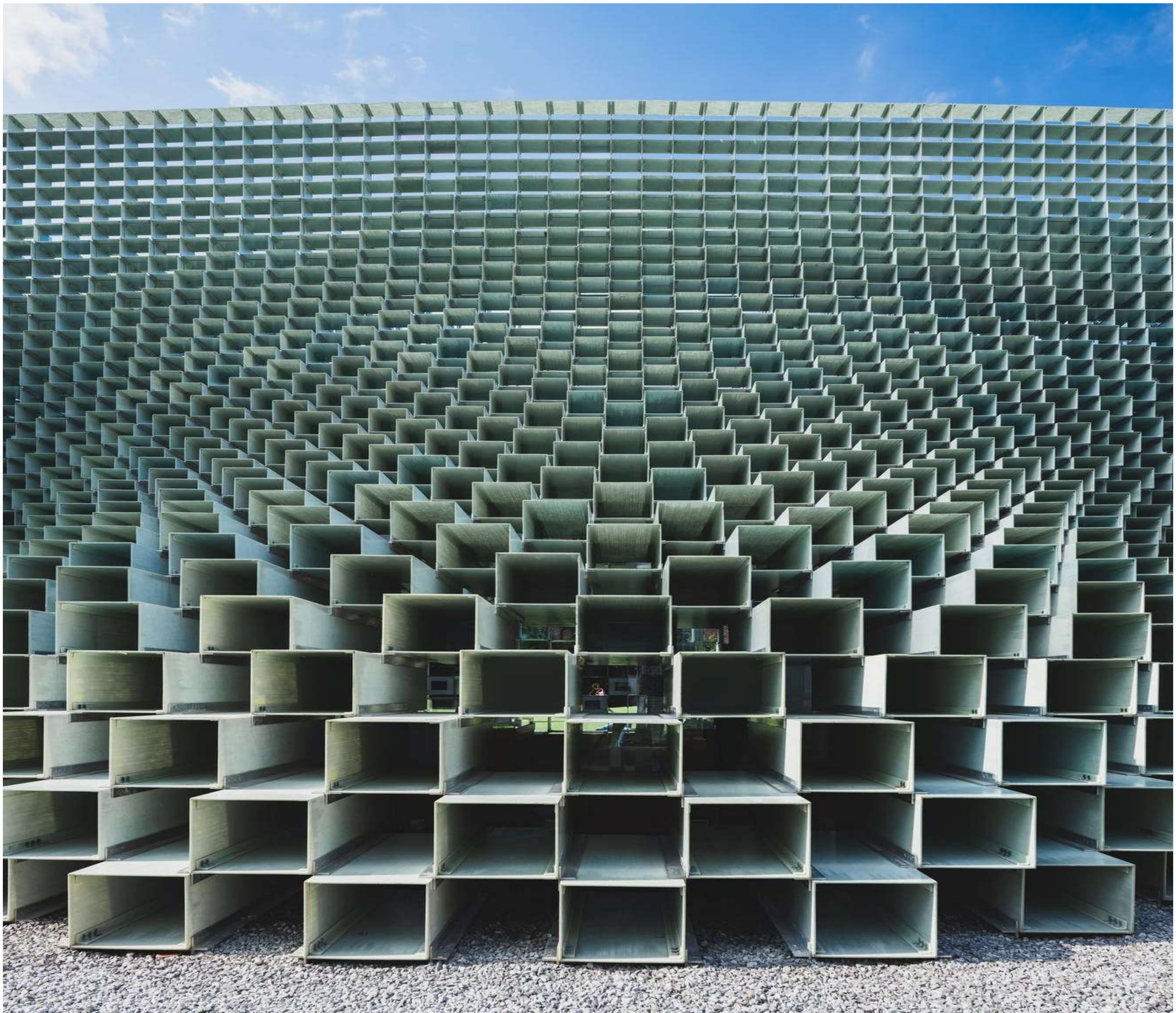

THE INCENTIVES FOR AND THE PROBLEMS FACED IN ALUMINIUM RECYCLING: A CASE STUDY OF THE PROCESS OF SINGULATION FOR ALUMINIUM SCRAP OF 50-180 MM SIZE RANGE

Shlok Singhvi 1/29/21 Master Thesis

THE INCENTIVES FOR AND THE PROBLEMS FACED IN ALUMINIUM RECYCLING: A CASE STUDY OF THE PROCESS OF SINGULATION FOR THE ALUMINIUM SCRAP OF 50-180 MM SIZE RANGE

by

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Regards,

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ABSTRACT

Aluminium recycling is a crucial process when it comes to recycling of metals. To make the metal industry part of a circular economy, this process must be efficient and for the interest of companies it should be economical. Singulation is such a process which does both the tasks.

In this work, aluminium scrap recycling has been positioned as a commercially beneficially process which encourages companies to take up the process and since the process is environmentally advantageous as well, there has been mentions of how the authorities provide policies which support this process.

The first part of the work looks at how and why aluminium is produced which looks into the processes such as Bayer and Hall-Heroult and into multiple uses of the aluminium alloys and also mildly touches upon some of the compatible alloy series. Aluminium is a highly recyclable material so it is interesting to study about what happens one it has reached its End of Life (EOL) stage.

Sorting is an essential stage in the recycling of aluminium and there are solutions which encourage sorting based on alloy series which again is economically and ecologically beneficial. And for this to happen efficiently, singulation is essential.

Singulation of aluminium is important to achieve better efficiency in the process of recycling which is the aim of companies such as Reukema. Although useful, singulation has many challenges. Since it is a solution which depends on the problem i.e., there is no universal way to singulate every kind of material, the problem here has challenges such as entangling of material, their landing on top of each other are just some of such problems which are looked at here.

By simulation, it was found that the arrival pattern of the material follows a homogenously random distribution for smaller size fraction but a highly regularized distribution for large size fractions but smoothens to a homogenously random distribution as we increase the number of particles for both size fractions.

The experiments performed after developing a time series were compared to a simulated singulation process and the results were not ideal in terms of singulation since the chute was not included in the process. The experimental setup needed to be optimised which could lead to even better and accurate results. Higher particle speed on the vibrating feeder could have played a crucial role.

