system at this point. This comes from the aluminium profiles used in other applications than the building industries. The system also takes into account the presence of some 7xxx alloys scrap in the sorting mix. This is highly hypothetic today, but it is expected that in the future, sorting processes will allow differentiating better between the different aluminium alloys, and then make possible to get hold of more scrap for billets remelting (Bohling, 2012).

Clean old aluminium scrap market (market M4)

This process represents the market of post-consumer building profiles scrap, well sorted and which could be reused directly by remelters provided that a few technological improvements are made in the remelting process. Indeed, today no remelting facility is using post-consumer scrap in France (Le Bouquin, 2012). Therefore, in our system all the scrap reaching the old scrap market is considered either exported or used for other applications than building profiles. For the same reasons, no imports are assumed. The main outlet for post-consumer scrap today is either secondary foundries or export to other Europeans countries such as Spain, but more and more to developing countries such as India and China, especially since the beginning of the economic crisis in 2008.

However, the scrap reaching this market is considered as clean aluminium profiles scrap. Therefore, is should be possible to reuse it in remelters, providing that some minor improvements are made in the collection and sorting processes.

New aluminium scrap market (market M5)

The current situation of the new aluminium scrap market is that the supply of process scrap is not sufficient to cover the demand of the industry. The economic crisis has led to a decrease in the total industrial production, so less process scrap is generated, but the remelters and secondary foundries still need scrap to fulfil their capacity in order to be profitable. During the last year, the French market has also become more and more sensitive to foreign pressure: the recession has turned a formerly local business into a more international market, pulled up by the growing needs for raw materials in developing countries.

This status leads to higher scrap prices and more tension on this market. This is all the more true for high quality scrap, such as aluminium profiles without surface treatment, which can be used for a broader range of applications. To depict this situation, the new scrap market imports aluminium profiles both from other countries and industrial sectors. These imports are calculated using mass balance equations in order to fulfil the demand from the remelters. The exports amount to about 20 % of the total amount of scrap reaching the market (Le Bouquin, 2012), and are expected to grow if the economic pressure on process scrap from foreign countries is not settling down.

2.1.3 Mathematical modelling for the static model

The system is represented as a diagram showing the different flows, processes, and stocks. An example of such a diagram is shown on the figure 8. The material flows are represented with arrows, the industrial processes with rectangles, and the markets with diamonds. A market is defined as a specific process in which there are exchanges of goods without any physical transformation on them. In this process, there is only one stock, for the use process, called S2, and the yearly stock variation is called ΔS2. The system boundaries are figured by the dashed frame.

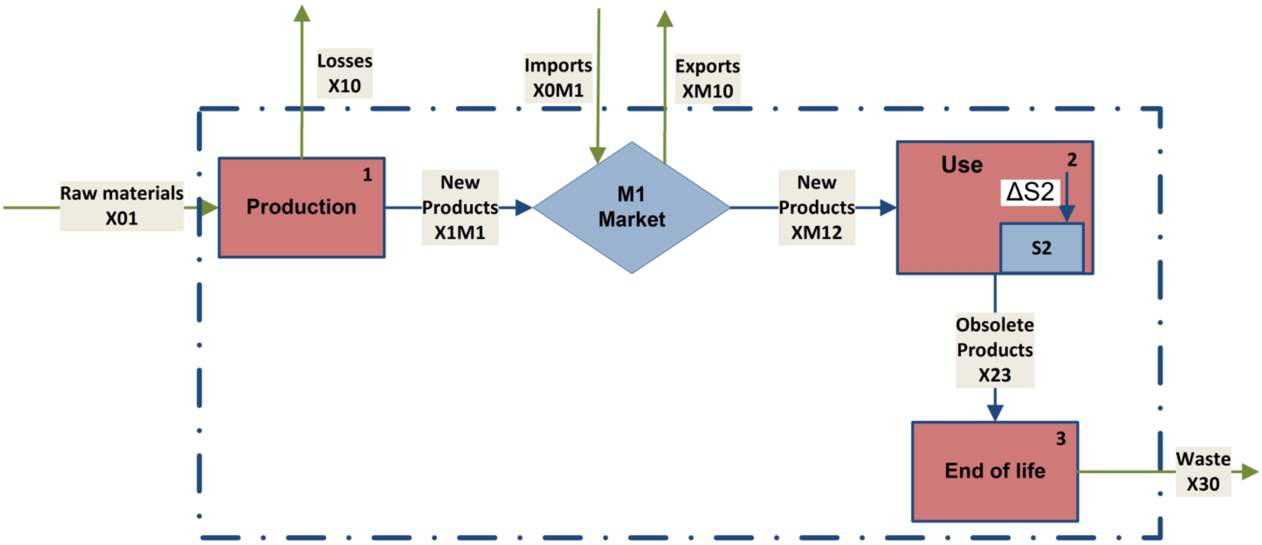

Figure 8: Example of a MFA diagram

Each individual process follows the laws of mass balance. Therefore, for each process, the yearly inputs (I) minus the yearly outputs (O) are equal to the yearly stock variation (ΔS):

$$\Delta S = \sum I - \sum O$$

For the system above, we then have 4 mass balance equations:

$$\left\{\begin{array}{ll} X_{01} - X_{10} - X_{1M1} = 0 & (1) \\ X_{1M1} + X_{0M1} - X_{M10} - X_{M12} = 0 & (2) \\ X_{M12} - X_{23} = \Delta S_2 & (3) \\ X_{23} - X_{30} = 0 & (4) \end{array}\right\}$$

Then, to resolve the system, we need model approach equations, which link system variables to parameters. They describe for instance yields of processes, share of imports, etc., usually through the use of transfer coefficients (named k_{xyz} …) or other parameters (stocks, consumption values…):

$$\left\{\begin{array}{ll} X_{10} = k_{x10} * X_{01} & (5) \\ X_{M10} = k_{1M10} * X_{1M1} & (6) \\ X_{0M1} = k_{0M12}\, X_{1M2} & (7) \\ S_2 = S & (8) \\ X_{M12} = C & (9) \\ X_{23} = EoL & (10) \end{array}\right\}$$

We then have 10 equations for 10 variables (8 flows, one stock, and one stock variation). It is then possible to calculate each flow as a function of the independent input parameters.

2.2 Dynamic modelling

2.2.1 Time scale

The long average lifetimes of the aluminium joinery products would make necessary to use data that go very far back in time for the dynamic model to provide good estimates of the current scrap availability. However, as the aluminium joinery is a quite recent industry, it is useless to go further back than the 1960s, because both the volumes produced were too small to be significant and the production data were not carefully recorded. The inputs needed for the model are then figures on the historic production of aluminium joineries from 1960 to 2010.

The forecasts of the model go as far as in 2100, again because of the long lifetimes of the products. Nevertheless, it is quite utopic to forecast the size of the annual production further ahead than 2020, so the results should be considered with the greatest caution. In order to try model the future evolution, three growth scenarios for the period 2010-2100 were considered (see part 2.2.3). In any case, even if these long-term scenarios are not relevant to understand the current situation and develop a logistic model for the Window-to-Window project, they remain interesting to assess the future potential of this source of aluminium supply.

2.2.2 Determination of lifetimes for different aluminium joinery products

As there is little information available on the lifetime of aluminium joineries, it is useful to start by looking at the lifetimes of buildings. Indeed, the lifetime of a building component cannot exceed the lifetime of the building itself, so this would give an upper value.

A study using a generation life table for several cohorts conducted on dwellings in New Haven, CT, concluded to expected lifetimes between 100 and 150 years, with a lifetime distribution function best described by a lognormal distribution (Müller, et al., 2007). Another study by Gleeson (1985) used a current life table approach on a sample of buildings in Indianapolis, IN, and found an average lifetime of 99.6 years. However, Johnstone (2001), using the same data, estimates the average service lifetime to be between 96 and 118 years. On the other hand, Komatsu et al. (1992) found lifetimes ranging from 28 to 41 years for different building types in Japan, which could also be explained by regional differences. The commercial buildings seemed to have a shorter lifetime than dwellings. However, these numbers are to be used carefully, because they apply mainly to traditional Japanese houses, in an earlier historic period, so we can expect large differences with French buildings. The definition chose for the average lifetime was "when the half of a cohort should be demolished", which generally leads to smaller values, especially when the lifetime distribution function follows a lognormal distribution.

Previous studies on dynamic modelling have already addressed the issue of the scarcity of precise lifetime data and the lack of consensus in the literature, and hence chose to represent the lifetime of buildings by a normal distribution for the sake of simplicity (Müller, 2006; Bergsdal, et al., 2007). The same will be done in this study.

To study the stock dynamics of the Norwegian dwelling stock, Bergsdal et al. (2007) chose to examine 3 different scenarios: a high scenario with a fixed lifetime of 125 years, a low one with a fixed lifetime of 75 years, and a medium one with one with a lifetime of 150 years for dwellings constructed in 1800, progressively decreasing to 100 years in 2000 and 95 years in 2100. This hypothesis is supported by the fact that dwellings were designed to have longer lifetimes in the past. In the same kind of study, Sartori et al. (2008) chose to use three different scenarios, with mean values of 75, 100 and 125 years. In all cases a normal distribution with a standard deviation of 25 years was chosen.

It is generally considered that a building would be in average completely renovated once during its lifetime, which means changing most of the aluminium joineries as well. Sartori et al. (2008) considered an average renovation period of 40 years for an average lifetime of 100 years. Therefore, a good estimate would be to assume that the lifetime of aluminium joineries is about slightly less of half the lifetime of a building: if they are not changed before, they would be changed during the renovation anyway, so half the lifetime is more or less an upper value. We then have an upper value for the lifetime of aluminium joineries ranging approximately between 30 and 75 years.

In theory, it would also be better to use different lifetimes for the different aluminium joinery products. This is mostly due to the fact that aluminium joinery products usually do not reach the end of their service lifetime because of deterioration but because they become obsolete. Indeed, aluminium joinery products are usually replaced for three main reasons:

- *functionnal obslescence:* for instance, if new products provide better insulation, especially if this is needed to meet new environmental criteria.
- *style obsolescence*: if a company wants to change the façade of its building to make it look more modern, if a building is renovated in a new style and the old joineries do not fit anymore, when the landlord changes and is not pleased with the old appearance ...
- *destruction or renovation of the building*: here, nothing is wrong with the aluminium products, but since they are part of the surrounding building, they will be removed.

Hence, independantly of the designed lifetime of a product, which is usually very long for aluminium joineries, a product that is mostly used in applications that make one of these three types of obsolescence more likely to occur would tend to have a shorter lifetime in average.

Indeed, some items, like shop fronts and curtain walls to a lesser extent, will tend to have a shorter lifetime because there seems to be more turnover in commercial than in residential buildings (Komatsu et al., 1992), since they are more dependant to economic considerations. This applies also to partition walls, because there are mostly used in office buildings, and are designed to be very easy to remove if there is a need for change in the company. Other products like sunshades are more fragile, and then their expected lifetime wille be shorter. On the other hand, products that are mostly used in dwellings and do not play a major role for insulation, such as doors or conservatories, would tend to have a longer lifetime.

However, even if we can easily make hypotheses on which types of products will tend to have the longest lifetimes, no data exist on the quantification of such differences. Moreover, the statistics available on the breakdown of the historic aluminium production for buildings into the different product categories are so imprecise that it would most probably not improve the overall quality of the results to make such refined distinctions. Thus, it was decided to only differentiate products with thermal break from standard joineries. The reason main is that statistics on the share of thermal break products are available. Besides, we can expect standard products without thermal break to be replaced faster in the future due to the comfort gain they provide and increased environmental concerns.

Rombach (2002) gives an average lifetime of 30 years for aluminium products in the building and construction sector. This is also the value used by a LCA study on aluminium windows (SNFA, 2008), while R&D specialists in Technal state higher values, with an averag of 50 years (Mendez, 2012). Schlesinger (2007, *CH3: Scrap collection*, p. 28) assumes lifetimes of 40 years for the building and construction sector. The OEA (2007) gives a range from 15 to 50 years for aluminum products used in buildings. Hence, in this study two lifetime scenarios have been considered to correspond with these long and short lifetimes estimates (see table 1 below):

Table 1: Values used to define lifetime scenarios

Parameter	Product type	Short Lifetimes	Long Lifetimes
Lifetime (years)	Thermal break	35	50
	Standard	30	40
Standard deviation (years)	Thermal break	17.5	25
	Standard	15	20

The two scenarios follow a normal distribution. The standard deviation was arbitrarily set to half of the average lifetime for all the scenarios. The reasonning for doing so is that no information is available on this specific question, and it seems to represent well the high variability for the lfietime of such products.

The following graph represents graphically the different scenarios chosen. The left graph shows the mortality rate per year, which means the percentage of the initial inputs from a given year discarded each year. The right graph is the survival function, which shows the percentage of the initial inputs from a given year still present in the in-use stock over time.

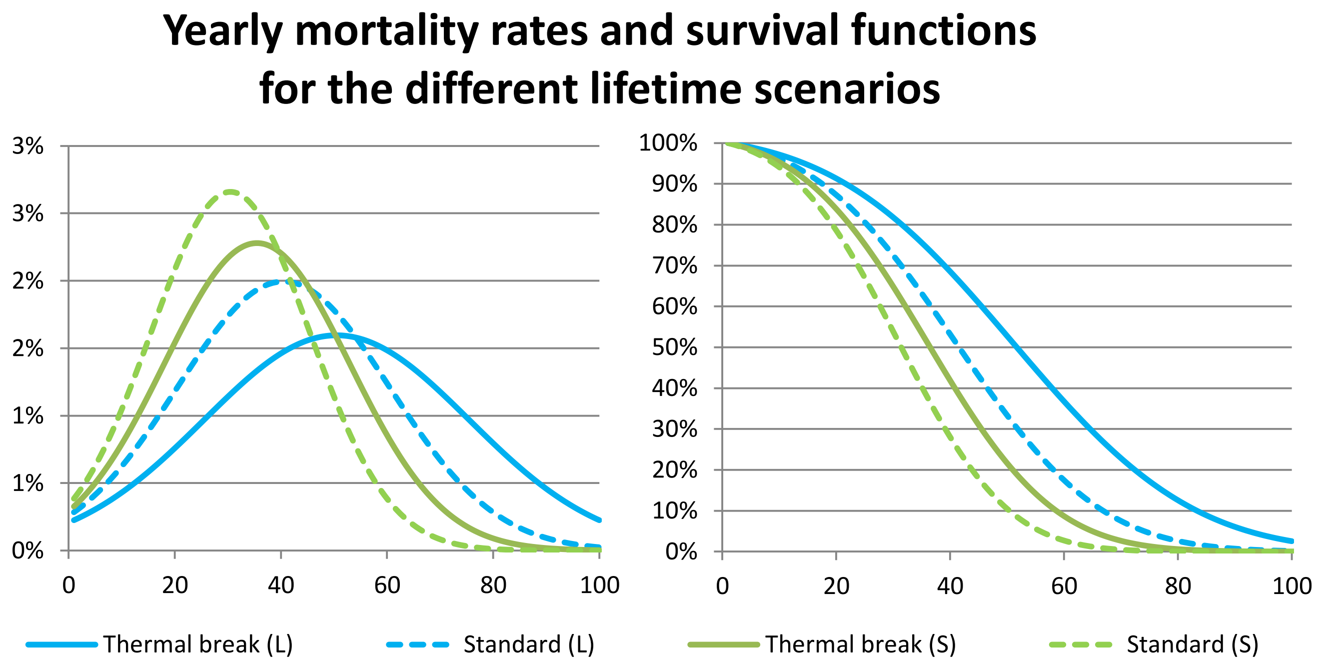

Figure 9: Long (L) and Short (S) lifetime scenarios for thermal break and standard products

2.2.3 Scenarios development

The likely future evolution of the outputs of scrap was estimated using three typical scenarios for the becoming of the French aluminium joinery market. These scenarios were then combined with the two different lifetime scenarios to predict the likely yearly outputs of extruded scrap from French buildings.

Scenario 1: continuous and steady geometric growth

This scenario is based on the assumption that the total French aluminium joinery market will keep growing geometrically at the same pace it is doing today, which means a yearly increase of 3%.

As shown on the figure 10 below, this scenario seems quite unrealistic in the way that it leads to a spectacular increase of the inputs during the next century. However, this is consistent with the growth rates experienced by this sector so far, and there is no way to tell if or when the production will stabilize, so this scenario is still worth to look upon. Moreover, the growth rates for the construction sector in Western Europe are forecasted to be around 1.3 % between 2010 and 2020 (EUROCONSTRUCT, 2011). Since the market share of aluminium joineries is currently growing at the expense of wood, this scenario does not seem so unrealistic, at least for the next years.