1. INTRODUCTION

Aluminium, a moniker taken from the Latin word ‘alumen’ meaning aluminium sulphates, is an essential metal in the modern world. The fact that it is the 3rd most plentiful metal in the crust of earth makes it even more desirable to use and is therefore the 2nd most utilized metal in the world after steel [1],[2]. Being malleable, ductile, strong, light and conductive, it is widely used in the manufacturing of cars and bikes, construction materials, food packaging products, electrical products, most commonly in large transmission lines where it is preferred over copper due to its light weight and it has many more applications [3]. Aluminium is produced by a combination of Bayer’s process and the Hall-Heroult process. Bauxite is the most useful ore for the purpose of aluminium production as it contains 45-60% aluminium oxide which is then used to produce aluminium [4]. Aluminium is a very popular metal in the industrial world since it can combine with many other elements to form compounds known as alloys which are used in a variety of ways. Aluminium alloys have a special numbering system with multiple series for identification and there are more than 400 registered aluminium alloys with the North American Aluminium Association Inc. One of the most widely used aluminium alloy is Alloy 6061 with magnesium and silicon being the major alloying elements alongside aluminium [5],[6].

The use of aluminium as an industrial metal came about recently at the end of the 19th century. The demand of aluminium has grown to 69 million tonnes per year at present globally [7]. The global aluminium production for January 2020 alone was 5,451 thousand metric tonnes and Europe produced 640 thousand metric tonnes of primary aluminium whereas China was the leading producer with 3,080 thousand metric tonnes of primary aluminium produced [7]. Here, primary aluminium is the aluminium tapped from electrolytic cells during electrolytic reduction of metallurgical aluminium oxide (alumina). There are two types of aluminium waste, post-consumer waste which includes cans, packaging and other end of life products. These need to be collected and sorted before being recycled. The second type and presently still the more abundant is the pre consumer scrap which is the waste produced as a result of the process of the production of aluminium or which arises during the manufacturing process. This waste directly goes for recycling and is melted directly. Since a huge amount of aluminium has been produced every year for many years, recycling of aluminium also came about as a huge opportunity both environmentally and commercially.

It is estimated that around a third of all the aluminium produced is recycled. And, around 75% of all the aluminium ever produced is still in use and has not reached the end-of-life stage. Recycling of aluminium consumes only 5% energy as compared to the production of primary aluminium. This is an environmental factor which makes aluminium recycling favourable [8],[9]. Aluminium is essential for the European economy with 39% of the aluminium produced by Europe is used in the mobility industry and 24% being used in the construction process [10]. Europe is also the leading region in the world in terms of aluminium recycling with North America being second. The European union has been very active when it comes to metal recycling and has classified aluminium scrap and alloys as not waste [11]. European Aluminium has set out a vision of reducing the GHG emissions during aluminium production by 80-95% as compared to 1990 and are way ahead of time in reaching that target [12].

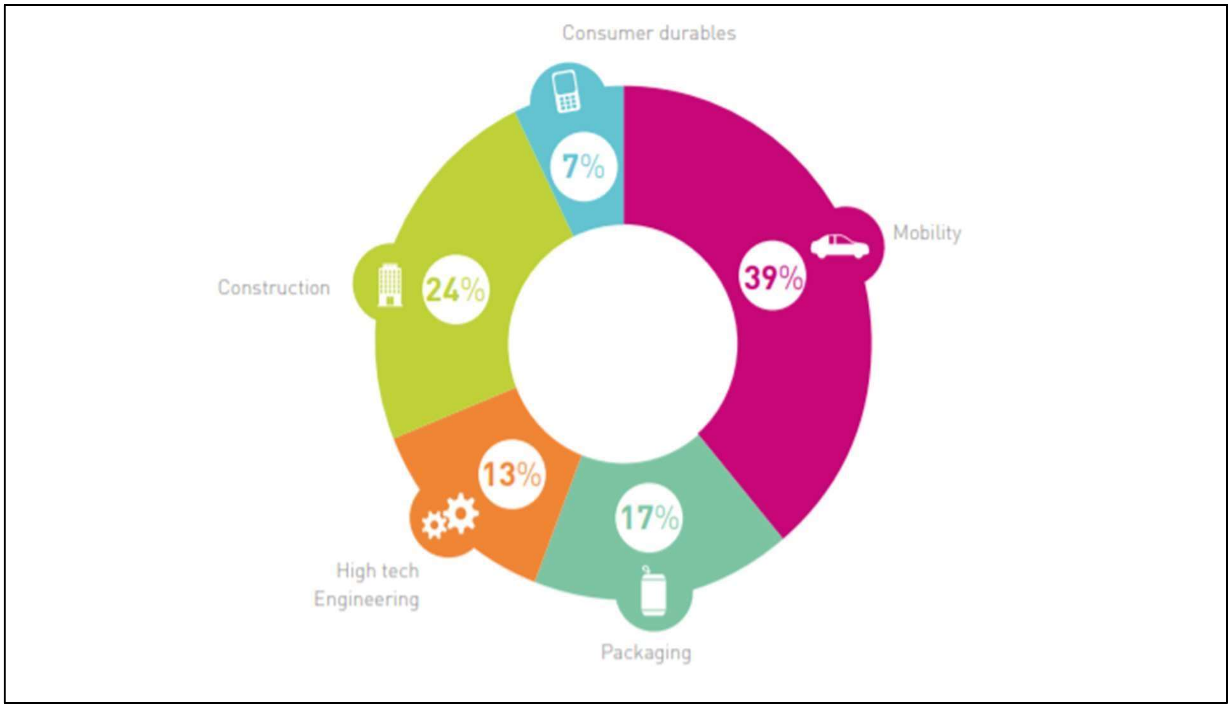

Figure 1. European Aluminium Usage [10]

Netherlands, as with Europe, has also got high rates of aluminium recycling. There are laws such as the LAP3 which is the national waste management plan where aluminium (and other non-metals) recycling plans have been set out [13].

Economically, aluminium recycling has been rapidly increasing globally. The fact that aluminium can be recycled repeatedly without any loss of properties makes it very desirable commercially. Reukema is one such company which has benefitted from recycled aluminium trading. They have been trading for more than 100 years and now want to become scrap metal recyclers. But in the desire of becoming recyclers, there are multiple problems and one such problem is the singulation of large aluminium pieces. To majorly solve this problem of singulation and to make Reukema an efficient aluminium recycler, the present project is being done.

1.1 Singulation

Since Reukema aims to recycle its own aluminium scrap, the recycling process needs to be optimised for greater economic and performance efficiency. Most of the post-consumer aluminium waste is made up of combination of alloys and other materials and these need to be separated for better processing. The separation process includes a very important step of singulation.

What is Singulation?

Singulation is the process where scrap particles are aligned in a file on a conveyor belt with spaces between subsequent particles. If the flow of scrap is well singulated, it makes the inspection of the scrap, particle by particle, easier and that in turn makes it easier for the particles of different alloys to be separated from the flow.

This process is prominent in the parcel industry where thousands of parcels need to be identified and separated for further process via artificial intelligence. The parcel industry is a great example of how to singulate particles.

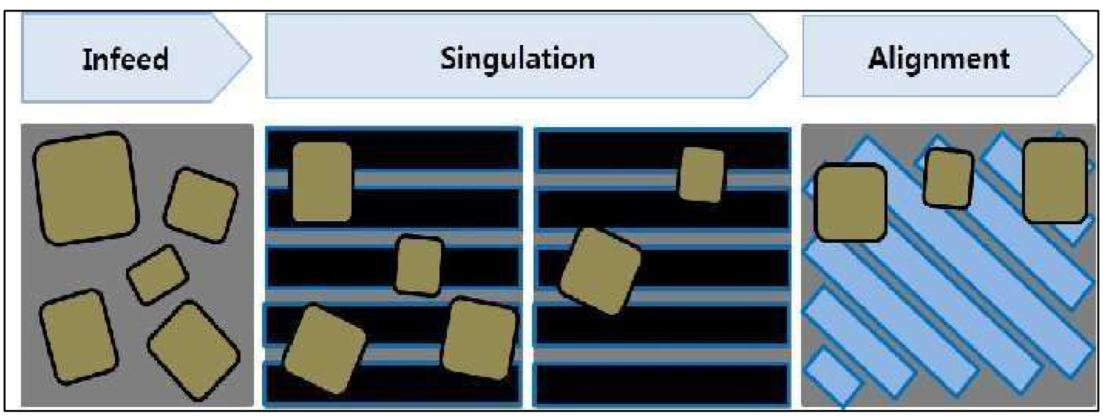

Figure 2. Singulation Process in the Parcel Industry [14]

What are the problems with singulation?

The process of singulation is made difficult when, in almost all cases, two or more particles end up on top of each other or interlocked with each other. This makes their separation difficult. Also, not all particles are of uniform shape which gives rise to uncertainty of their behaviour when under the process of singulation.

What are the processes that have been used to singulate metal?

To separate the interlocked pieces, there have been many processes used such as a vibrating Zigzag separator which places each piece one after the other but requires pieces of uniform shape [15]. Another example is the vacuum separator which uses vacuum to separate pieces but has a very low processing rate and efficiency [16]. There have been other processes such as the unscrambler [17], multiple lane singulator [18] and a form fit singulator [19] but these have been used to singulate water bottles, food products, parcels etc. and not metals. The most successful technology has been the LIBS or the Laser Induced Breakdown Spectroscopy which makes plasmas on the surface of the metal to identify it and then separate it. But the drawback is that it only operates on small metal pieces of up to 60 mm and hasn't been successful for larger pieces [20].

1.2 Objectives and Sub-Objectives

The objective of the project is to study the step of singulation for large aluminium pieces in the process of aluminium recycling and how to optimise it. In the lead up to the process of singulation, it is studied that why is aluminium recycling essential in the current trend of circular economy, and what incentives are being provided to promote aluminium recycling. There have been mentions of the processes used to make aluminium, aluminium alloy classification, what happens to aluminium after it reaches the EOL stage etc. but these are used to showcase the holistic approach taken in the aluminium recycling policy making and are not part of the scope of this study.

The scope of this work is only to study what are the incentives and policies which encourage aluminium recycling and what are the problems faced during recycling with the focus being on the case of problem of singulation and how singulation works for large aluminium scrap pieces (50-180 mm) in the process of aluminium recycling.

For the process of singulation, a pile of each size fraction (50-100mm, 100-180mm) will be transferred on a vibrating feeder in order to get a monolayer of aluminium scrap and then they will be transferred to a chute where they will be expected to get singulated once they reach the sorting belt by virtue of acceleration. Each process will be monitored by cameras.

The following are the sub-objectives which would lead to achievement of the objective.

1. To develop a time series for the arrivals of the particles for the process of singulation.
2. To study the effect of size of aluminium scrap, change in frequency of the vibrating feeder and change in speed of soring belt on the efficiency of singulation and to compare it with simulated scrap singulation.
3. To study the some of the incentives and policies regarding aluminium recycling from around the world.

The experimental setup can be better understood in figure 3.

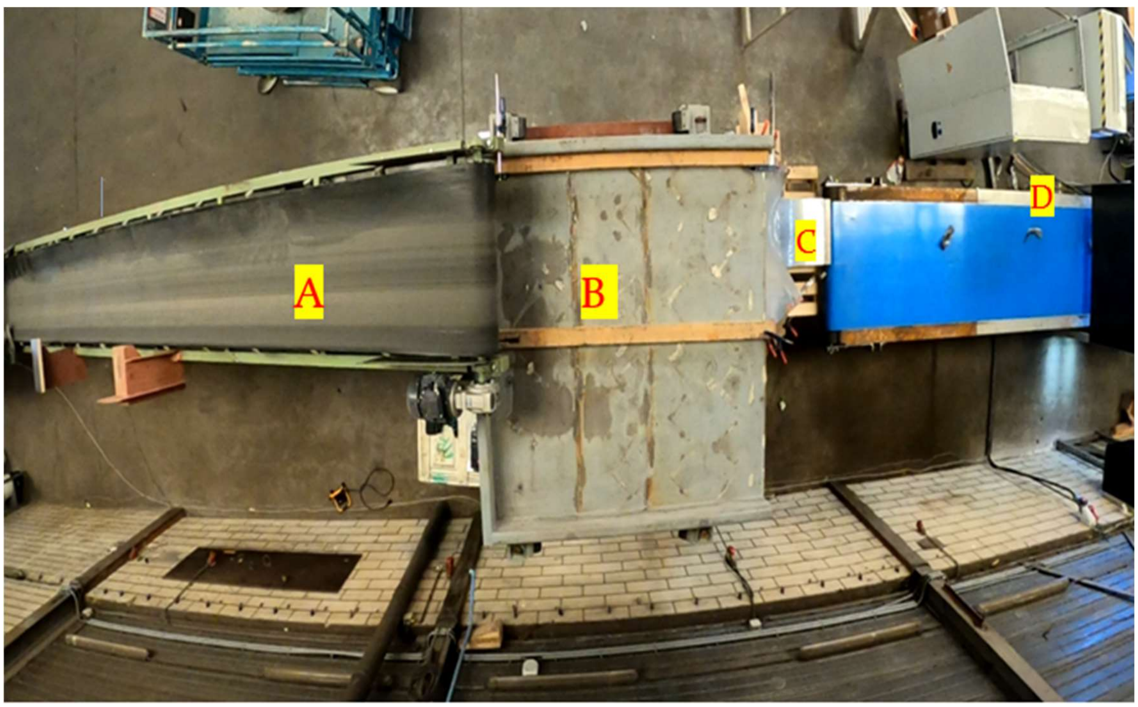

Figure 3. Experimental Setup with (A) Input Conveyor, (B) Vibrating Feeder, (C) Chute, (D) Sorting Belt

2. BACKGROUND INFORMATION

This section seeks to present the background information on aluminium recycling starting with the metal production process itself. Then, the purpose of production of aluminium, aluminium alloy designation systems, what happens when the produced aluminium reaches its end of life (EOL) stage and the policies adopted in various regions to deal with it are mentioned. This section also explains some of the recycling processes which are most commonly used for aluminium scrap recycling. As a whole, this section tries to build up a strong base for the followed work.