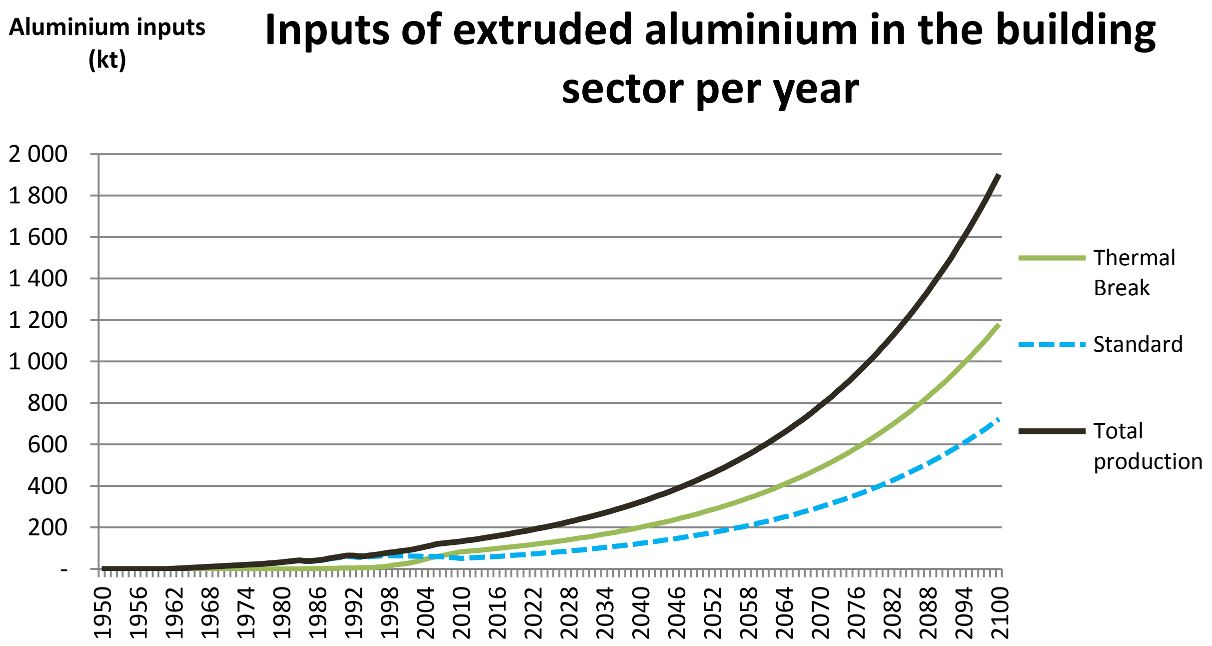

Figure 10: Inputs scenario 1, continuous and steady geometric growth

Scenario 2: slow-down of production growth – linear pattern

In this scenario, it is expected that the production will keep growing at a constant arithmetic pace. It is assumed that thermal break profiles have now reach their maximum share of the market, and that both standard and thermal break profiles will keep growing by 2000 tons/year each, corresponding to the actual growth rates.

When looking on the figure 11 next page, one might object that this shape is quite unrealistic as well, but in the absence of better estimates, this gives an idea of what could be the production if the economic conditions were not as favourable as in the scenario 1.

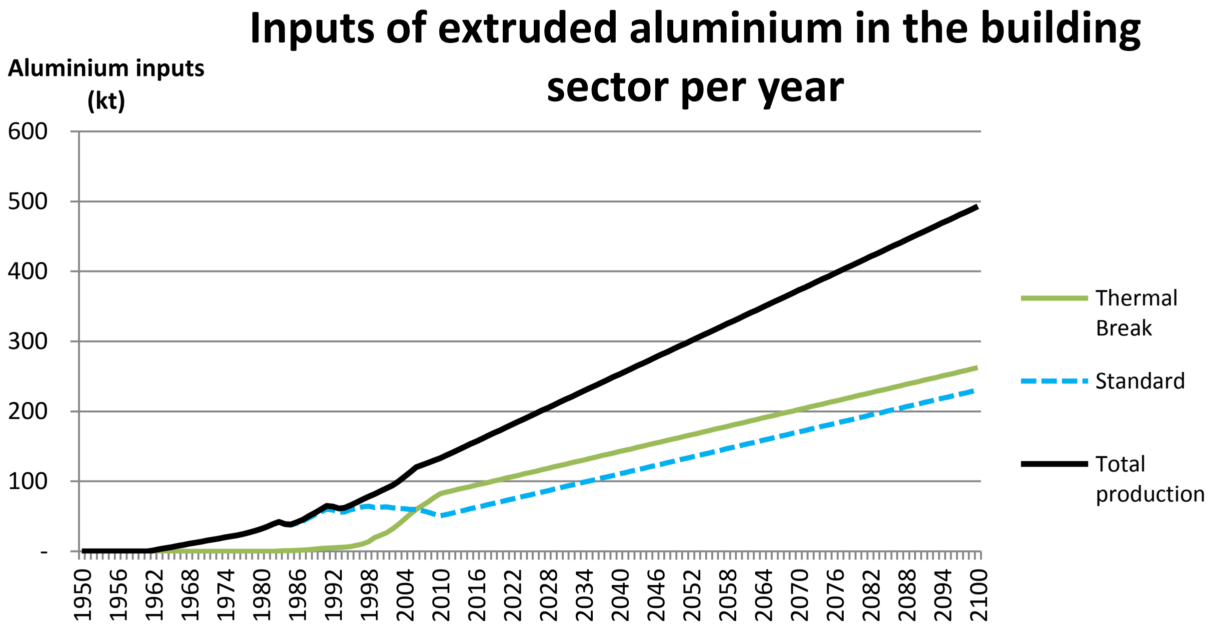

Figure 11: Inputs scenario 2, slow-down of production -linear pattern

Scenario 3: production peak

Here, we consider that the production will keep growing, then reach a maximum, and then start declining. This is likely to happen if aluminium joineries are made obsolete by another technology. Geometric growth rates were used, starting at 3 % in 2012, reaching 0 % in 2040 and progressively going down to – 3 % in 2100.

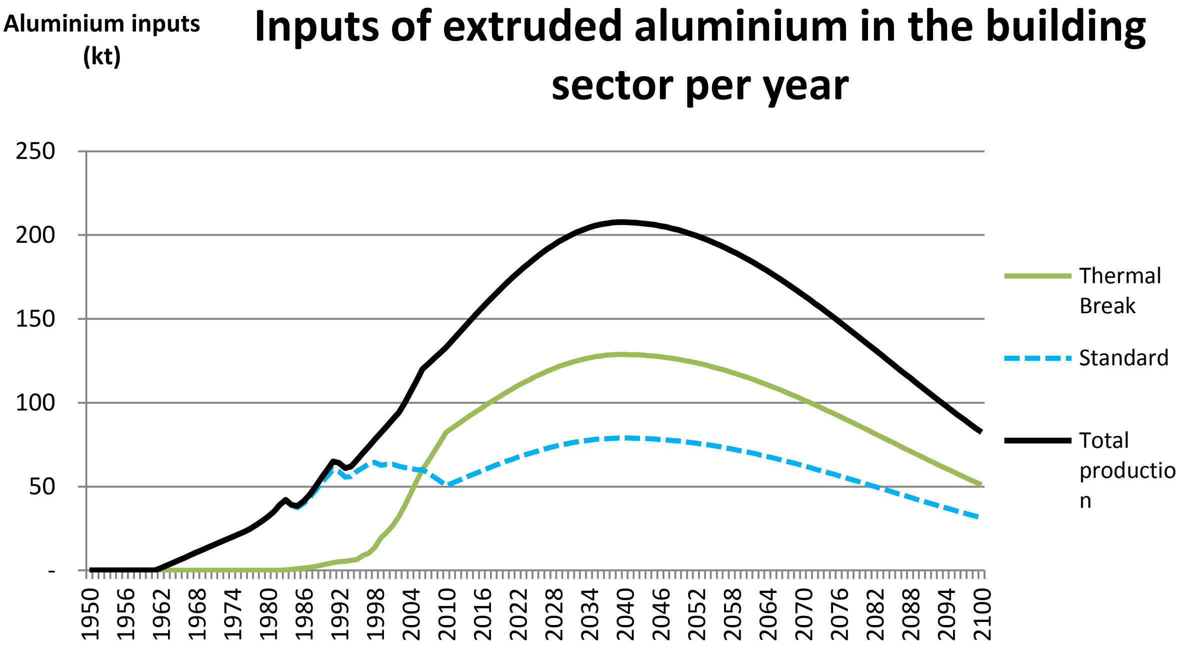

Figure 12: Inputs scenario 3, production peak

2.3 Sensitivity analysis

A sensitivity analysis was performed for the most interesting flow of the static model: the total flow of post-consumer scrap reaching the old scrap market (sum of the flows $X_{14\text{-}M4}$ and $X_{12\text{-}M4}$), which summarises the availability of post-consumer scrap in France. The aim of the sensitivity analysis is to determine which parameters referring to the collection and beneficiation subsystem have the higher influence on this flow. Then, the results of the analysis can be used to focus on improving the parameters with the greatest impact.

Another use of sensitivity analysis is to be able to identify which parameters require the highest accuracy: if the sensitivity of a parameter on a flow is high around the NOP, a small uncertainty on the parameter will have a strong influence on the flow. On the other hand, a parameter with a relative sensitivity close to zero for a given flow will have almost no effect on the value of the flow; it is therefore less critical to measure its value precisely.

The sensitivity of each parameter is tested using a One-Factor-At-a-Time (OFAT) approach, which means that the sensitivity of each parameter is changed independently from the other ones. This method is quite approximate as the interactions between the different parameters are neglected, and because it does not cover the whole spectrum of the available changes in the parameter values (if some changes add to each other for instance). However, this approach was chosen for the sake of simplicity and the immediate interpretation of the results it enables.

The complete mathematical expression of this flow in terms of the different parameters is as follows:

$$\begin{aligned} X_{OS} = S_{bn} * k_{x14M4} + O_w * {} & [k_{x8bM3} * k_{x78b} + k_{x9M3} * (1 - k_{x78b})] \\ & * [1 - k_{xM30a} - k_{xM30b} - k_{xM310}] \\ & * [k_{x12M4} + k_{x1314} * k_{x14M4} * (1 - k_{x120} - k_{x12M4})] \end{aligned}$$

This flow is then expressed as a function of 12 system parameters. The relative sensitivities are calculated from the partial derivatives of the total flow with respect to each parameter. The derivatives are calculated at the normal operating point (NOP), which is the actual value of the parameter in the system studied. The relative sensitivities are obtained using the following equation, with $X_{OS}$the total flow of old scrap going to the market, P_ia given parameter, and $\bar{S}(X_{OS}, P_i)$ the relative sensitivity of X_{OS}relative to P_i:

$$\bar{S}(X_{OS}, P_i) = \left.\frac{\partial X_{OS}}{\partial P_i}\right|_{NOP} * \frac{P_i}{X_{OS}}$$

A relative sensitivity of 1 means that a change in the value of a parameter (close to the NOP) will result in the same proportional change in the value of the flow. When the relative sensitivity is smaller than 1, the parameter has a relatively low effect on the flow. On the other hand, relative sensitivities bigger than one render a strong impact on the flow, usually with some kind of leverage effect or positive feed-back loop. A negative sensitivity means that an increase in the value of the parameter will result in a decrease on the value of the flow.

2.4 Data sources

In addition to the existing literature on this topic, which is quite few, other data sources were used to build the model, taking advantage of the cooperation with the inside of the industry.

2.4.1 Institutional sources

GLFA (Groupement des Lamineurs et Fileurs d'Aluminium)

The GLFA is the trade union of the French extruders. It records data from internal sources, and produces tables that give the production of building profiles per final destination in France for different years. These data are very detailed, and also provide information on the geographical repartition of the production, which was not used in this model, but could be interesting for modelling regional flows in the future.

The drawbacks are that the categorisation into different sectors and products is not always very relevant and easy to follow, and the international trade is not taken into account. Since about 2/3 of the aluminium profiles used in the building sector in France are imported, the extrapolation from the GLFA figures is quite inaccurate, but there were no other sources available on this topic. This is not a problem for estimating the yearly volumes of aluminium profiles used in aluminium joineries, because these data were available through HBSF sales figures, but it remains very hard to estimate the relative importance of the other industrial sectors in terms of use of aluminium profiles. For this reason, there is very little information on the aluminium profiles used in other industrial sectors. This is not a problem for the production subsystem, but it is impacting the accuracy of the results for the collection subsystem as these profiles eventually come back inside the system boundaries through collection.

EAA (European Aluminium Association) Extrusion shipments

The EAA is the organisation representing the aluminium industry in Europe. Its main missions are to monitor and manage topics of common interest, update and diffuse the European aluminium statistics, encourage studies in all relevant areas of aluminium and organise the generic communication and promotion of aluminium (EAA, 2012). The EAA also includes the OEA (Organisation of European Aluminium Refiners and Remelters) which is more relevant for recycling topics.

The main sources used from the EAA are the annual statistics that record apparent consumption of building profiles in all European countries, split between BS companies and direct sales. Compared to the data from GLFA, this takes into account the imports and exports to give the apparent consumption, which is the critical number to determine the yearly stock addition. However, only the apparent consumption is displayed, and there is no more precision about the final use of the profiles. Hence, it is impossible to know for instance how many profiles are used to make windows, and how many to make doors.

2.4.2 Site visits and questionnaires

Internal plants owned by Hydro

Three different plants owned by Hydro have been visited, to understand the process of importance for this project. This included the remelting facility in Lucé in central France, the extrusion plant in HAT Toulouse and the building system operations (design, surface treatment, marketing, distribution and logistics) of HBSF in Toulouse. These visits enabled to grasp the main issues of the upper stages of the value chain.

External visits

Some information about processes in which Hydro is not directly involved has also been collected through site visits and questionnaires. Two different questionnaires have been made: one for scrap dealers and one for metal builders (see Appendix B).

Scrap Dealers

Five sites in three companies (Derichebourg, Decons, GDE) were visited, together with Hydro's employees also involved in the project. Derichebourg is the main player in the French aluminium scrap market, GDE is the second, but mostly established in the West part of France, and Decons is an important local actor in the South-West. The main goal of these visits was to have an overview of the different sorting techniques used to process aluminium scrap as well as to understand the main motivations and challenges of scrap collection from the scrap dealers' side. It was also helpful to understand better the logistics of scrap collection.

HBSF customers (metal builders)

Other site visits have been made to customers of HBSF, either directly or through other Hydro's employees associated in the W2W project. The aim was to visit metal builders of different sizes and specialities (window producers, façade builders, new construction vs. refurbishment, installers etc.). These visits and the use of the questionnaires have made possible to understand the main concerns of metal builders for scrap collection, their usual scrap generation rate, their opinions towards the W2W project and the key logistics criteria to implement the project.

2.4.3 Internal sources

Internal Hydro and HBSF sources were also used. People at HAT Toulouse were interviewed to understand better the extrusion process, and internal marketing studies from HBSF were used to quantify the current and historic production of aluminium joinery products. The characteristics of the products were discussed with R&D specialists of HBSF.

More generally, this project benefited from the experience of the 6 people in the working group:

- Hans Bjerkaas, from the Hydro's Extrusion Competence Centre and project manager.
- Gilles Le Bouquin, plant manager of the Hydro's remelting plant in Lucé, France.
- Jean-Marc Dizel, HBSF Marketing Intelligence Manager.
- Christian Mourier, Responsible of Projects at the HBSF sales department.
- Oscar Sanchez, Head of New Activities in HBS Europe.
- Patrick de Valicourt, Purchasing Manager in HBSF.

3. Results

3.1 Stock dynamics of extruded aluminium in French buildings (dynamic model)

3.1.1 Historic production

In order to estimate the amounts of post-consumer scrap currently available in France, and the likely future evolution of this resource, it was necessary to gather data on the past production. The long life time of aluminium joinery products (about 50 years) makes it necessary to obtain figures as far as in the 60s, which corresponds to the introduction of aluminium in the joinery market.

If some studies exist on this topic, none has been examining the production of all types of aluminium joinery products in such a long time range. Therefore, it was necessary to make estimates in order to produce useable figures from data that that were sketchy at best. Five main sources of data were used:

- Historic figures for Technal and HBS yearly production and market share. Data were available from 1985 to 1997.
- Strategic studies conducted by Jean-Marc Dizel in 2006 and 2010.
- Studies conducted by BATIETUDE every 2 years from 2002 to 2010.
- Strategic study conducted by the European Aluminium Association in collaboration with Péchiney (former French aluminium producer) in 1999, analysing the evolution of the French aluminium joinery market from 1992 to 2000 (EAA, Péchiney, 1999).
- Different internal HBS production and sales values on the share of profiles with thermal break from 1993 to 1996, 1997 to 2001, 2000 to 2005, 2010 and 2012.

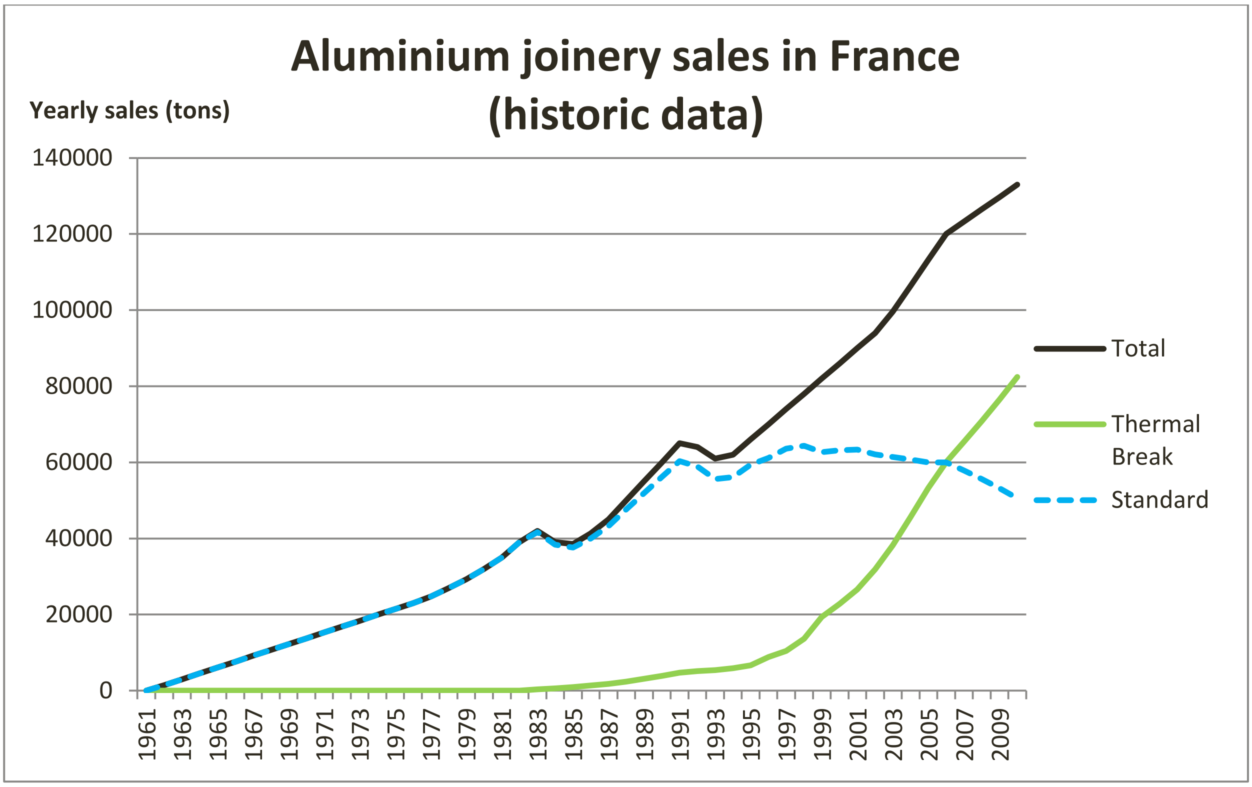

Figure 13: Historic data of aluminium joinery sales in France

In the figure 13 on the previous page, we can notice that aluminium joinery has experienced a steady growth since its introduction on the market 50 years ago. The average geometrical annual growth rate during that period amounts to 9.7 %. This continuous growth has been only interrupted twice, in 1984-1985 and in 1992-1994. These decreases are due to the conjunction of economic crises in the building sector in France with an increase of the market share of PVC products at the expense of aluminium joineries, which are typically more expensive (Dizel, 2012).

When looking at the share of profiles with thermal break, we see a relatively slow growth from the introduction of this technology in the mid-eighties to the end of the nineties. Then, the increase is much faster, due to the combination of two factors: first, the technology had become more mature at this time, and more importantly, extended thermal regulations in the building sectors have made progressively the use of thermal break almost mandatory.

The share of thermal break profiles in 2010 was 62 % of the total production. The slopes of the two curves for thermal break and standard profiles in 2010 might suggest that this share will keep increasing very fast in a near future. However, this does not hold true, because thermal break has already more or less reached its peak capacity, for several reasons. Indeed, a finished aluminium joinery product is an assembly of several profiles. Even windows, conservatories etc. with thermal break, include some standard profiles (put in the inner side of the window), which are stuck together with thermal break profiles. An evidence of this is the sales figures of Technal for the beginning of the year 2012: while 100 % the windows sold included thermal break, this represented only 79 % of the profiles sold for windows (Technal, 2012). Unless new radical technological changes are made, this number seems to be a reasonable maximum for the share of profiles with thermal break in windows production.

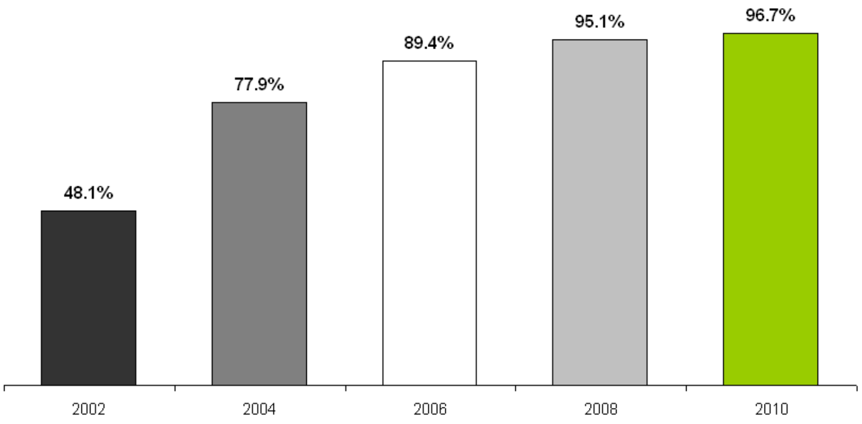

Figure 14: Evolution of the share of thermal break in aluminium windows sold in France from 2002 to 2010 (source Dizel from BATIETUDE 2010)

The share of thermal break in building profiles is also limited by the product categories that do not need them. For instance, the need for good insulation is smaller for inner doors and conservatories, and curtain walls almost never use thermal break, because in this system, the inner and outer aluminium profiles are not in contact with each other, so the insulation is done by the air layer inside the structure. Therefore, it is very unlikely that the share of profiles with thermal break will exceed 65-70 % in the future.

An attempt to derive historic production data of the different product categories has also been made, as shown on the figure 15 below. These data were obtained from the same sources as the other historic production data, but the shares of each product type were less precisely recorded. Therefore, a lot of extrapolations were necessary to be able to draw this curve, which makes the results disputable.

Hence, the results are not reliable enough to be used efficiently by the dynamic model. Besides, given the large uncertainties on the lifetimes of the different products, it is very unlikely that the total accuracy of the forecasts provided by the model would have been improved by considering the stock behaviour of each product category.

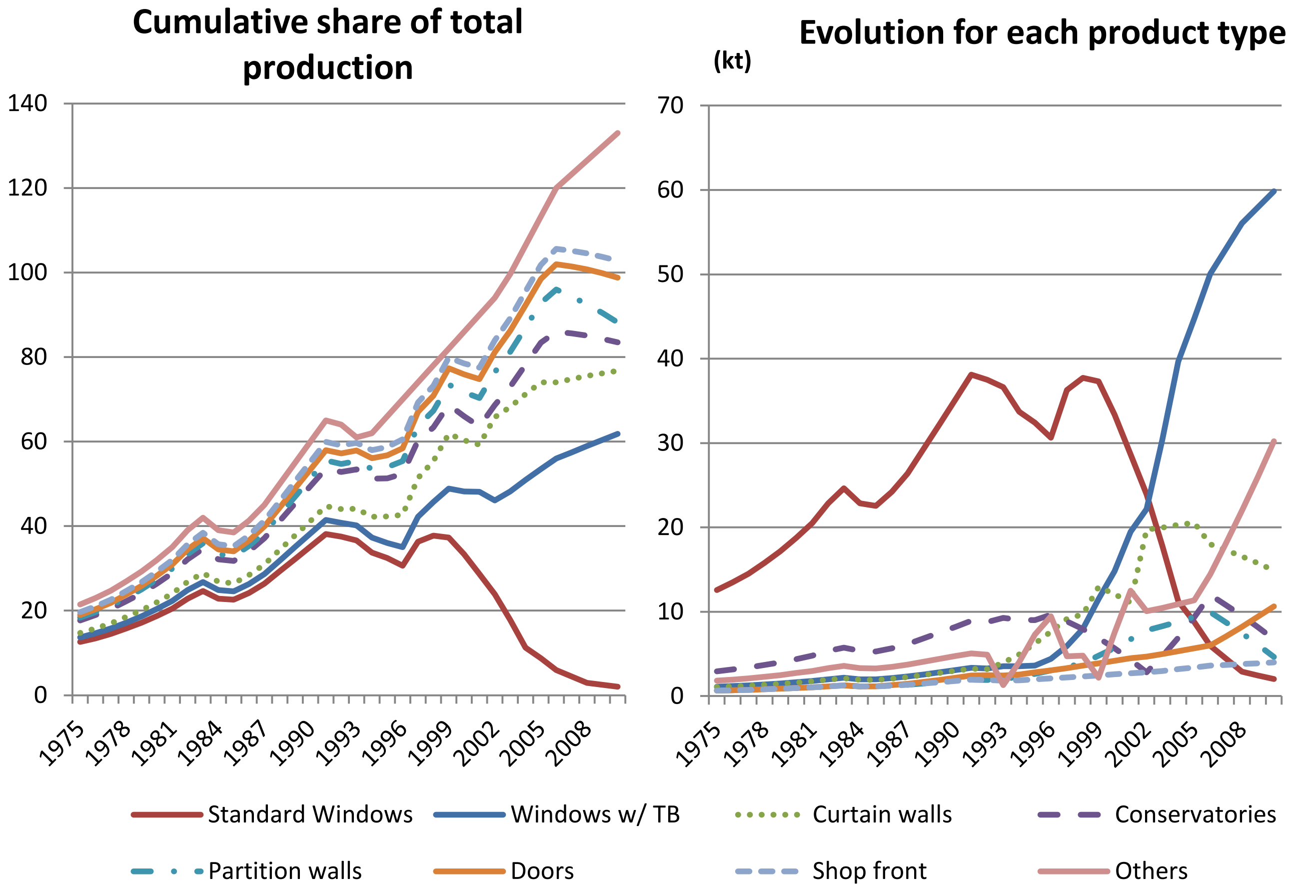

Figure 15: Historic production of aluminium joineries - Breakdown by product categories

If the results show reasonable patterns for some product categories, such as windows were data were more easily available, this is not the case in general. The curves for conservatories and curtain walls show strong inflexion points which are representative of inconsistencies in the different data sources. Indeed, several sources had to be used for different years, and it proved impossible to harmonise them. This is even more obvious for the category “Others”, which gathers all the other types of products. Depending on the source used, some products are included in the list and some are not, which makes the numbers for this category completely misleading.

For these reasons, it was decided not to use these data for the forecasts of the dynamic model, but to stick instead with the previous split into two product categories for the building profiles, standard and with thermal break.

3.1.2 Current availability of post-consumer scrap

Depending on the lifetime scenario chosen, the dynamic model gives an estimation for the current availability of post-consumer scrap (yearly outputs from the in-use stock) ranging between 26.9 and 40.4 kt/year, including from 4.6 to 6.6 kt/year of profiles with thermal break.

Short lifetimes

Under the hypothesis of short lifetimes, the total outputs of scrap available are 40.4 kt / year in 2012. This includes 6.6 kt of profiles with thermal break.

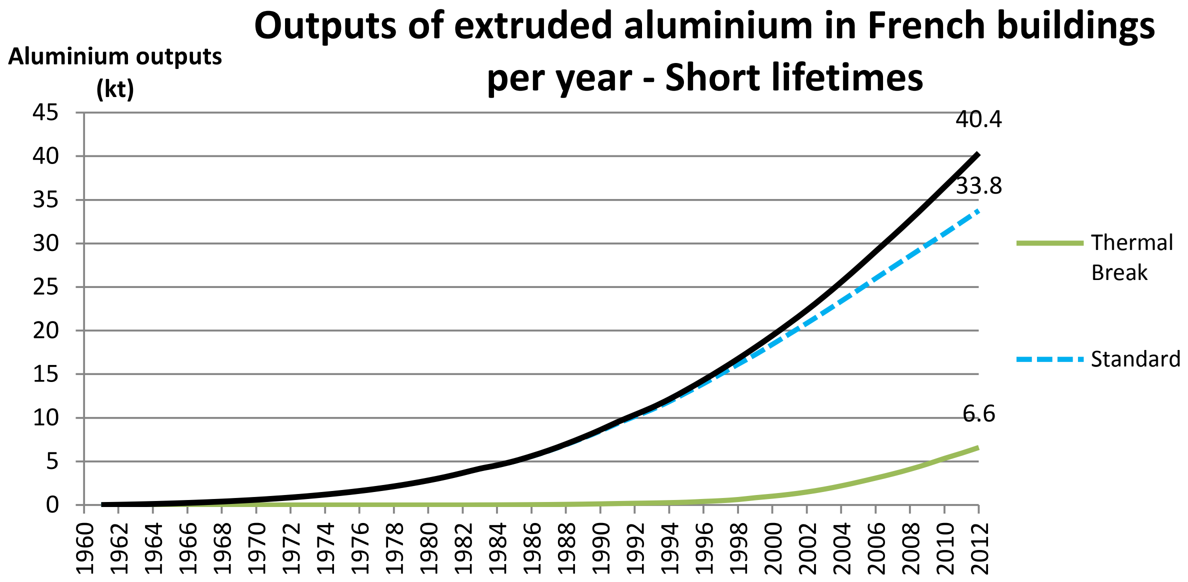

Figure 16: Outputs of extruded aluminium in French buildings per year - Short lifetimes

Long lifetimes

With longer lifetimes, the amounts of post-consumer scrap generated in 2012 are much smaller: 26.9 kt in total, including 4.6 kt of profiles with thermal break.

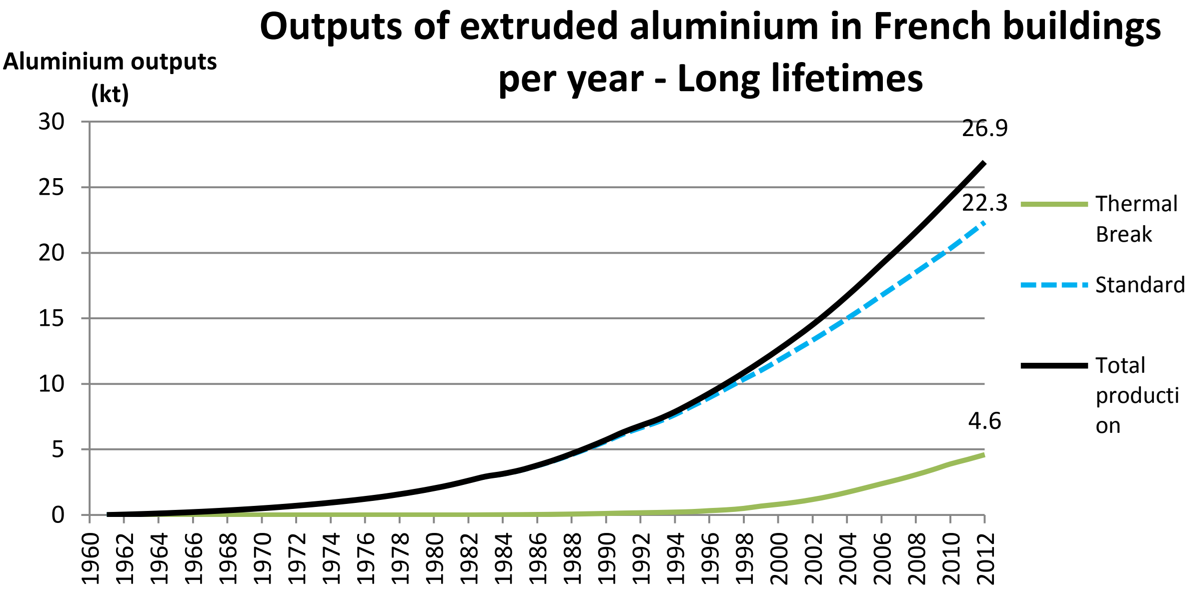

Figure 17: Outputs of extruded aluminium in French buildings per year - Short lifetimes

3.1.3 Future projections

To predict the future evolution of the outputs of extruded aluminium (and hence the available post-consumer scrap), several scenarios have been examined, assuming different evolution of the growth rates for production volumes coupled with different lifetimes of products.