2.1 Aluminium Production

In the aluminium production section, two essential aspects of aluminium scrap are discussed. The process of production deals with the question of how is primary aluminium produced which eventually becomes aluminium scrap and the types and purpose section addresses the questions that why is aluminium produced and how are the properties of aluminium changed with addition of other elements so as to use it for a particular purpose.

2.1.1 The Process of Production

Processes involved in the production of aluminium have remained more or less same since they were invented. There are ongoing innovations to improve the older methods such as the inert anode process [21] but at present there are two main processes to achieve the production of Aluminium. They are:

Bayer Process:

The Bayer process was invented by Karl Bayer in 1887 in Russia when he improved the process of manufacturing alumina for the textile industry. Even today the Bayer process is virtually unchanged and almost all the alumina supply of the world for aluminium production is derived from this process.

This process is the first step towards pure aluminium production. In the Bayer process, bauxite ore is refined to obtain aluminium oxide. The process is described as follows:

i. Initially, using mechanical equipment, the Bauxite ore is crumpled and then is added to NaOH (Caustic Soda) and processed to make a slurry which has very fine ore particles, in a grinding mill.

ii. The watery suspension/slurry is then put in a digester which is a tank that behaves like a pressure cooker. Then the slurry is heated to 110°-270°C under a pressure of 340 kPa for 30 minutes to multiple hours.

iii. This slurry, which is hot and currently a solution of sodium aluminate, is run through patterns of flash tanks which are used to decrease pressure and gather heat which is capable of being used again in the process of refining.
iv. The slurry is then pumped to a settling tank and as it lies here, the impurities which didn't dissolve in the caustic soda get settled at the base of the tank. The residue or the 'red mud' which collects at the bottom consists of fine sand, iron oxide, and oxides of trace elements.
v. This liquid is then pumped via many cloth filters and any fine impurities which still remain in the solution are trapped by these filters.
vi. The liquid which has been filtered is then pumped through a series of very high precipitation tanks. Alumina Hydrate seed crystals are added via the apex of each tank. As these crystals settle through the liquid, they grow since dissolved alumina gets attached to them hence making them heavier.
vii. These crystals are removed once they get to the base of the tank. They then are transferred to a kiln for calcination after washing. A screw conveyor is used to mobilise this regular stream of crystals into a rotating, cylindrical kiln which is at an angle so that gravity can move the material through it. A very high temperature of 1100°C removes the water molecules which leaves anhydrous crystals of alumina. The crystals pass through a cooler once they leave the kiln [4],[22].

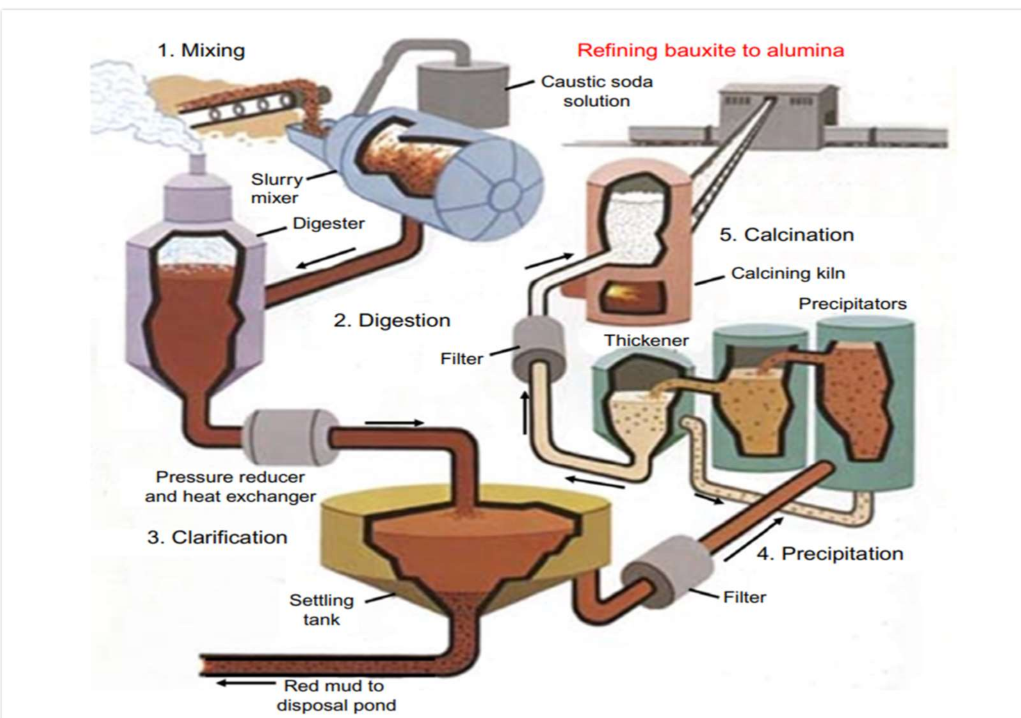

Figure 4. Bayer Process [22]

Hall-Héroult Process:

The Hall-Heroult process was invented by Charles Martin Hall and Paul Heroult in 1886. They invented it independently but almost simultaneously hence, the name Hall-Heroult. It is an important industrial process for the smelting of aluminium. The process is as follows:

i. Alumina to metallic aluminium smelting takes place in a reduction pot. The bottom is lined with carbon which is one of the electrodes and opposite electrodes comprise of multiple rods of carbon suspended above the pot which are lowered into an electrolyte solution a few inches higher to the surface of the molten aluminium which collects at the bottom of the pot. These pots are arranged is rows of 50-200 pots connected in series to form an electric circuit.

ii. Within one reduction pot, molten cryolite dissolves alumina crystals at temperatures of 960-970°C to form an electrolyte solution which conducts electricity from the suspended carbon rods to the carbon rods which are aligned with the bottom. A direct current is passed through the solution. There occurs a reaction which breaks the bonds between aluminium and oxygen atoms in the alumina molecule. The released oxygen gets attracted to carbon rods and forms carbon dioxide whereas the aluminium atoms get settled at the floor as molten metal. This is a continuous process.

iii. The molten Al is 99.8% pure and is gathered in a crucible which is moved down the potline. Then this metal is moved to a holding furnace and then cast as ingots. This also is a continuous process [4],[23].