Scenario 1: continuous and steady geometric growth

1a - Short lifetimes

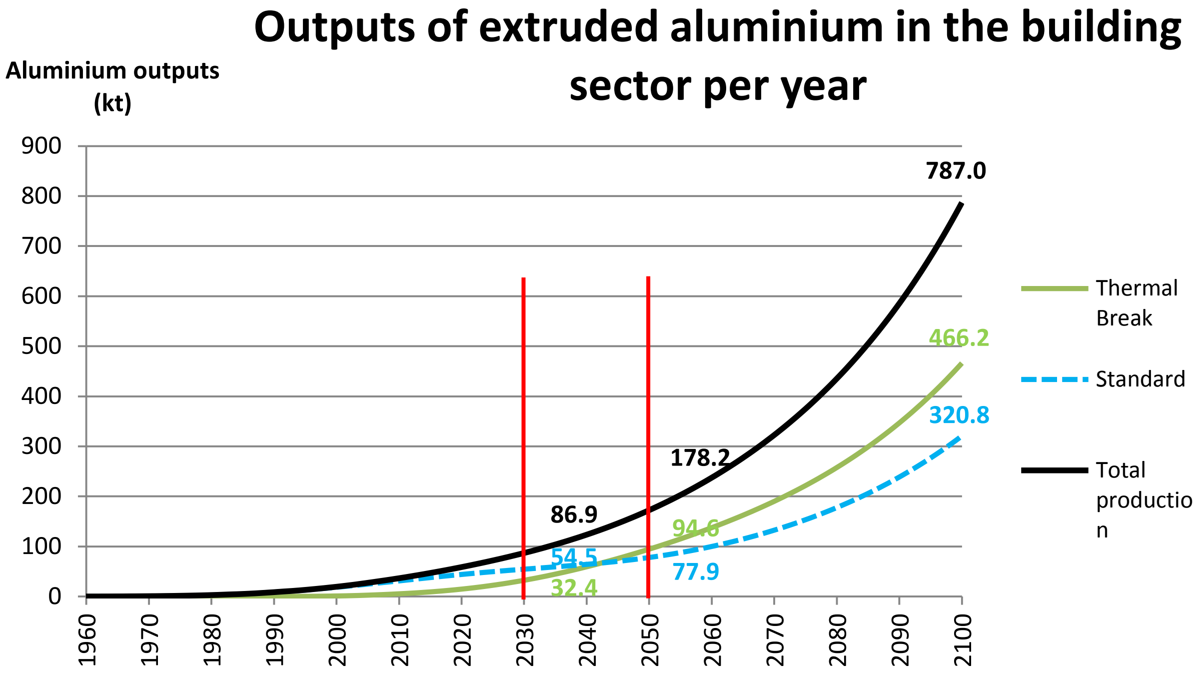

Figure 18: Outputs scenario 1b, continuous and steady geometric growth - hort lifetimes

1b - Long lifetimes

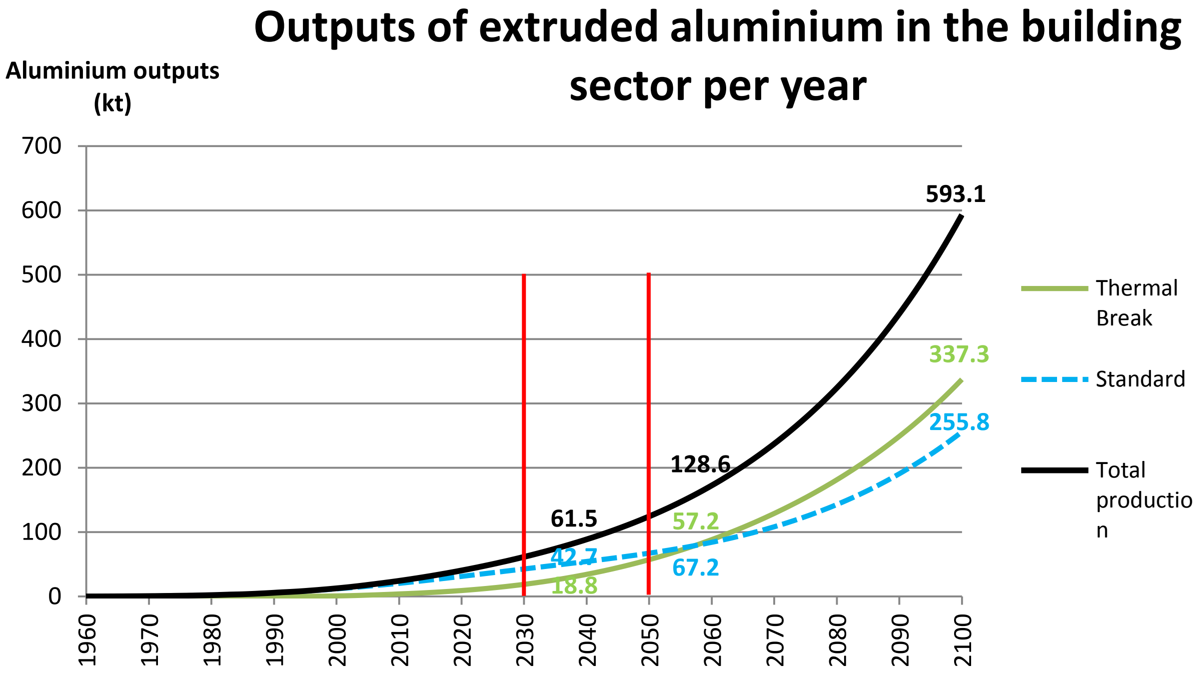

Figure 19: Outputs scenario 1b, continuous and steady geometric growth - long lifetimes

Scenario 2: slow-down of production growth – linear pattern

Compared to the scenario 1, this one shows a slower increase in the outputs, but still predicts a multiplication by more than 2 until 2030 and by almost 10 in 2100.

2a - Short lifetimes

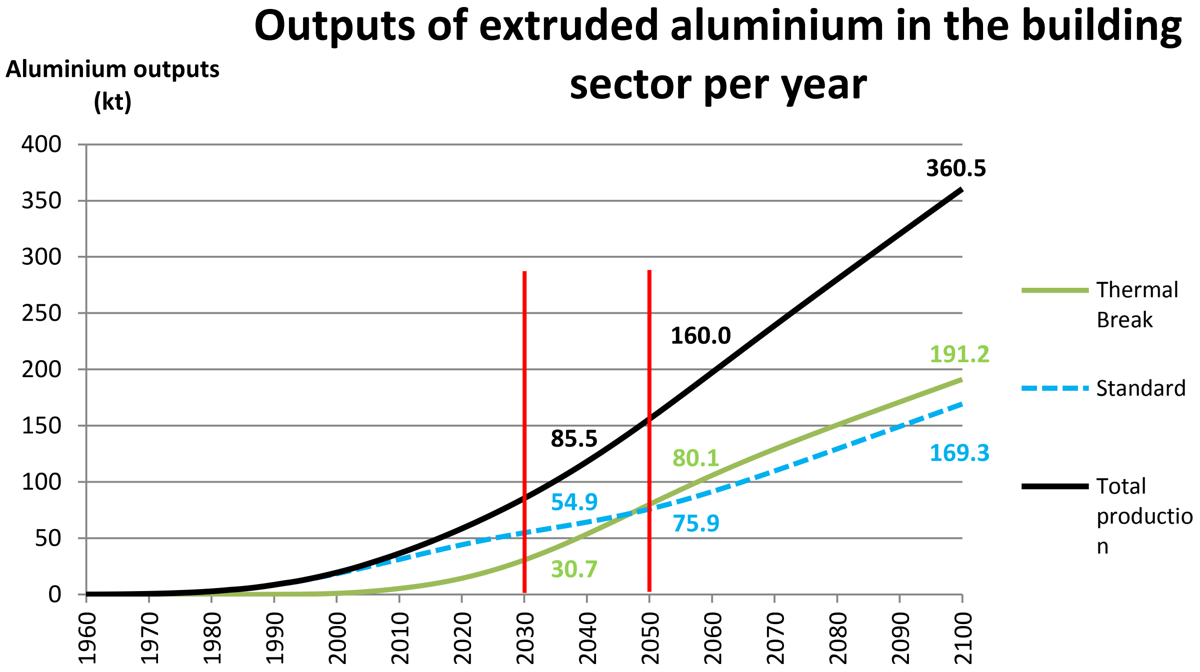

Figure 20: Outputs scenario 2a, slow-down of production, arithmetic growth - short lifetimes

2b - Long lifetimes

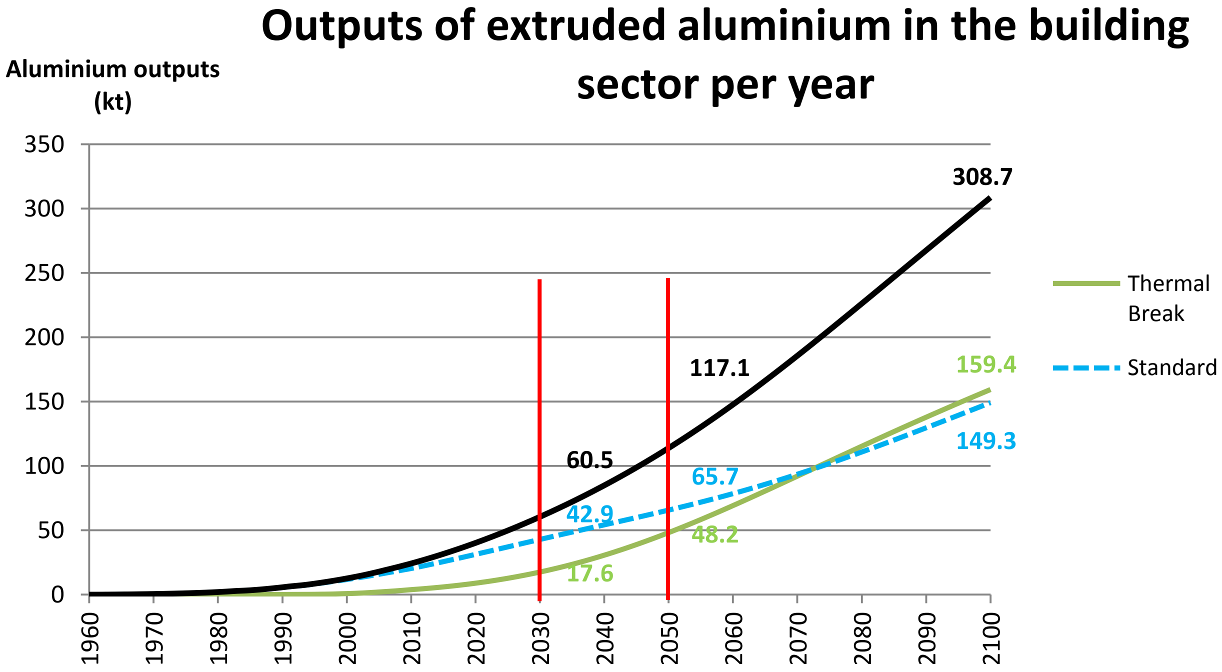

Figure 21: Outputs scenario 2b, slow-down of production, arithmetic growth - long lifetimes

Scenario 3: production peak

Due to the long lifetimes of products, the impact of a production peak will be shifted in time by about 40 years. Therefore, even in this case, the outputs of post-consumer scrap will grow and remain more or less steady during the whole next century, at a level higher than today.

3a - Short lifetimes

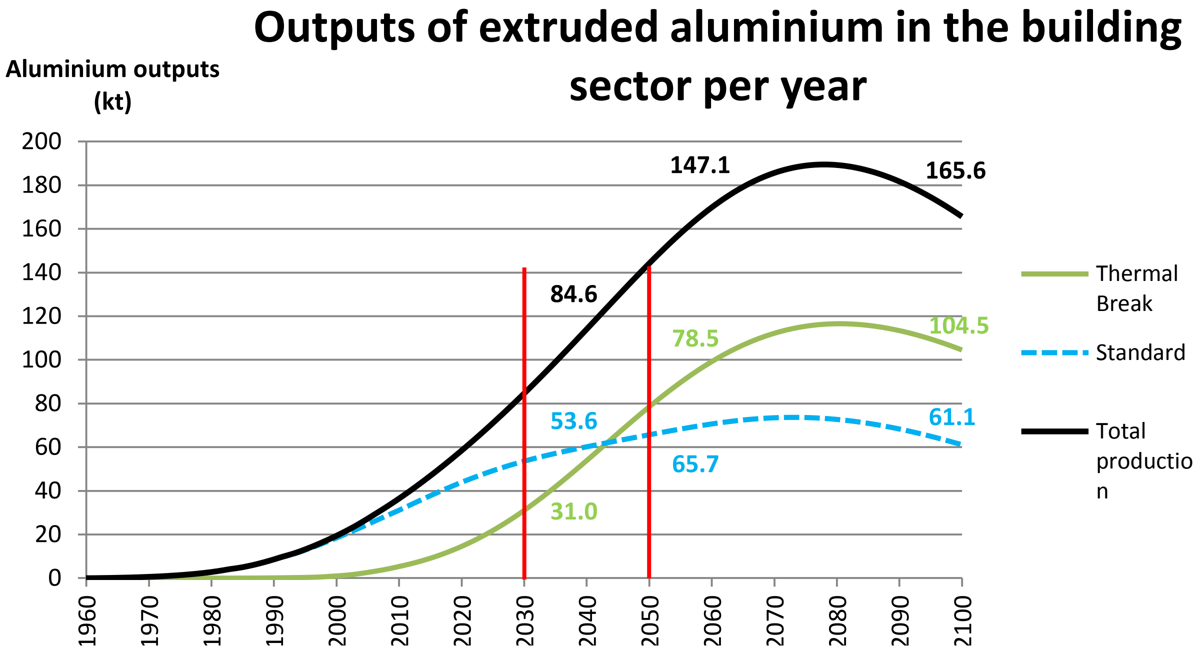

Figure 22: Outputs scenario 3a, production peak - short lifetimes

3b - Long lifetimes

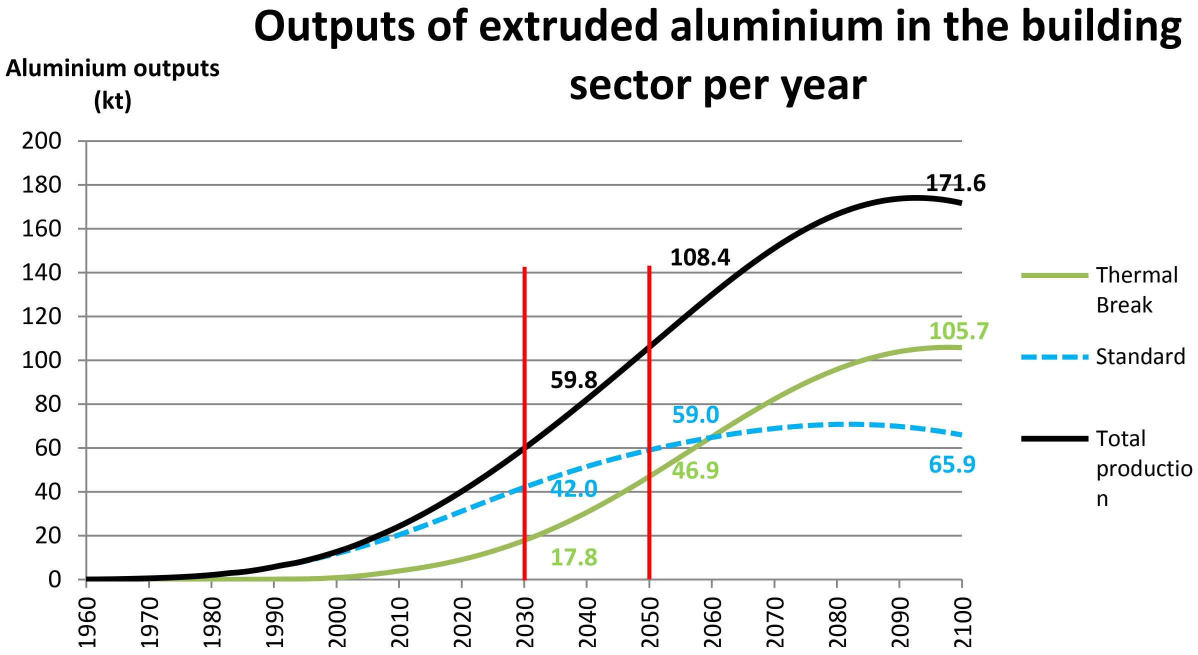

Figure 23: Outputs scenario 3b, production peak - long lifetimes

It is interested to notice than in all scenarios, the share of thermal break profiles in the collected scrap will increase significantly, bringing new challenges for recycling.

Evolution of the total stock of extruded aluminium in French buildings for each scenario

The dynamic model also enables to predict the future evolution of the in-use stock. Of course, the results differ substantially depending on the scenario considered, ranging from about 5 Mt to 45 Mt. However, in any case these figures are higher than the actual numbers (about 2.3 Mt). This represents between 37 and 339 years of the current yearly new products installation, emphasizing the potential of French buildings as an urban mine in future.

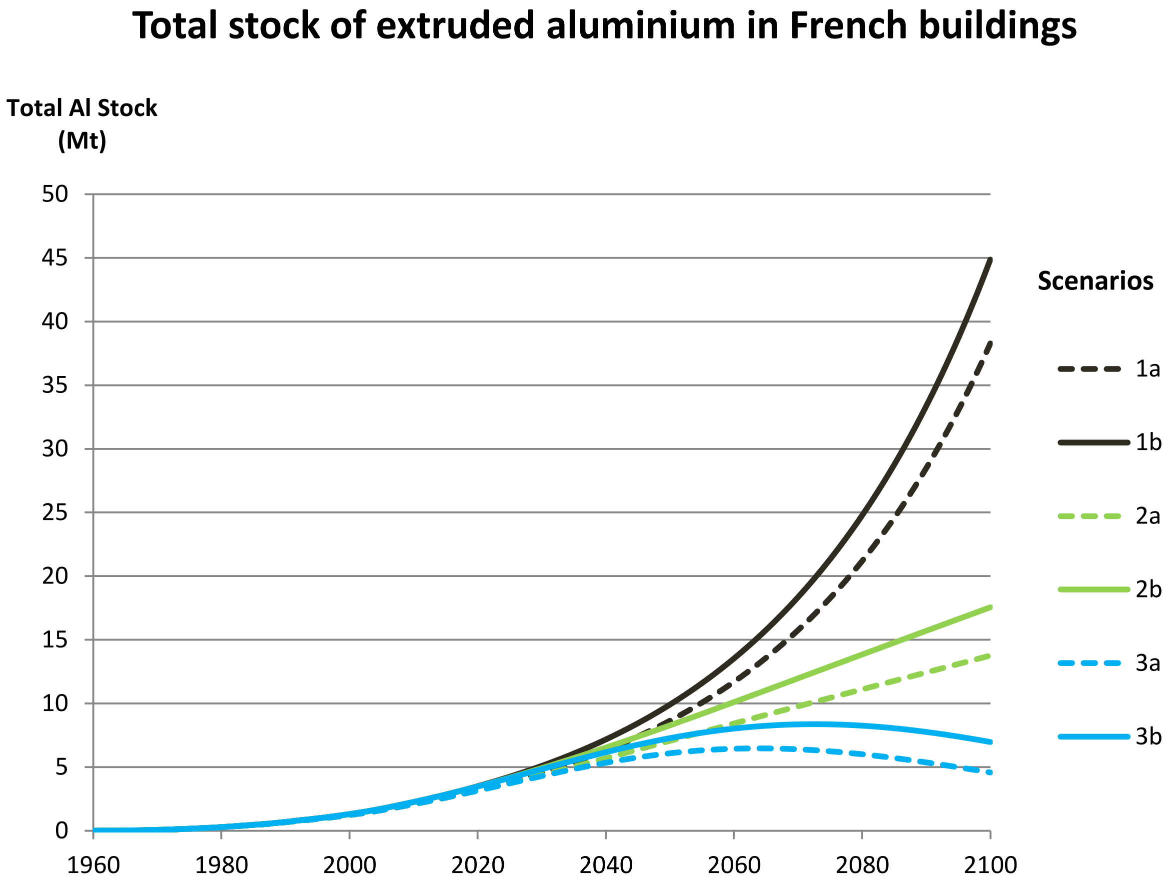

Figure 24: Future evolution of the total extruded aluminium stock in French buildings for each scenario

3.2 Life cycle of extruded aluminium in French buildings (static model)

3.2.1 Overall system

The figure 25 below shows the overall system as it was defined, with the interactions between the 3 subsystems and the outside of the system boundaries.

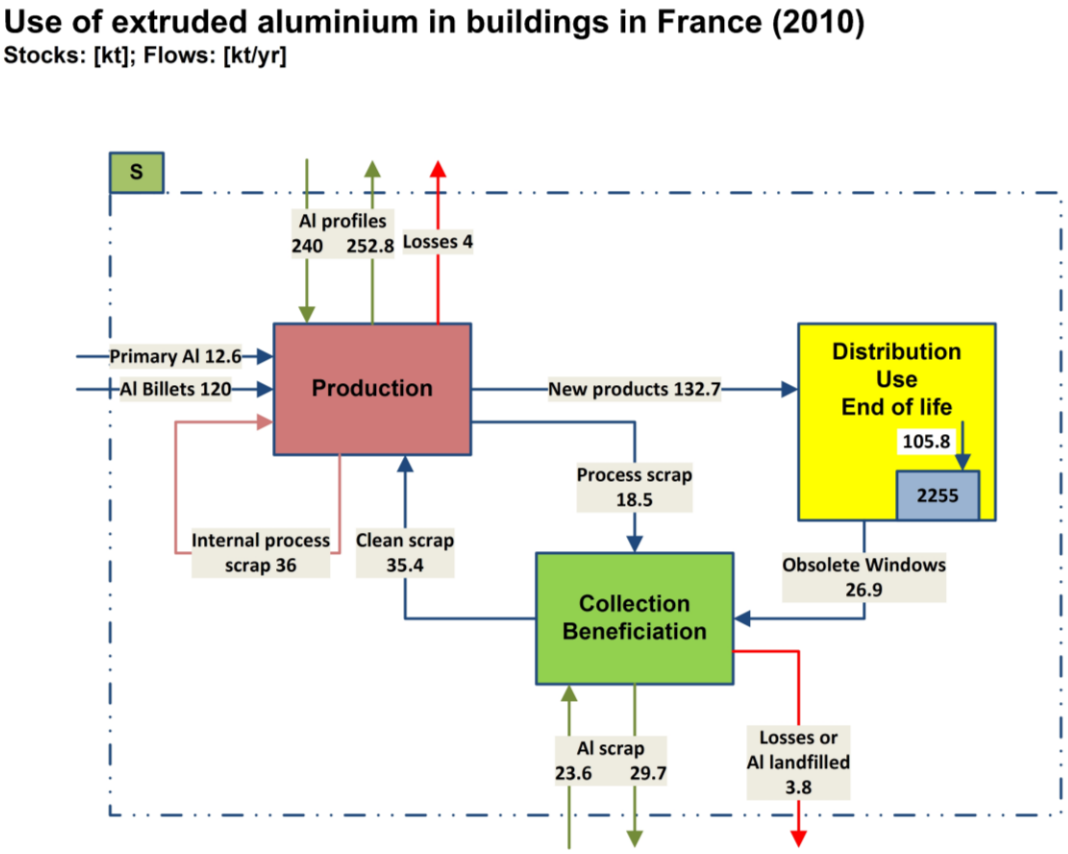

Figure 25: MFA diagram of the overall system

The total amount of aluminium lost in the system each year is 7.8 kt, a relatively small number compared to the production figures. In the figure 25 above, the scrap landfilled is showed leaving the system even if the landfilling process is located inside the system boundaries: this is just a simplification that enables to show the losses more graphically for the overall system.

Each year, 57.5 kt of process scrap are generated, among which 36 kt are extrusion scrap directly recycled through conversion agreements with the remelters. There is twice as less post-consumer scrap at the moment, 26.9 kt only, but as mentioned in the previous section this number is expected to grow significantly in the near future.

3.2.2 Subsystem 1: Production

The MFA diagram of the production system is shown next page (figure 26). Here, we see that the total installation of new products amounts for 132.7 kt/year, 59.7 kt/year through the construction of new buildings and 73 kt/year through refurbishment. The losses amount to 4 kt/year, which amounts to 3 % of the total installed volumes. We also notice that if international trade plays a major role for the billets and profiles markets, this is not the case for the finished products.

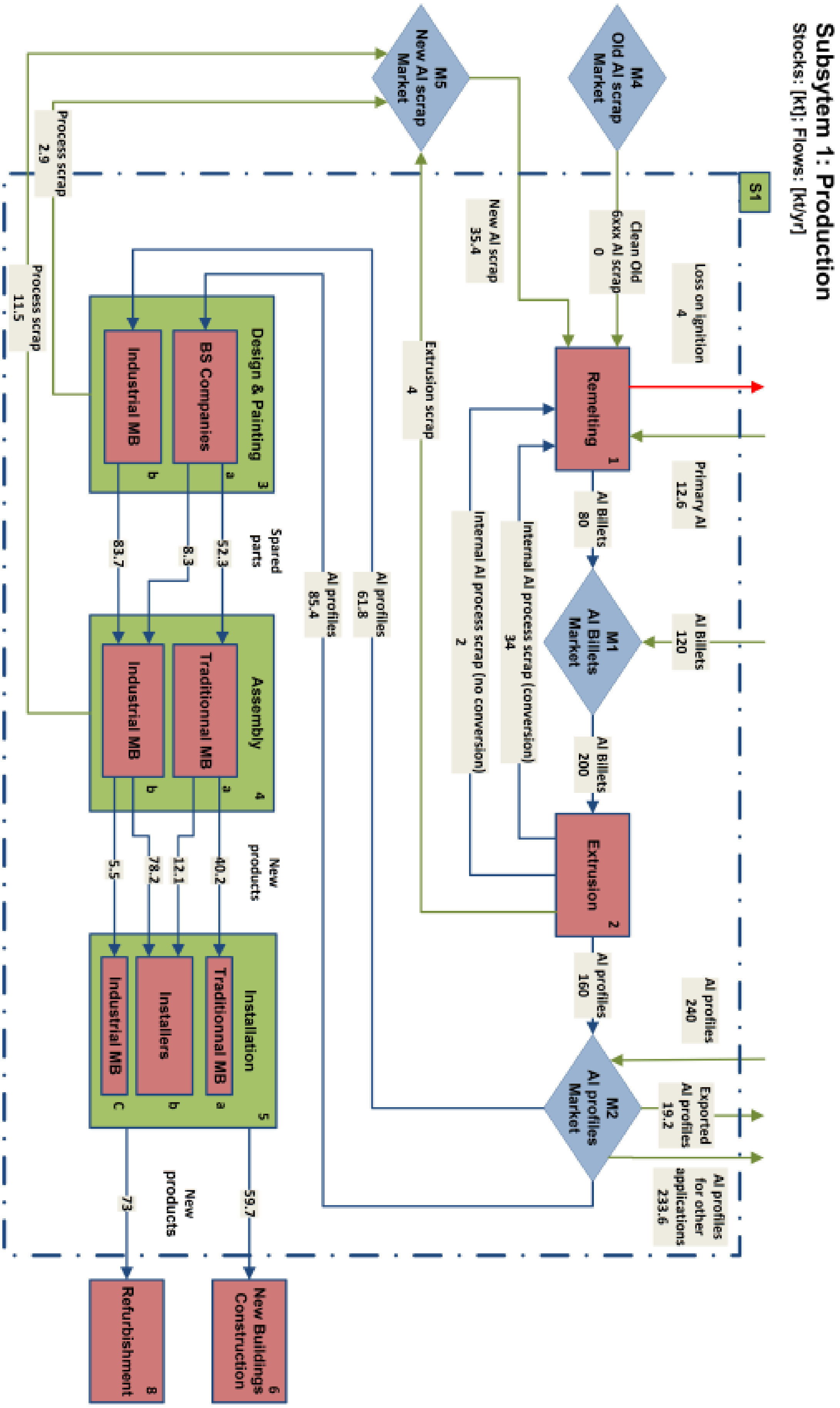

Figure 26: MFA diagram of the subsystem 1 (Production)

3.2.3 Subsystem 2: Distribution, use and end of life

The MFA diagram for the subsystem 2 is presented on the figure 27 below. We notice that the yearly net stock addition is large, about 4 times as much as the yearly outputs. This is due to the long lifetimes of the products, and the fact that the market is a relatively recent one. Hence, steady state has definitely not been reached, and it is not likely to happen in the next years. The yearly stock addition amounts to about 5 % of the current in-use stock. It means that the in-use stock represents 20 years of stock addition at the current rate. When compared to the average lifetime of the products, this confirms the pattern for a large increase in the in-use stock in the next years.

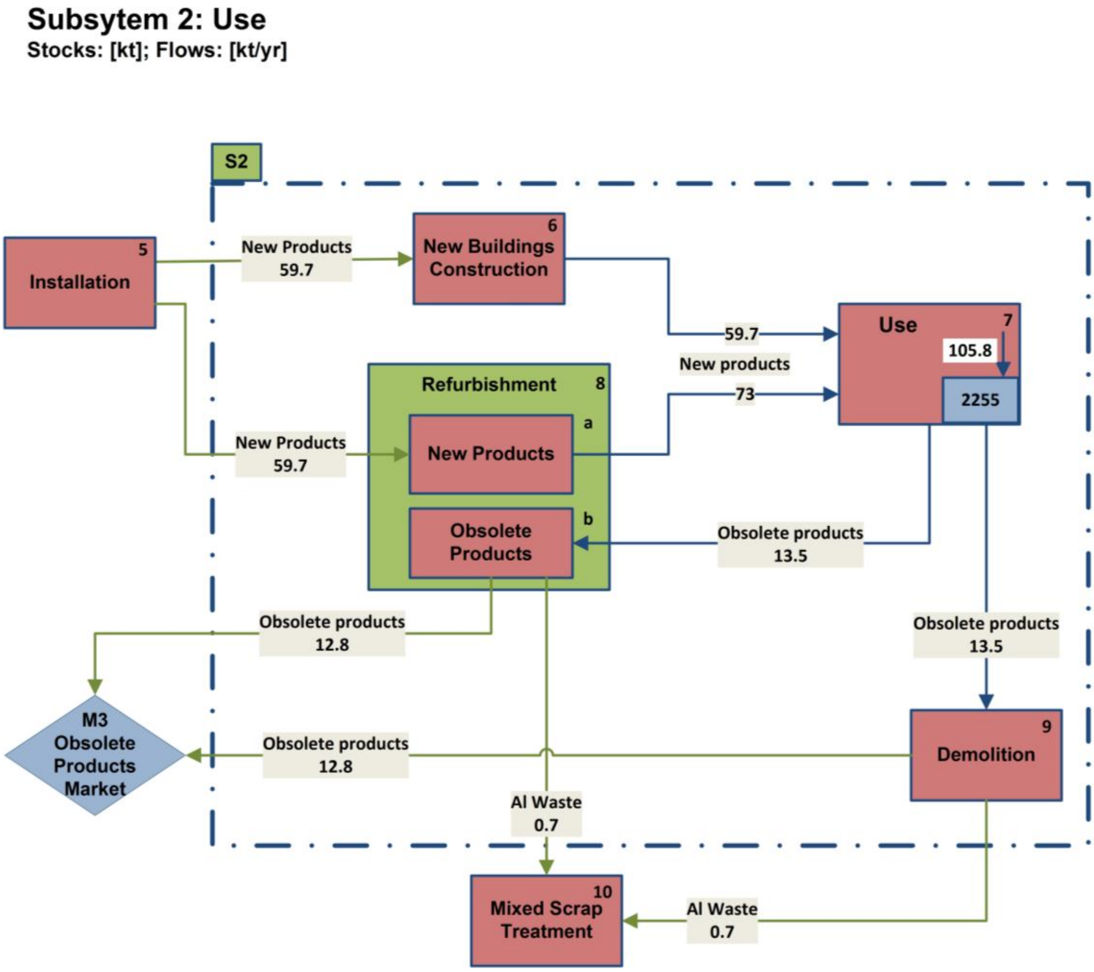

Figure 27: MFA diagram of the subsystem 2 (Distribution, use and end of life)

3.2.4 Subsystem 3: Collection and beneficiation

The MFA diagram for collection and beneficiation subsystem is shown on the figure 28 next page. The losses in this subsystem amounts to 3.8 kt/year, which represents 14 % of the post-consumer scrap yearly outputs. This yield, including both collection and beneficiation losses, is in accordance with previous studies from Rombach (2002) and TU Delft (2004).

In order to provide enough raw materials for the remelters, 20 kt/year of process scrap have to be added in the system through the new scrap market, either from other industrial sectors (12.6 kt/year) or from abroad (7.4 kt/year). This illustrates the current tension on the new scrap market, the rising prices and the difficulties encountered by remelters to secure their supply of scrap.