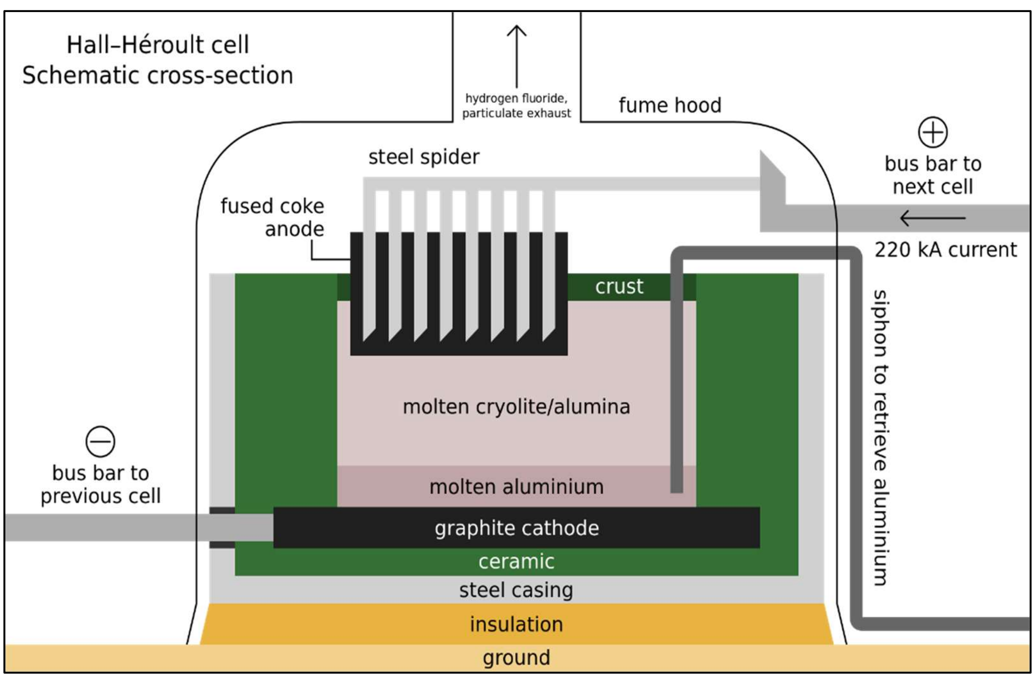

Figure 5. Hall-Heroult Process [24]

2.1.2 Types and Purpose

Aluminium is a heavily used metallic element. It is used as a crucial structural material in buildings, aircrafts, machinery parts, beverage cans and food packaging because it has high corrosion resistance and mechanical strength to mass ratio.

Aluminium became popular due it being an excellent alternative to steel in many applications. With various usages, many alloys of aluminium came about which had different characteristics to each other so as to fit in for a particular purpose. And, with numerous alloys, it became essential to allocate some system so as to identify these alloys. The Aluminum Association inc. of the USA came up with the Aluminum Alloy Temper and Designation system and is in charge of allocating and registering aluminium alloys. This system is internationally accepted by various global organizations including the 'Vereniging Nederlandse Metallurgische Indusrie' (VNMI) or the Association of Dutch Metallurgical Industry of the Netherlands.

The Teal Book which is titled 'International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys' and the Pink Book entitled 'Designations and Chemical Composition Limits for Aluminum Alloys in the Form of Castings and Ingot' contains the alloy chemical composition of all the registered alloys. Both, the wrought and the cast aluminium have different systems of identification [25].

Wrought Alloy Designation System:

This is a 4-digit wrought aluminium alloy identification system. The first digit indicated the principal alloying element that has been added to the alloy and is repeatedly used to describe the aluminium alloy series.

The second digit, if not 0, suggests a modification of the specific alloy. The last 2 digits are arbitrary numbers given to identify a particular alloy in the series.

Example: In alloy 4235, the number 4 indicates that it is from the silicon alloy series, digit 2 indicates the 2^{nd} modification to the original 4035 alloy, and 35 identifies it in the 4xxx series.

Although all alloys in this numbering system perfectly follow the system except the 1xxx series which are the pure aluminium. Here, the last 2 digits indicate the minimum aluminium percentage above 99% [5],[25].

Alloy Series	Principal Alloying Element
1xxx	99.000% Minimum Aluminium
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium and Silicon
7xxx	Zinc
8xxx	Other Elements

Table 1. Wrought Aluminium Alloy Designation System

Cast Alloy Designation System:
This system is based on a 3-digit plus decimal designation. As in the wrought alloy designation system, the first digit indicates the principal alloying element which has been added to the aluminium alloy.
The 2nd digit and the 3rd digit are arbitrary numbers assigned to identify the specific alloy in the series. The number after the decimal indicates if the alloy is a casting (.0) or an ingot (.1 or .2). There is a prefix in form of a capital alphabet which points to a specific alloy's modification.

Example: Alloy A475.0 where A indicates a modification to the alloy 475.0. 4 indicated that the alloy is from the silicon series. 75 identifies the alloy within the silicon series. The number after decimal i.e., .0 indicates that the casting is a final shape casting and not an ingot [5],[26].

Alloy Series	Principal Alloying Element
1xx.x	99.000% minimum Aluminium
2xx.x	Copper
3xx.x	Silicon plus Copper and/or Magnesium
4xx.x	Silicon
5xx.x	Magnesium
6xx.x	Unused Series
7xx.x	Zinc
8xx.x	Tin
9xx.x	Other Elements

Table 2. Cast Aluminium Alloy Designation System [5]

After understanding the identification system, it is clear that different series of alloys are bound to have different characteristics and hence, different applications. It is known that within the series mentioned above, there are two

noticeably different types of aluminium. The ones which gain strength when heated i.e., the Heat Treatable Alloys and the others being the Non-Heat Treatable Alloys.
Heat treating heats the solid, alloyed metal to a specific point as the alloy elements get evenly distributed with the aluminium putting them in a solid solution. The metal is then cooled rapidly which freezes the solute atoms in place. Then the process of aging takes place at room or low temperature. Non-Heat Treatable Alloys are strengthened via cold working which occurs while rolling or forging methods and is result of working the metal to make it stronger [6].

These two different types of aluminium within the series of alloys aid in understanding the applications and characteristics of the alloys.