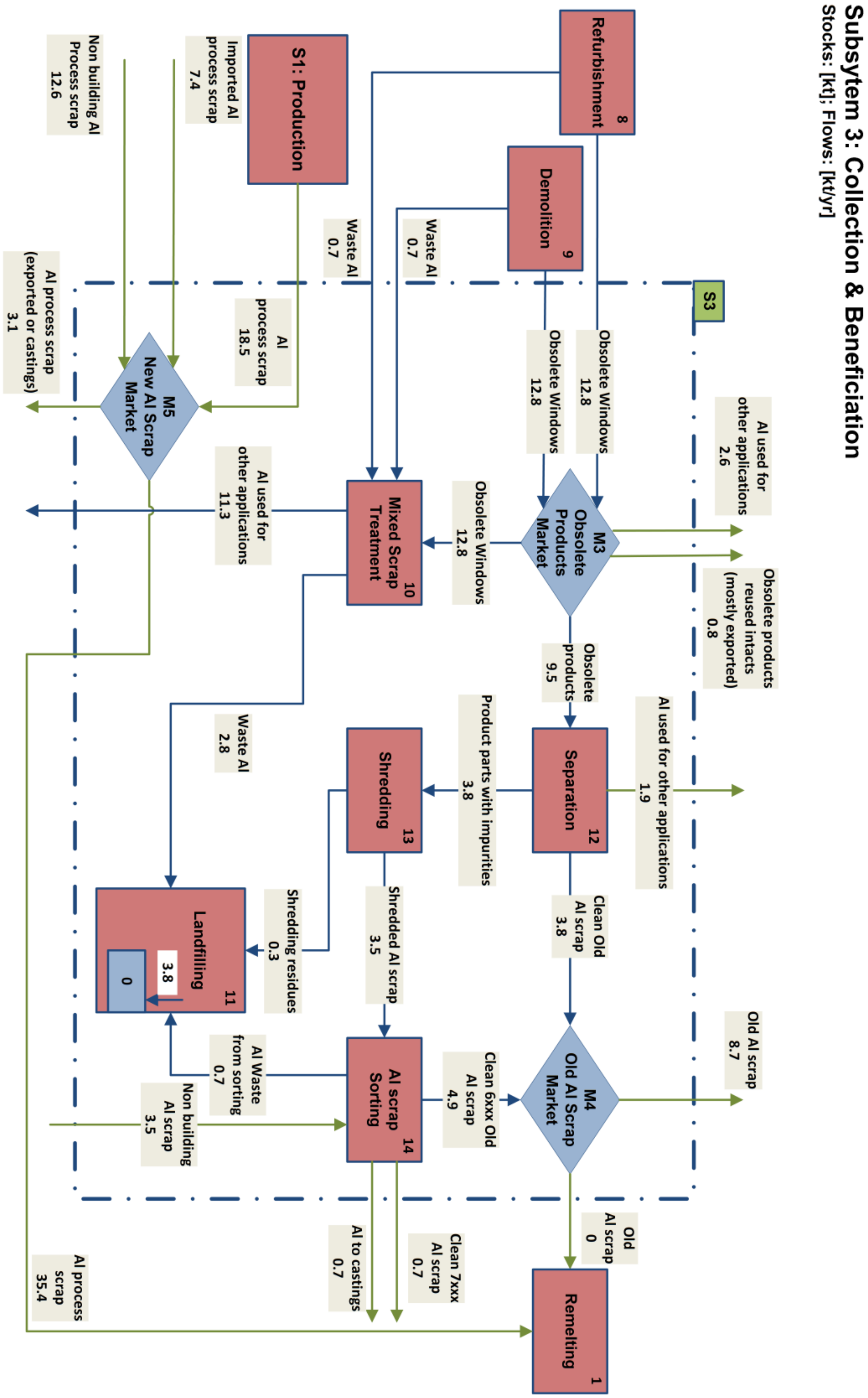

Figure 28: MFA diagram of the subsystem 3 (Collection and beneficiation)

The numbers for the in-use stock and yearly outputs are taken from the dynamic model, using the long lifetime scenario: it is therefore a pessimistic hypothesis in terms of post-consumer scrap availability. If the values from the short lifetime scenario had been used instead, the flow of post-consumer scrap reaching the old profiles scrap market would have been 11.8 kt/year instead of 8.7 kt/year, an increase of 36 %.

3.3 Sensitivity analysis

The table 2 below shows the results of the sensitivity analysis for the flow of post-consumer scrap reaching the old scrap market. The relative sensitivities have been calculated for each parameter at the Normal Operating Point.

Table 2: Results of the sensitivity analysis for the flow of post-consumer scrap reaching the old scrap market.

Parameter	Value	$\frac{P_i}{X_{OS}}$	$\left.\frac{\partial X_{OS}}{\partial P_i}\right\|_{NOP}$	$\bar{S}(X_{OS}, P_i)$
Ow	27	3.107	0.231	0.718
Snb	3.5	0.403	0.700	0.282
kx8bM3	95%	0.109	3.285	0.359
kx78b	50%	0.058	0	0
kx9M3	95%	0.109	3.285	0.359
kxM30a	10%	0.012	-16.867	-0.194
kxM30b	3%	0.003	-16.867	-0.058
kxM310	50%	0.058	-16.867	-0.970
kx12M4	40%	0.046	3.379	0.156
kx1314	92%	0.106	3.796	0.402
kx14M4	70%	0.081	6.993	0.563
kx120	20%	0.023	3.379	0.078

When looking at the results, we first notice that no parameter has a relative sensitivity equal or greater to one. This suggests that the flow of post-consumer scrap should be quite steady. This result might appear surprising, but this is due to the fact that the model takes into account two main sources of scrap: obsolete products coming directly from refurbishment or demolition of old buildings, and extruded aluminium scrap coming from other industrial sectors. Therefore, increasing only one source will have a limited effect since the other supply will have a buffering effect on the flow. For instance, the relative sensitivity of the flow of post-consumer scrap from the building sector is only 0.718 because of the importance of the non-building scrap. However, this is still higher than the sensitivity towards the non-building scrap, because the main source of supply is from discarded joinery products.

The parameters with the highest relative sensitivities are k_{xM310} (with a negative value), the percentage of obsolete product ending up in mixed scrap treatment, O_w the yearly outputs of post-consumer scrap, k_{x14M4} the yield of the sorting process and kx_{1314} the yield of the shredding process. This attests quantitatively the importance set up the pre-sorting of post-consumer scrap for the W2W project.

Yield improvement for the beneficiation processes comes after, and is probably harder to achieve: a yield of 92 % for a shredder is already a quite high value. Of course, the yearly outputs from the stock are also an important parameter. Obviously, it is not possible to increase its value directly by dismantling more products, but the dynamic model shows that the outputs will rise significantly in the future. The fact that this parameter has a high sensitivity on the flow of post-consumer scrap available also points out one of the limit of the model: it is highly dependent on the results from the dynamic model, which also exhibits high uncertainties.

On the other hand, Kx78b, the share of obsolete products coming from refurbishment, has a relative sensitivity of 0, because the collection rates for refurbishment and demolition are assumed to be the same. This is actually an interesting result, because the high uncertainty on this parameter will have a negligible influence on the flow of post-consumer scrap available.

It is also worthwhile mentioning the influence of the current values of the parameters. Indeed, since the sensitivities are calculated at the NOP, this has an impact on the results. For instance, the parameters k_{xM30a}, k_{xM30b} and k_{xM3010} have the same absolute sensitivity of -16.867. Nevertheless, k_{xM3010} has a higher relative sensitivity, because its value is already higher. In other words, this means that changing a parameter that currently affects a large fraction of the flow has more impact that changing a parameter that has only a marginal effect at the moment.

Another particularity of this system is the independence between the flow of post-consumer crap and the upstream production system. Indeed, the lifetime of the products and hence the residence time in the in-use stock is such that the current production has no direct effect on the generation of post-consumer scrap, contrarily to shorter-lived products such as packaging. Therefore, if the generation of process scrap is of course highly relying on the current production and more subject to fluctuations depending on the economic context, the availability of post-consumer scrap is only determined by the historic production and the transfer coefficients of the collection system.

4. Discussion

4.1 Uncertainty analysis

Some parts of the system are more accurately known than others. For instance, most of the subsystem 1 (production) is well documented. This study benefited from the inside expertise of industrial actors in this sector, so the transfer coefficients for the remelting and extrusion process are very well known, even though they may vary from plant to plant. Therefore, the relative errors for all these flows should be around 10 %. Indeed, small errors might also be caused by the multiplicity of the data sources used and the necessity to harmonise figures from different years or different scope of study. For instance, the definition of aluminium joineries is not always the same, the product categories considered may vary, as well as the geographical boundaries and the way international trade is handled.

The uncertainties are a bit higher when it comes to the split between the different actors of the aluminium joinery industry, such as building system companies and metal builders, because it is harder to analyse a market with so many players. The market shares also evolve quickly, so the situation might change in the near future. However, this quantification was mostly done to provide a basis for a qualitative interpretation of the value chain, and a change in these splits will not have a large influence on the overall system. Moreover, the total flows of production and installation of new windows are well documented, with relative errors supposedly smaller than 10 %.

For the subsystem 2, the dynamic model is the main data source used. Therefore, the uncertainties are directly linked to those on the historic production and lifetimes of aluminium joinery products. For the in-use stock, the values range from 2085 to 2255 kt depending on the lifetime scenario chosen. By taking into account the possible errors on the historic production in addition, it is reasonable to assume a standard deviation of about 500 kt, which represents a relative error of 22 %. For the output flow of post-consumer scrap, the uncertainties are slightly higher, because it is more dependent on the lifetime of products. The values from the dynamic model range between 26.9 and 40.4 kt/year depending on the lifetime scenario chosen. When adding the uncertainties on the historic production, the standard deviation for this flow should lie between 10 and 15 kt/year, hence a relative error of about 40 %.

In the collection and beneficiation subsystem, the uncertainties are much higher than for the production subsystem. As mentioned before, this subsystem is highly hypothetic and represents a simplified vision of the current situation. The yields of the different industrial processes are quite well known, but the real problem lies in the uncertainties on the split between the different collection channels (how much scrap is pre-sorted, directly shredded, etc.).

A more detailed uncertainty analysis was performed on the current availability of post-consumer scrap. The standard deviation for the flow of post-consumer scrap currently available for remelting was then calculated using a Gaussian approach, according to the formula:

$$\Delta S_{Old\ Scrap} = \sqrt{\sum_i \left(\left. \frac{\partial \boldsymbol{X_{OS}}}{\partial \boldsymbol{P_i}} \right|_{\boldsymbol{NOP}} \right)^2 * \Delta S_{\boldsymbol{P_i}}{}^2}$$

The uncertainties used for the different relevant parameters are listed in the table 3 next page. Normal distributions were assumed, for all the parameters, with a confidence interval of 1σ (~68 %).

Table 3: List of parameters used for the uncertainty analysis on post-consumer scrap availability

Parameter	Value	$Relative\ Error$	ΔS	$\left.\frac{\partial X_{OS}}{\partial P_i}\right\|_{NOP}$
Ow	27	40.8 %	11	0.231
Snb	3.5	100 %	3.5	0.700
kx8bM3	95%	5.3 %	0.05	3.285
kx78b	50%	30 %	0.15	0
kx9M3	95%	5.3 %	0.05	3.285
kxM30a	10%	100 %	0.1	-16.867
kxM30b	3%	100 %	0.03	-16.867
kxM310	50%	50 %	0.25	-16.867
kx12M4	40%	50 %	0.20	3.379
kx1314	92%	3.3 %	0.03	3.796
kx14M4	70%	14.3 %	0.1	6.993
kx120	20%	100 %	0.2	3.379

The calculated standard deviation was $\Delta S_{Old\ Scrap} = 5.9$ kt/year.

We have then $Old\ Scrap = 8.7\ \pm 5.9\ kt\ /year$. This uncertainty is quite high, corresponding to a relative error of about 68 %, but this is not surprising given the large uncertainties on some parameters. However, this gives a range for the availability of post-consumer scrap between 3 and 15 kt/year, which gives an acceptable order of magnitude for the available resource.

A Monte-Carlo simulation was also conducted, using the Simulación 4.0 plugin for MS Excel. For all the input parameters, truncated normal distributions were assumed so that all the values in the simulation have to be positive. For the transfer coefficients, the truncating condition was that the values should lie in the interval between 0 and 1. The simulation was then run using 10 000 iterations in order to obtain a satisfactory accuracy. A summary of the results is presented on the figure 29 below and in the table 4 next page.

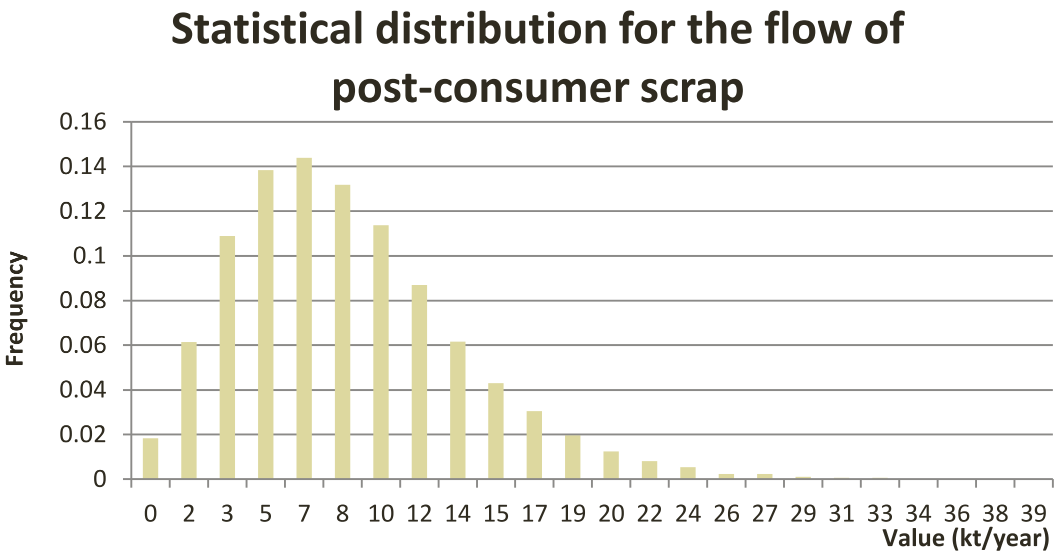

Figure 29: Results of the Monte Carlo simulation – probability distribution for the flow of post-consumer scrap

Table 4: Results of the Monte Carlo simulation - Summary values for the flow of post-consumer scrap

Parameter	Value (kt/year)
Maximum	40.2394
Minimum	0.0014
Mean	8.7083
Variance	26.9951
Std. Deviation	5.1957
Dev./Mean	59.66 %

The standard deviation is slightly lower than the one calculated using the Gaussian approach: this is due to the constraints added by the truncated normal distribution, which is actually more representative of the physical flows.

It is also interesting to point out the fact that the parameters with the largest uncertainties are those about the organisation of the collection system. Hence, if a W2W system is implemented, these uncertainties would be reduced, and the collection rates will most likely increase. For this reasons, it makes sense to consider the higher part of the range as a good hypothesis for a target of the W2W project. This is all the more true that the data used came from the pessimistic scenario of the dynamic model with long lifetimes. Therefore, it seems reasonable to believe that a successful W2W system in France would be currently able to collect as much as 10 kt/year of post-consumer scrap.

4.2 Opportunities and challenges to implement the W2W collection system in France

The MFA calculations show the existing potential for implementing a W2W system in France. However, such a project would change radically the way the issue of end of life management for building components is currently handled in France. In this part, we will try to assess the main challenges to be addressed for such a system to be successful, as well as the opportunities for the different actors.

4.2.1 Logistic issues

First, if such a system has not been implemented yet, it is mostly due to the logistic difficulty to collect post-consumer scrap efficiently. In the absence of an organised collection system, it is currently not profitable to sort post-consumer scrap well enough to enable reusing it for remeltingn new billets.

So, to launch the W2W project, it appears that it would be easier to start by collecting scrap from the metal builders customers of HBSF. The reason for that is that there are located closer to Hydro’s activities in the value chain, and deal with scrap which is not already mixed with other materials. They also have no direct interest in the scrap business, which makes it easier to collect scrap for them. They would mostly generate process scrap (mainly cut-offs from product assembly), but also some post-customer scrap collected from refurbishment. Even though the post-consumer scrap will play a minor role in the beginning, collecting this scrap at source will still have positive effects on the collection rate and quality of the sorting. This would also help designing the collection chain and establishing a business model for the project.

After some interviews with metal builders part of the customer network of HBSF, some of their main habits and concerns have been identified. First, the organisation of the scrap collection that prevails in this case is usually as follows: a given scrap dealer installs a skip for free in the production yard of the metal builders, and they empty it with a truck whenever it is full. In this case, the craftsman does not have to pay anything for the storage and transport, and the scrap dealers pays a price per ton determined in advance in the contract. This price is subject to fluctuations linked to the price of raw metals and scrap. Usually, the scrap dealer and the metal builder will agree on a formula to calculate the price as a function of the price of raw aluminium on the London Metal Exchange (LME). The price is then automatically updated on a regular basis. In this case, the scrap dealer is the same for the whole duration of the contract.

Another possibility is that the scrap dealer is taking care of its own skips, and then asking scrap dealers to empty it when they are full. In this case, the metal builder is usually able to obtain better prices, especially since he is not captive of a given scrap dealer and can then create a competitive environment. Nonetheless, this requires a better organisation, so only the most industrialised metal builders will choose this opportunity.

In the case of very small metal builders, like for small craftsmen companies and family businesses, the organisation is usually more flexible and unofficial. Frequently, the workers of the company will be responsible for the scrap, and will share the profits between them as a premium. Then, there is no written contract with an official scrap dealer. Instead, the scrap would be sold to a local unofficial scrap dealer who will pay by cash, at a price negotiated between him and the employees. For this reason, the scrap will not appear in the accounts of the company. This is an important issue, because in this case, the manager of the company will be reluctant to change this organisation to avoid paperwork as well as displeasing the employees and paying taxes. This “black money” is also sometimes used to buy services more discretely and without paying taxes. Thus, it will be difficult for HBSF to get hold of the scrap from the small metal building companies for these reasons.

The size of the metal building company, and hence the amounts of scrap generated is also a critical issue in terms of logistic costs. Indeed, considering the loss rate of 8 % for the product assembly, it is possible to evaluate the amounts of scrap generated from the sales figures of HBSF. The results of this analysis show that about half of the customers of HBSF will generate less than 2 tons of scrap per year, which is not enough to make it profitable to collect the scrap. Hence, apart if some special logistic scheme is set up, this scrap will not be collected. A possibility would be to use the trucks that deliver the new profiles from HBS to its customers to bring back scrap from the metal builders. However, this brings new logistics complications, mostly because each truck is touring around several customers. Thus, it would not be possible to load scrap in the truck if it still contains new profiles destined to other customers.

For this reason, it was decided initially to focus on the customers who order more than 50 tons of profiles to HBSF yearly. This represents about 50 customers, mostly located in the West of France, in the North and around the Rhône area. A pilot case will be studied to start building the logistics of the project towards these main customers.

In average, the acceptable time between two emptying of the skips seems to be between 1 and 3 months, depending on the size of the company and the scrap generation rate. The size of the process scrap profiles is generally quite small, as there are cut-offs (usually less than 1 m). However, post-consumer scrap profiles can be longer, which could increase the storage and transport costs as longer profiles needs more volume for a given mass. Another option would be to shear them before filing up the truck, but this requires heavy equipment.

Another issue is that metal builders do not only generate aluminium scrap. Usually, when a scrap dealer signs a contract with a metal builder, he will take care of all the waste, even the non-profitable part. Therefore, it seems difficult to collect the aluminium scrap only, which is a problem for HBSF, who does not want to involve in the waste management business.

For all these reasons, it seems more reasonable to involve scrap dealers in the project, because they already have the know-how and network needed to collect scrap efficiently. Due to the multiplicity of the actors in the scrap dealing markets, it seems necessary to conduct this project in cooperation with one of the main players (such as Derichebourg, GDE, Véolia, Galoo or SITA), because they are the only ones to own a network that covers the major part of France. Another alternative would be to sub-contract the scrap collection to a national network of regional actors, such as the PRAXY network. It consists on cooperation between different medium-size scrap dealers with a local implantation which results on the coverage of most of French territory.

4.2.2 Technological feasibility

The use of post-consumer scrap in aluminium billets present several technological challenges, both for remelting and extrusion. There are usually more impurities in post-consumer than in process scrap, which makes the remelting process trickier. For instance, organic impurities can cause the furnace to overheat. For the same reasons, there are also currently technical limitations on the admissible amount of coated profiles in the furnace (this should not exceed 15 % of the scrap inputs). The same applies for profiles with thermal break, which need an additional shearing process before remelting. The possibility to use thermal break profiles in remelting furnaces is actually under testing period, but even if successful, there will still be a limitation in the acceptable share (Le Bouquin, 2012). And finally, the alloy composition of post-consumer scrap is less precisely known than for process scrap, which makes it more complicated not to exceed the strict tolerances on alloying elements for 6060 billets presented on the table 5 below. Besides, extruders actually require stricter specifications (displayed on the line 'Target'). The low concentrations in copper and zinc are especially challenging for recycled billets (Bjerkaas, 2012). Therefore, in the current state of technology, it seems very complicated to remelt billets using post-consumer scrap only. It is more likely that the use of post-consumer scrap in remelting plants will increase progressively, starting at a low share of the total scrap inputs in order to maintain the high quality standards of the billets.

Table 5: Chemical composition for 6060 alloy (Schlesinger, 2007; Ch2, "The Ore Body", p. 11; Bjerkaas, 2012)

Alloy	% Si	% Fe	% Cu	% Mn	% Mg	% Cr	% Zn	% Ti	Others	
									Each	Total
6060	0.30–0.6	0.10–0.30	0.1	0.1	0.35 - 0.6	0.05	0.15	0.1	0.05	0.15
Target	0.30–0.6	0.10–0.30	**0.02**	**0.06**	0.35 - 0.6	**0.02**	**0.02**	**0.02**	0.05	0.15

The use of billets made out of post-consumer scrap is also a challenge for the extruders. Indeed, in order to constantly increase the production yields, the alloys used in the billets as well as the surface treatment are continuously improved. The billets used for extrusion today in France exhibits better characteristics than the standard requirements, with concentration of impurities well below the standard tolerances. Therefore, the use of billets made out of post-consumer will most probably result in a slow-down of the production rates, at least at the beginning, and hence reducing the economic profitability for the extruder (Viet, 2012; Bjerkaas, 2012). For these reasons, studies are actually conducted to assess the feasibility to remelt and extrude billets made out of post-consumer scrap without sacrificing quality and profitability.

4.2.3 Economic feasibility

The economic feasibility was not the main focus of this report, and the project is currently in a too early stage of development to provide comprehensive answers on this topic. However, the current scrap market prices give an idea of the target for the costs of collection and treatment of scrap.

Today, scrap dealers buy aluminium process scrap is bought around 1000 €/ton from metal builders, and sell it about 1550 €/ton. Profiles with thermal break have less value (around 1250 €/ton), but are bought less than 800 €/ton. The price difference between scrap containing 6060 alloy profiles only and scrap used by secondary foundries is about 150 €/ton, which is also approximately the cost for shredding (when the aluminium profiles are pre-sorted, shredding is not necessary). As a comparison, the prices of the LME at the same period were around 2000 €/ton (Profession Recycleur, 2012). Then, the cost of collection and treatment will have to be in any case under 500 €/ton for the project to be profitable. The current high prices for secondary foundry alloys also make necessary to lower the beneficiation costs as much as possible, otherwise it would be more profitable not to sort the scrap and sell it directly to refiners.

4.2.4 Consequences on the different actors along the value chain

If this project were to be implemented, this would modify in deep the actual organisation of the French collection system, as well as the interactions between the different actors. Thus, it is important to study the possible effects on the different stakeholders in order to identify the best opportunities and avoid creating conflicting situations in the market.

Remelters

The remelters would highly benefit from this project. Today, about 6 kt/year of process scrap are missing for the French remelting plants to run at full capacity. They also suffer from the high scrap prices and the increased tensions on the high quality wrought alloys scrap market since the economic crisis. Therefore, the W2W project would secure a steady source of supply for them, and could even possibly lead to a decrease in scrap prices. If post-consumer scrap were to be collected in large quantities, this would also represent a steadier source of supply than process scrap, which is more likely to be subject to economic fluctuations.

On the other hand, the remelting of post-consumer scrap or profiles with thermal break also brings more constraints in the remelting process. The composition of the mix put into the furnace has to be closely monitored, and less pure scrap leads to a slower production and more losses on ignition.

Extruders and Building system companies

The direct advantage for extruders and building system companies is not as clear, apart if the implementation of the project results in a drop in the billets price. For the extruders, this would bring technological difficulties about the extrusion process, and most likely slowly reduce the production rates. Nevertheless, most of the extrusion presses in France and in Europe are not operated to their full capacity today because of low demands due to the economic crisis. There might be as well more quality problems, especially on technologically advanced profiles.

The advantage would mostly be a commercial one: for aluminium producers, it becomes increasingly important to boast environmental excellence, which, in the case of aluminium, implies the use of recycled aluminium. Due to new regulations and more public concern, environmental performance becomes more and more important in the choice of building components. Public procurement incentives in Europe and particularly in France start including environmental criteria. It is then a way for HBSF to gain market shares, and thus an opportunity for extruders if the production of aluminium products is encouraged.

For Hydro, synergies can also be found through the vertical integration of the group. A successful agreement can be signed between remelters, extruders and building systems to share the constraints and benefits of this project. Hydro could then benefit from this competitive advantage that they will have towards other groups, either because they are too small to use this integration, or because they will arrive too late on the market. It would make sense in the environmental policy of the company to integrate the end of life management at each stage of the value chain, and oppose a systemic approach with strong arguments to the current discussions on recycled content of products.

Metal builders

The metal builders would be in general little affected by this project. Indeed, most of them already collect their process scrap as well as the post-consumer scrap that they get hold of in refurbishment projects, and sell them to scrap dealers. The main concern is that small metal builders usually sell their scrap more or less illegally to small scrap dealers, but they should not be implied in the project, at least not in the first stages.

On the other hand, even if they could benefit from more environmentally products, the interest seems quite shy. A study conducted on 100 Spanish metal builders by Burgos & Mestres (2011) showed that if 60 % of them were aware of the urgent need to recycle aluminium, and convinced that it would be a major issue in the future as well as a competitive advantage, 66 % thought that their clients will not be ready to pay a premium or “green” products. The remaining 34 % considered in average that 2 % premium would be acceptable. Still 90 % of them were willing to involve into scrap business relationships with HBS. If the interviews made in France were conducted at lower scale, it mostly confirmed these results. Most of the scrap dealers are willing to work with HBS on a collection system, even if they are not all convinced of the necessity. However, they will not accept to pay higher prices and think that it will have a limited impact on their customers. In terms of logistics, they also require the same flexibility that they experience today with scrap dealers.

A way to structure the project would be to involve the metal builders into a green network for scrap collection. This would fit perfectly with the organisation of Technal, which operates mostly through a dedicated network of metal builders called “Aluminiers”. Hence, there is a project to build a network called “Aluminiers Verts” (green metal builders), with specifications to make the metal builders part of Hydro’s efforts towards end of life management. This would have several advantages, including reinforcing the vertical integration of Hydro on this topic, and hence getting closer to where the scrap is generated in the value chain. However, it is yet to define the overall strategic significance of this network, and how to share the roles, constraints and profits between the different actors.

Scrap Dealers

For scrap dealers, the W2W project could be seen as a threat. Indeed, if Hydro involves in the collection and recycling business, they might be afraid to be bypassed and see Hydro as a competitor. However, the project will most probably involve one of several scrap dealers, as Hydro does not want to support all the investment costs alone, and is not really eager to involve in a business apart of its core activities. Hence, this project could present interesting opportunities for scrap dealers to make more values of their scrap than they currently do, and create jobs. This would also secure a part of their supplies of scrap as the metal builders will deal only with the scrap dealer chosen for the project.

Nevertheless, the choice of the scrap dealers involved in the project seems very sensitive, as it would most likely disrupt natural balances locally. A threat exists for Hydro as well: as the remelting facility in Lucé has to buy aluminium from scrap dealers it will put it in a difficult situation if it is seen as a direct competitor.

Social benefits

This project would enable three important social benefits. First, increasing the end of life recycling of aluminium and reuse the scrap to make new joinery products will obviously reduce the need for primary aluminium, and hence a large part of the environmental impacts associated with this industry.

Secondly, as this will most probably require more precision sorting and tailor-made collection, more manpower will be needed, at least in the beginning. This would mean creating jobs in a sector that has been heavily impacted by the crisis: as an example, GDE, a major national actor in the collection and recycling sector which was steadily growing before, has seen a drop in its employees from 1170 in 2008 to 700 in 2010 (GDE Environnement, 2012).

And finally, recycling aluminium scrap to remelt new billets in France will decrease the exports of scrap to developing countries. As the French bauxite mines are almost completely depleted, keeping the aluminium scrap inside Europe in general and particularly in the country is a strategic issue for the future, when urban mining will remain one of the only few remaining natural resources in Europe.

4.3 Current environmental performance of the system and prospective benefits of the W2W project

It could be said that the environmental performance of the system is already quite good system in terms of recycling content, because the inputs of primary aluminium amount to about 10 % of the yearly inputs in the in-use stock. The total losses of aluminium (7.8 kt/year) are also very small, which reflects the sustainability of the system.

However, this is formulation would be misleading for several reasons. First, only 40 % of the billets used in France come from remelting, while the rest is exported, and comes mostly from primary aluminium production. Besides, the flows of international trade and exchanges with other industrial sectors for extruded profiles are very large. Since we have no information about the provenance of these profiles, it is very hard to assume a number for their recycled content. And finally, the remelting of new billets uses only process scrap. The recycling content is then maintained artificially high, mostly because the extrusion process generates large amounts of scrap. Therefore, in an end of life perspective, the system performs badly, because it is currently not able to recycle any of the waste it produces. So as the industrial processes produce lots of scrap, and since the preferred solution for handling the post-consumer scrap today is cascading to secondary foundries instead of direct recycling, this systems lays at a low-level in the waste disposal hierarchy.

The only way to truly improve the environmental performance of the system in terms of end of life management would be to set up a real W2W collection system. The results from the models show that it should be possible to reuse from 8.7 to 11.8 kt/year of post-consumer scrap for remelting of new billets.

To give a very crude (and most likely optimistic) estimate of the potentially avoided environmental impacts by a successful W2W system, we can use the data provided by the OEA (2007), which considers that the production of 1 ton of recycled aluminium (for the production process only) is saving about 1.3 tons of bauxite residues (red mud), 15 860 L of water (used mostly for cooling), 2 tons of CO_2 and 11 kg of SO_2. Considering that it should be possible to reuse 10 kt/year of post-consumer scrap if the W2W is successful, the savings will be: 13 kt of bauxite residues, 158 600 m3 of water, 20 kt of CO_2 and 110 tons of SO_2.

This savings have been compared with the results of the LCA on aluminium windows conducted by the SNFA (2008). In their study, they already allocated the benefits of future aluminium recycling to the new products, so this was corrected in order to obtain the impacts for the production of one window. The estimated savings from the W2W project have then been compared to the environmental impacts generated by the production of one window for three categories.

Table 6: Potential savings attributable to the W2W project - comparison with the production of one window

Impact category	Savings W2W	For 1 window	Savings W2W (Number of windows)
Water consumption (m^3)	158 600	0.380	416 898
Global Warming Potential (kg eq. CO_2)	20 000 000	36	555 556
Acidification Potential (kg eq. SO_2)	110 000	0.137	800 416

Given the fact that 2 610 000 aluminium windows have been installed in France in 2010 (BATIETUDE, 2010), the W2W project could be credited with environmental reductions equivalent to as high as 20 % of the impacts generated by the total production of aluminium windows in France.

However, this would hold true only if the project would focus on recycling of post-consumer scrap. Otherwise, the benefits of recycling should not be attributed to process scrap. Indeed, if it is of course preferable to recycle this scrap, it does not result from any improvement in the system: it is on the contrary a measure of the inefficiencies in the production subsystem.

The MFA model shows that the critical point to improve the overall performance of the system is the efficiency of the collection. The best way to reduce the environmental impacts associated with the production of aluminium joineries would then be to sort better the profiles that have reached their end of life directly on the deconstruction site or right after, in order to be able to reuse them for remelting. Then, an improvement on the yield of the sorting processes as well as an increase in inputs of post-consumer scrap from other sectors would also benefit to the overall environmental performance of the system, but only in a second step.

4.4 Gaps of knowledge

4.4.1 Static model

There is a generally good knowledge of most of the upstream processes in the value chain of aluminium joinery. However, what happens after the end of life is less understood, because the multiplication of actors involved and the share of the underground economy make traceability difficult. Even if site visits have been made to metal builders and scrap dealers, the sample is too small to be truly representative of the very diverse situation. It would be interesting to learn more about the behaviour of metal builders and scrap dealers, as well as their possible expectations towards the W2W project. Therefore, further study on the French scrap market and a comprehensive statistical survey on scrap dealers and metal builders would help improving the results and build a successful logistic model.