Wrought Alloys:

Wrought aluminium alloys are present in higher quantities when compared to cast aluminium alloys, hence, characteristics and applications of wrought aluminium alloy series based on the two types mentioned above are discussed first and are as follows:

Heat Treatable Alloys:

2xxx Series: Here, Copper is the principal alloying element. These alloys have high strength and toughness. Although, when compared to other series, these alloys are not as resistant to atmospheric corrosion and so are painted or clad for extra protection. These alloys are often used for aircraft and aerospace applications.

4xxx Series: This series, where Silicon is the principal alloying agent, is the only series which has both heat treatable and non-heat treatable alloys. These alloys have good flow characteristics and can be easily joined by soldering or brazing. These alloys are mainly used as weld filler alloys and also for forgings.

6xxx Series: These Aluminium-Magnesium-Silicon alloys have a very high corrosion resistance and impeccable extrudability. Due to these characteristics, this alloy is extensively used in construction work. They are also used in crash protection systems.

7xxx Series: The Aluminium-Zinc alloys are considered to be the strongest aluminium alloys. The aircraft industry has heavily relied on the usage of these alloys. They are also used in riveted construction .

8xxx Series: These are alloys which are not covered in other series. The alloys here are mostly highly conductive, have high strength and hardness. The alloys with Iron and Nickel are used in conductors. Lithium alloys are used in aerospace applications [5],[6],[27].

Non-Heat Treatable Alloys:

3xxx Series: The principal alloying element in this series is Manganese. These alloys exhibit good resistance to atmospheric and chemical agents but have high formability. Alloys of this series are used in cooking utensils and chemical equipment. Some are used in the bodies of beverage cans.

5xxx Series: These are Aluminium-Magnesium alloys which are readily weldable, have excellent resistance to corrosion and have high toughness are used in building and construction.

The 1xxx series is Pure Aluminium. Its Exceptionally high formability, resistance to corrosion and electrical conductivity makes it ideal for electrical applications. They are also used as foil and strip for packaging [5],[6],[27].

Cast Alloys:

The characteristics and applications of cast aluminium alloy series based on heat treatability and non-heat treatability are as follows:

Heat Treatable Alloys:

2xx.x Series: These are Aluminium-Copper alloys which have high strength at room and elevated temperatures. Some of these alloys are used in the aerospace industry. Some are also used as piston heads, bearings etc.

3xx.x Series: The Aluminium-Silicon plus Copper or Magnesium alloys are known to have excellent fluidity and high strength. They are readily weldable too. These castings are most widely used due to their flexibility and are used for sand and permanent casting as well as the new squeeze/forge cast technologies.

7xx.x Series: Zinc is the principal element here and these alloys have excellent machinability and great appearance. Uses include furniture, garden or farming tools and mining equipment.

8xx.x Series: These Aluminium-Tin alloys have excellent machinability. They are used for bushings and bearings and are relatively hard to cast [27].

Non-Heat Treatable Alloys:

4xx.x Series: Aluminium-Silicon alloys have excellent fluidity and are used for intricate castings such as cast parts of typewriter, dental equipment etc.

5xx.x Series: These are Aluminium-Magnesium alloys which are tougher to cast but provide good finishing characteristics. They have high corrosion resistance, machinability and have a good surface appearance. These alloys are regularly used as door fittings and window fittings [27].

Therefore, it is clear that the aluminium and its alloys are very handy and have their applications in various industries such as electrical, building and construction, transportation, packaging, petroleum and chemical to name a few.

There are many alloys which are used with each other or can be used for the same purpose. This makes these series of alloys compatible. The table below gives some examples:

Alloy Series	**Applications**
5xxx and 6xxx	Construction, Transportation, Chemical and Petroleum Industry
2xxx and 7xxx	Aircraft and Aerospace Industry
4xxx and 5xxx	Welding

Table 3 Alloy Series with Similar Applications [27]

2.2 End of Life (EOL) of Aluminium

This section deals with what happens to production scrap and post-consumer aluminium, it also looks at why aluminium is highly recyclable and describes some of the common methods used to recycle aluminium.

2.2.1 Recycling of Aluminium

As mentioned earlier, around 75% of aluminium which has been produced ever, is still in use. Due to its long lifespan, aluminium is widely used in volume heavy applications such as in buildings and transport vehicles. This makes the available quantity of end-of-life aluminium scrap very limited today. This available volume is way below the current requirements because of continuous and rapid market growth and hence, the requirement is fulfilled by the primary aluminium industry. But the recycled aluminium industry is in itself huge.

Aluminium is considered to be the one of the most recyclable metals and this makes it essential both environmentally and commercially. It perfectly fits to the concept which is gaining popularity amongst academicians, industries, political decision-making and the society which is the concept of circular economy.

Circular economy looks beyond the traditional linear economy and aims to redefine growth by focusing on positive society wide benefits. A circular economy is one in which goods which are on the verge of their service life are converted into resources. Generally, waste has been traditionally considered as something without any value but in a Resource-Efficient circular economy, waste would be only those residual materials which have reached to a point where they can provide no economic value. Under this economy, the material which was considered to be waste in a linear take-make-waste economy would be recovered through an elevated level of management and greater efficiency at all stages of production and consumption. Scrap metals, though, have been of value throughout. Such waste has been traded in order to make gains financially and is a huge industry in itself. The basis of a circular economy is to design out waste and pollution, keep materials and products in use and to regenerate natural systems. In linear economies, there is a large consumption during the process of production which leads to escalated levels of waste. There is also minimal effort in trying to reuse or recycle the waste which is sent for disposal. But, in a circular economy, it is made sure that almost all outputs come in use as inputs to other manufacturing processes or are released as benign emission and not as pollutants [28].

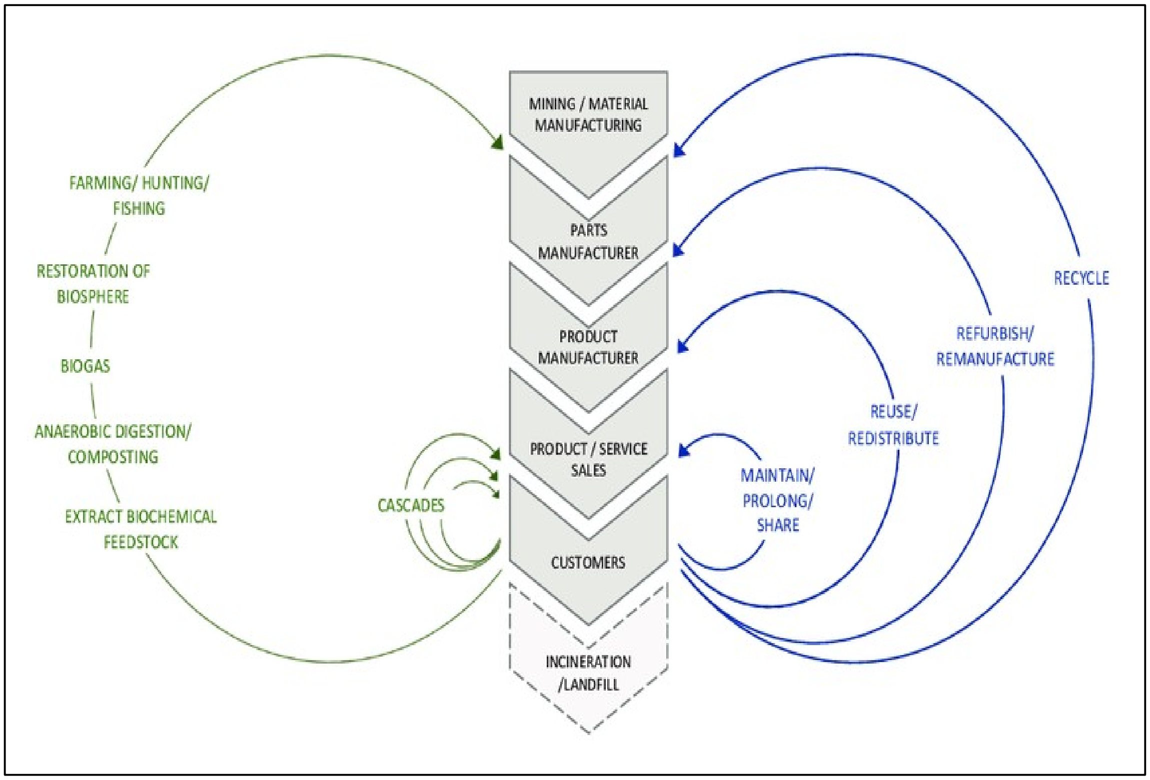

Figure 6. Circular Economy [28]

Since aluminium with its alloys possesses properties such as being lightweight, durability, electrical conductivity, flexibility and many more, recycling the material is highly useful. It requires only 95% less energy to recycle aluminium than to produce primary aluminium and recycling of post-consumer aluminium products saves 90 million tonnes of CO_2 and over 100,000 GWh of electrical energy, which is equivalent to the annual power consumption in the Netherlands. Another benefit of aluminium is that it can be recycled over and over without any loss of properties which makes it a highly useful material when it comes to reducing cost of buying primary raw material. Many world-renowned organizations have made circular economy their goal so as to benefit the environment and also to maximise efficiency. Apple, one of the world's biggest companies, uses 100% recycled aluminium which has made its products have nearly half the carbon footprint when compared to earlier products [29]. Samsung, another giant company in the electronics industry, has aimed to make its products out of recycled material and aluminium is around 20% of the products they make [30]. Global aluminium recycling rates are high, approximately 90% for transport and construction applications and about 60% for beverage cans. Hindalco Novelis are the world's largest recycler of aluminium and recycles more than 60 billion used beverage cans each year. They created the first and largest automotive closed loop recycling system in the world under which scrap aluminium is recycled from the automotive manufacturing process and it keeps the value of the alloy intact and also reduces recycling, transportation costs plus the carbon footprint is also reduced [31]. These various examples support the fact that recycling of aluminium has very high rate and the focus should shift to a better and more efficient collection system which could increase the rate of recycling even more.

Today, recycled aluminium which includes both pre- and post-consumer scrap represents 36% of European supply of aluminium. By 2050, it is expected that the global demand for primary aluminium will grow by 50% to around 110 million tonnes. The European demand is expected to be around 9 million tonnes per year up to 2050. This demand in 2050 will be met equally by primary as well as recycled aluminium production if everything happens as planned. And, as forecasted, the amount of post-consumer aluminium which is present for recycling will be higher than double its value by 2050. This shall increase to 6.6 million tonnes per year in 2030 and 8.6 million tonnes by 2050 from 3.6 million tonnes in 2019.
As aluminium demand and consumption keeps on increasing, the industry of aluminium recycling and the idea of a circular aluminium industry keeps achieving importance. [32]

2.2.2 Processes Used in Recycling of Aluminium

The metal recycling industry is a cash rich industry and it has grown a lot more since the concept of circular economy has surfaced and aluminium being one of the most recyclable materials has been a major part of this industry. Aluminium is recycled chemically once it has been collected, sorted and treated properly. Scrap is treated according to its previous use and origin. The purpose of treatment is to increase bulk density, to remove non-aluminium scrap, and to reduced impurity level.
The very first step is comminution as scrap appears in a lot of shapes and sizes. The main advantage here is that materials such as rubber, plastic, magnesium etc. which are undesired, have a possibility to get removed. There are a variety of machines available for this purpose such as rotary cutters, rotary shears and rotary shredders [33]. There are other methods as well such as high-pressure water jet comminution.
Since a variety of aluminium alloys are used in a variety of applications, there are a lot of combinations of aluminium with other materials such as zinc, copper, steel, rubber, glass or even plastics and this creates the necessity of properly screening this scrap before the process of melting so as to enhance efficiency and

reduce impurities. Physical sorting of scrap is, therefore, a good way to avoid mixing of metals and elements. Various sorting methods are required for different types of scrap with the aim to separate aluminium scrap from various other materials [34].

Below are mentioned some of the main sorting technologies:

Magnetic Separation:
It is an age-old form of material separation which is used to separate non-ferrous material from ferrous material. Drum magnets and overhead magnets are the most commonly used magnets in the secondary aluminium industry. The scrap moves close to a permanent magnet and this causes the ferrous material to get attracted to the magnet since a magnetic field is responsible for the attraction. The non-ferrous material passes through without ant attraction and hence, are sorted. This method is very useful while separating used beverage cans [35].

Eddy Current Separation:
In this method, eddy currents are generated in the metals. A belt with a certain magnetic field which is produced by a polar wheel of high frequency which is where materials arrive. The non-ferrous metals, when in this magnetic field, experience currents due to the induced electromotive forces and get lifted and dropped in collecting duct whereas the inert material falls into another container. This process is useful in recovering high-value materials with impeccable selectivity [36].

Dense Media Separator:
Difference is densities of material is an essential property for separation of aluminium scrap from other materials. Sink float method is a very regularly used method under this section of methods. Liquids or slurries of known specific gravity are used to separate the non-metallic fraction. Due to density differences, some materials sink and some float and due to this behaviour, they can be separated. Since a lot of such slurries used are based on water, the extra step of drying the separated material makes this process longer and costly. Fluidised bed sink float method is deemed to be a way to prevent such wet separation [34].