There are also some unknowns about the relative share of new construction compared to refurbishment. On this topic as well it would be interesting to have access to statistical data collected on a large scale. It should also be possible to assess the response of these two markets to external parameters such as the economic situation: if the renovation market is supposed to be less affected, this hypothesis is not quantified enough. A trend for the evolution of this share in the next years would also be an interesting input for the design of the business model of the W2W project.

Unfortunately there were also very few studies available on the end of life collection rate of aluminium from buildings. The main reference on this topic is the 2004 study from TU Delft, but the size of the sample used is very small: 9 buildings, only 2 of them located in France. Other surveys with a larger number of buildings monitored would be necessary to confirm these results.

And finally, even if hypotheses have been made, it is not possible to predict exactly the consequences of the setup of the W2W project on the material flows. This model is thus brought to evolve to take into account of the changes introduced by the W2W project in the collection system.

4.4.2 Dynamic model

When it comes to the dynamic MFA model, the main concern is the availability of historic data. This is all the more true that the aluminium joinery product have in average a very long lifetime, and are seldom replaced in the absence of a new regulation. Another difficulty is the relatively young age of the aluminium building industry compared to the lifetimes of products: Technal, one of the precursors, is only 50 years old, so only a very little percentage of the total accumulated production has already reached the end of life. This makes it harder to understand and design collection systems for aluminium products. Therefore, the results from this study would benefit from a comparison with data obtained from other sources (from the historic production figures of a Technal's competitor for instance). Better data on the breakdown of the historic production between the different product categories is also needed, as the results as they are today are not accurate enough to be of any use for the model.

There are also large uncertainties on the lifetimes of the different joinery products, and the hypotheses made here are very crude. A comprehensive survey on the lifetime of the different building components will be really helpful to improve the accuracy of the dynamic model. It would make even more sense to conduct such a study in the coming years that more and more products will reach the end of life. In a few years, the age of the market will become such that a majority of the products from the first cohorts would be expected to have reached obsolescence. Then, it should be possible to make detailed studies on the vintage inputs as it has already been done for buildings in several occasions. Nevertheless, as the installation of aluminium joinery is less precisely recorded than the construction of new buildings, it might still prove very hard to obtain representative samples.

4.4.3 W2W project

The W2W project is still at a very early stage of development, and many unknowns remain before the full scale implementation. First, it seems that the first steps will be to improve the collection rates of process scrap, especially by collecting process scrap at source through the customers of HBSF. There are still some issues to address before putting that into practice, like the logistic model of the collection system, the share of responsibility between the different actors (internal in Hydro and external) and the business model. It seems necessary to work in cooperation with one or several scrap dealers for this project to be successful, but the modalities are yet to be defined.

Furthermore, even if it is nowadays possible to remelt directly process scrap, and even if studies predict that is should be the same with post-consumer scrap, the feasibility at an industrial scale remains to be proved. There is currently a testing program run in cooperation between Hydro's extrusion plant in Toulouse and the remelting plant in Lucé to remelt and extrude billets containing post-consumer scrap. The first results are encouraging, but there are still some problems with the quality of the billets that prevent from obtaining high-quality profiles when extruding them as fast as standard billets.

High uncertainties remain as well about the economic feasibility of this project. If the price difference between post-consumer and process scrap is in favour of the success of the project, it is also subject to fluctuations due to economic considerations. Besides, it is not certain that Hydro would be able to take care of all the stages in the collection process with still making profits. The repercussions on the different actors, mainly scrap dealers, should also be taken into account. Indeed, this project presents a risk of significantly disturbing the French scrap market, which could lead to tensions between Hydro and the other stakeholders.

Thus, the project will primarily focus on process scrap, which is not the initial goal of the W2W scheme. This would be easier to implement at the beginning, but it will also strongly decrease the environmental relevance of the project. Besides, the MFA model shows that the supplies of process scrap are quite limited, and are likely to decrease in the future if the production processes are improved. On the other hand, the availability of post-consumer scrap will greatly increase in the coming years. Therefore, even if closing the loop with process scrap might appear sufficient to secure the supplies of the remelting plants today, the W2W project needs to address the issue of post-consumer scrap in order to be successful in a long term perspective and to meet its initial environmental dimension.

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Appendix

A. Mathematical description of the flows, stocks and parameters

A1. Processes

Process name	n°	Stock
Remelting	1	-
Extrusion	2	-
Windows design and painting	3	-
Windows assembly	4	-
Windows installation	5	-
New buildings construction	6	-
Use	7	S7
Refurbishment	8	-
Demolition	9	-
Mixed Al scrap treatment	10	-
Landfilling	11	S11
Separation of windows parts	12	-
Shredding	13	-
Sorting of Al scrap	14	-

Table 7: List of the physical processes in the system

Process name	n°	Stock
Al billets market	M1	-
Al profiles market	M2	-
Obsolete windows market	M3	-
Old Al scrap market	M4	-
New Al scrap market	M5	-

Table 8: List of the markets in the system

A2. Flows

Good flow name	From	To	Symbol
Al Billets from remelting	1	M1	X_{1-M1}
Internal Al process scrap from extrusion (conversion)	2	1	X_{2-1a}
Internal new Al scrap from extrusion (no conversion)	2	1	X_{2-1b}
Al Profiles from extrusion	2	M2	X_{2-M2}
New Al scrap from extrusion	2	M5	X_{2-M5}
Al profiles sold by BS companies to Traditional Metal Builders	3a	4a	X_{3a-4a}
Al profiles sold by BS companies to Industrial Metal Builders	3a	4b	X_{3a-4b}
Al profiles sold by Industrial Metal Builders	3b	4b	X_{3b-4b}
New Al scrap from Window Design and Painting	3	M5	X_{3-M5b}
New Windows installed by Traditional Metal Builders	4a	5a	X_{4a-5a}
New Windows sold from Traditional Metal Builders to installers	4a	5b	X_{4a-5b}
New Windows sold from Industrial Metal Builders to installers	4b	5b	X_{4b-5b}
New Windows installed by Industrial Metal Builders	4b	5c	X_{4b-5c}
New Al scrap from windows assembly	4	M5	X_{4-M5}
New Windows for construction	5	6	X_{5-6}
New Windows for refurbishment	5	8a	X_{5-8a}
New Windows in new buildings	6	7	X_{6-7}
Obsolete Windows from refurbishment	7	8b	X_{7-8b}
Obsolete Windows from demolition	7	9	X_{7-9}
New Windows in refurbished buildings	8a	7	X_{8a-7}
Obsolete Windows from refurbishment ending up in mixed scrap	8b	10	X_{8b-10}
Obsolete Windows collected from refurbishment	8b	M3	Xb_{8-M3}
Obsolete Windows from demolition ending up in mixed scrap	9	10	X_{9-10}
Obsolete Windows collected from demolition	9	M3	X_{9-M3}
Al Waste landfilled	10	11	X_{10-11}
Big window parts with impurities (corners, handles…) sent to shredding	12	13	X_{12-13}
Clean 6xxx Old Al scrap (from cutting of window frames)	12	M4	X_{12-M4}
Shredding residues	13	11	X_{13-11}
Shredded Al window scrap	13	14	X_{13-14}
Waste from sorting landfilled	14	11	X_{14-11}
Clean sorted 6xxx Old Al scrap	14	M4	X_{14-M4}
Al Billets for extrusion	M1	2	X_{M1-2}
Al profiles for BS companies	M2	3a	X_{M2-3a}
Al Profiles for Industrial Metal Builders	M2	3b	X_{M2-3b}
Obsolete Windows from the market ending up in mixed Al scrap	M3	10	X_{M3-10}
Obsolete windows collected for separation of non-Al parts	M3	12	X_{M2-12}
Old Al scrap for remelting	M4	1	X_{M4-1}
New Al scrap for remelting	M5	1	X_{M5-1}

Table 9: List of flows internal to the system

Good flow name	From	To	Symbol
Imports of primary Aluminium for remelting	0	1	X_{0-1}
Aluminium scrap from non-building applications	0	13	X_{0-13}
Al Billets imported	0	M1	X_{0-M1}
Al profiles imported	0	M2	X_{0-M2}
Old Al scrap imported	0	M4	X_{0-M4}
New Al scrap imported	0	M5	X_{0-M5a}
New Al scrap from other applications	0	M5	X_{0-M5b}
Al lost (loss on ignition)	1	0	X_{1-0}
Al treated as mixed scrap and used for other applications	10	0	X_{10-0}
Al from separation of windows parts used for other applications	12	0	X_{12-0}
Clean sorted 7xxx Old Al scrap	14	0	X_{14-0a}
Old Al scrap sold as casting alloy after sorting	14	0	X_{14-0b}
Al Profiles exported	M2	0	X_{M2-0a}
Al Profiles used for other applications	M2	0	X_{M2-0b}
Al from collected obsolete windows used for other applications	M3	0	X_{M3-0a}
Windows reused intact (mostly exported)	M3	0	X_{M3-0b}
Exported Old Al scrap	M4	0	X_{M4-0}
Exported New Al scrap	M5	0	X_{M5-0}

Table 10: List of flows between the system and its surrounding (including inmports/exports)

A3. Stocks

Stock	Process	Symbol
Stock of extruded Al in use in the building sector	7	S7
Stock of extruded Al from the building sector landfilled	11	S11
Yearly stock change of extruded Al in use in the building sector	7	$\Delta S7$
Yearly stock change of extruded Al from the building sector landfilled	11	$\Delta S11$

Table 11: List of stocks and stock variations

A4. Parameters

Production values

Parameter name	Symbol	Value	Unit
Yearly production of Al billets in France from remelting	Pb	80.0	tons
Yeraly use of Al billets in France	Cb	200	tons
Yearly production of Al profiles in France	Pp	160	kt
Yearly sales of Al profiles to BS companies in France	Cp	61.8	kt
% of yearly sales of Al profiles to BS companies in France	Sbs	42%	-
Yearly installation of new Al windows in France	Cw	132.7	kt
% of Al mass used in buildings in France for new construction	SWnew	45%	kg/kg
Obsolete Windows from End of Life	Ow	27	kt
Stock of Al profiles in buildings	S7	2255	kt

Table 12: List of parameters used in the model (production values)

Transfer coefficients

Parameter name	Symbol	Value	Unit
Concentration of Primary Al in remelted billets	k_{01x}	15 %	kg/kg
% of old scrap from the market used to produce remelted billets	k_{M41x}	0 %	kg/kg
% of Al mass in remelted billets coming from other applications	k_{0bM5x}	15 %	kg/kg
% of Al mass lost during remelting process (loss on ignition)	k_{x10}	5 %	kg/kg
% of Al mass lost during extrusion process	$k_{x2(1-M5)}$	20 %	kg/kg
% of process scrap from extrusion directly remelted (conversion)	k_{x21c}	85 %	kg/kg
% of process scrap from extrusion directly remelted (no conversion)	k_{x21n}	5 %	kg/kg
% of process scrap from BS and painting operations	k_{x3M5}	2 %	kg/kg
% of BS production sold to Industrial Metal Builders	k_{M23a4b}	14 %	-
% of Traditional MB production sold to windows installers	k_{x4a5b}	23 %	-
% of Industrial MB production sold to windows installers	k_{M23b4b}	93 %	-
% of process scrap from windows assembly	k_{x4M5}	8 %	kg/kg
% of obsolete windows coming from refurbishment	k_{x78b}	50 %	kg/kg
% of Al mass in obsolete windows collected from refurbishment	k_{x8bM3}	95 %	kg/kg
% of Al mass in obsolete windows collected from demolition	k_{x9M3}	95 %	kg/kg
% of Al mass in obsolete windows market collected as mixed Al scrap	k_{xM310}	50 %	kg/kg
% of Al mass in mixed Al scrap reused in other applications	k_{x100}	80 %	kg/kg
% of Al mass from obsolete windows reused in other applications	k_{xM30a}	10 %	kg/kg
% of Al mass from obsolete windows reused intact	k_{xM30b}	3 %	kg/kg
% of Al mass from windows separation reused in other applications	k_{x120}	20 %	kg/kg
% of Al mass from windows separation sold directly as clean old scrap	k_{x12M4}	40 %	kg/kg
% of Al mass recovered after shredding of scrap	k_{x1314}	92 %	kg/kg
% of Al mass from sorting recovered as clean 6xxx old scrap	k_{x14M4}	70 %	kg/kg
% of Al mass from non-building scrap sorted sold as 7xxx old scrap	k_{0140a}	20 %	kg/kg
% of Al mass from sorting sold as casting alloys	k_{x140b}	10 %	kg/kg

Table 13: List of parameters used in the model (transfer coefficients)

Imports and exports

Parameter name	Symbol	Value	Unit
Mass % of Al Billets imported	k_{0M1x}	88%	kg/kg
Mass % of Al Profiles imported	k_{0M2x}	60%	kg/kg
Mass % of Al Profiles exported	k_{2M20a}	12%	kg/kg
Mass % of old Al scrap imported	k_{0M4x}	0%	kg/kg
Mass % of old Al scrap exported	$k_{(12-14)M40}$	0%	kg/kg
Mass % of new Al scrap imported	k_{0aM5x}	4%	kg/kg
Mass % of new Al scrap exported	$k_{(2-3-4)M50}$	20%	kg/kg
Mass of non-building Al in scrap collected for sorting	S_{nb}	3.5	kt

B. Questionnaires used for site visits

B1. Scrap dealers

Survey on aluminium scrap
- Questionnaire for scrap dealers

Sources of scrap

- *Where does the scrap come from (directly collected on demolition sites, bought from demolition companies, small independent scrap dealers…)?*

- *Is the scrap bought as clean aluminium or as a fraction of other general metal scrap?*

- *What is the split of aluminium scrap between the different sectors (building, automotive, packaging…)? What are the different shares, in percentage of the total volumes?*

building: ….. % transport: ….. % others: ….. %

- *What is the split between process scrap and post-consumer scrap (end of life after final consumption)?*

process scrap: ….. % post-consumer scrap: ….. %

Beneficiation practice

- *What is the processing of the aluminium containing scrap?*

- *Is the scrap shredded? If yes, what is the resulting size of the scrap pieces?*

- *In which form is the scrap sold after processing? For which use?*

Reuse of scrap

- *Who are the customers who are buying scrap today?*

- *What are the volumes of scrap processed yearly?*

Total Aluminium: ….. tonnes Total building sector: ….. tonnes
Total extrusion: ….. tonnes Total 6060 & 6063 alloys: ….. tonnes

- *What is the importance of export/import of aluminium containing scrap?*

Volume annuel importé : ….. tonnes Volume annuel exporté: ….. tonnes

- *What is the total yield of beneficiation operations?*

Yield (volume of aluminium processed and sold again /aluminium collected): ….. %

For aluminium scrap from building applications

- *Is there a sorting process between extruded and rolled aluminium during collection?*

Scrap quality

- Fraction of painted scrap: ….. %
- Fraction of scrap with Thermal Break: ….. %
- Fraction of scrap with attachments of other materials ….. %
- Average length of scrap parts: ….. cm

B2. Metal builders

Survey on aluminium scrap
- Questionnaire for scrap dealers

Sources of scrap

- *Where does the scrap come from (directly collected on demolition sites, bought from demolition companies, small independent scrap dealers…)?*
- *Is the scrap bought as clean aluminium or as a fraction of other general metal scrap?*
- *What is the split of aluminium scrap between the different sectors (building, automotive, packaging…)? What are the different shares, in percentage of the total volumes?*

building: ….. % transport: ….. % others: ….. %

- *What is the split between process scrap and post-consumer scrap (end of life after final consumption)?*

process scrap: ….. % post-consumer scrap: ….. %

Beneficiation practice

- *What is the processing of the aluminium containing scrap?*
- *Is the scrap shredded? If yes, what is the resulting size of the scrap pieces?*
- *In which form is the scrap sold after processing? For which use?*

Reuse of scrap

- *Who are the customers who are buying scrap today?*
- *What are the volumes of scrap processed yearly?*

Total Aluminium: ….. tonnes Total building sector: ….. tonnes
Total extrusion: ….. tonnes Total 6060 & 6063 alloys: ….. tonnes

- *What is the importance of export/import of aluminium containing scrap?*

Volume annuel importé : ….. tonnes Volume annuel exporté: ….. tonnes

- *What is the total yield of beneficiation operations?*

Yield (volume of aluminium processed and sold again /aluminium collected): ….. %

For aluminium scrap from building applications

- *Is there a sorting process between extruded and rolled aluminium during collection?*

Scrap quality

- Fraction of painted scrap: ….. %
- Fraction of scrap with Thermal Break: ….. %
- Fraction of scrap with attachments of other materials ….. %
- Average length of scrap parts: ….. cm