Hand Sorting:
Manual sorting is still a very common process and results in considerably high purity but is considered to be expensive due to very high labour costs. Countries with low labour cost such as Asian countries use this method. Although,

separating aluminium from other metals is relatively easy using this method but separating aluminium alloys is a challenge [34].

Laser-Induced Breakdown Spectroscopy (LIBS):
This method is one of the new and upcoming innovations in the sorting process. Here, an increasingly strong laser pulse is used to remove a minute amount of the material from its surface. There is generated a very hot plasma and analysing the light which is generated there with a spectrometer helps in determining the chemical composition. Earlier, it was required that the surface of the material be free of any coatings since the pulse laser was not able to penetrate deep into the material but now there are processes where laser is shot twice, once to remove the coating and the other to analyse the alloy. The increase in pulse energy also diminishes the effect of coatings. [37].

There is a plethora of aluminium products present in a wide range of forms and for various purposes they have different kinds of coating of many elements on them. Because of this, various undesirable elements might get mixed in the eventual chemical composition. So, de-coating is required before melting. It is a procedure via which oil, paint, ink, paper and plastic are ousted out of the surface to improve recyclability. There are various economic and environmental benefits of this process as well. Since, this process increases the scrap quality, the process quality increases of the system. Harmful emissions are also reduced since the gases which are evolved can be cleaned and then released [38].

The final process is the melting process of aluminium scrap. There are different types of furnaces available which are chosen based on multiple criteria. The two most important ones which are considered while furnace selection is metal content in the scrap and the volume of production. The furnace types which are most commonly used are either electric or fossil fuel furnaces. A major portion of secondary aluminium us produced in furnaces which are fired via fossil fuels such as rotary and reverberatory furnaces [34].

Sorting is an essential step in the process of aluminium recycling. Aluminium scrap which is sorted based on alloy series have high ecological and economic benefits. Sorting aluminium scrap randomly is an easier and more widely used process largely due to lack of technology. But there have been developments recently which allow sorting of aluminium based on alloys series. Sorting of alloys in series helps in using the material flows after remelting without downgrading or alloying additions. And due to these separation in pure series of aluminium alloys from 1xxx to 7xxx, recycling at the same value stage is possible. This makes recycling into groups based on alloy series very attractive.

But the technologies which are used to do such sorting requires one really important process i.e., to make this aluminium scrap particles positioned in such a way that they have enough space in between so as to increase the efficiency of such technologies when they operate in order to separate aluminium alloys in groups. This process is also known as singulation.

2.3 Singulation

As mentioned earlier, singulation is the process where scrap particles are aligned in a file on a conveyor belt with spaces between subsequent particles.
Singulation is a process which is highly useful in separating objects which are in close proximity or on top of each other. It is highly desired in the parcel industry, in food industry, in recycling and in many more industries. There is limited information on the singulation of metal scrap using the method in focus in this project.
Previously, singulation was defined as having three degrees. First degree singulation meant that articles are received in a 3-D arrangement and then are arranged in an untidy monolayer with intermediate and irregular spacing between them. Second degree singulation meant that articles arrive in an irregular monolayer and are arranged in row/s with intermediate and irregular spacing. Third degree singulation meant articles arrive in rows and are arranged in desired configuration with definite, predictable spacing.
It has been treated as a second-order problem which deals with the manner of feeding a machine. Historically, manual singulation had been observed as being the most sophisticated way of singulation. In addition to being slow and accurate, it was observed that the quickest people tended to move both their arms in phase with each other, singulating one degree at a time seemed to be quite efficient and all the humans used a 2-step process which consisted of grasping a group of objects in each hand and manoeuvring each object via their fingers as their arms were enroute from supply to destination. A 2-step process which was recommended for design of mechanical singulators [39].
There have been various methods of singulation developed for agricultural produce of symmetrical and regular shape. For irregular produce such as potatoes, a different method was developed since they have a shape from broadly spherical to elliptical to even pear shaped. Separation was also made difficult due to interlocking in concavities. This singulator was a lateral expanding singulator

capable of singulating many other agricultural produces. Multiple experiments showed that this singulator had a capability of singulating potatoes at rates of 8 tonnes/hr with an efficiency of 95%. Different size ranges though, had varying effects with 55-80 mm being the most favourable [40].

2.3.1 Reukema

Reukema is a 100-year-old metal trading company which trades in recycled aluminium and its alloys, copper, zinc, lead, brass, stainless steel, motors, zorba, cables and paper among other things. As a trading company, they follow the London Metal Exchange or the LME for pricing their metals per tonne. They use special percentages based on the type of metal or alloy and the amount of pollution there is in the sorted product.

As a new venture, Reukema, a trading company, want to recycle their own aluminium and hence want to become recyclers with the aim of recycling 30,000 tonnes of aluminium scrap per year. For this, they have setup a processing line at their company site in Harderwijk, the Netherlands where the line would include the singulation process, a sensor using process and further processes which are beyond the scope of this project.

Reukema is one of many companies which see the benefits of aluminium recycling, both economically and environmentally. In the next sections, there are mentions of policies and incentives which inspire and encourage companies like Reukema and in the later section there is a detailed study of how the process of singulation for aluminium scrap particles from 50-180mm size range, which is a case study of the problem faced by Reukema, is executed.

3. INCENTIVES AND POLICIES

The role of government bodies and institutions responsible for regulating recycling is essential to keep the process relevant. This section looks at the laws made by responsible authorities on how to deal with aluminium scrap recycling and contains the directives from the European Commission and the policies the Dutch government has made to manage the situation. Laws and initiatives of some other countries have also been discussed.

3.1 Europe

Aluminium has a very large lifespan when it comes to some applications and a limited lifespan when it comes to others. In 2008, the European commission came up with a Waste Framework Directive which establishes rules on how the EU should manage its waste and it defined the end of waste criteria which specifies when certain waste ceases to be waste and obtains a status of a product or a secondary waste material. It ruled that certain specified waste shall cease to be waste when it goes through a recovery or a recycling process and follows certain criteria i.e., the substance is commonly used for a specific purpose; there is a demand or an existing market for it; the use is lawful; and the use isn't harmful to the environment and human health.

The end-of-waste criteria for aluminium scrap was laid down in 2011. It stated that aluminium scrap or aluminium alloy scrap ceases to be waste if:

i. The waste used as the input in the recovery processes is only waste that contains recoverable aluminium or its alloys; is not hazardous; and shall not be filling and turnings that contain oils and barrels and containers.
ii. The waste used as input is treated in accordance with rules such as the scrap shall have been segregated as source or while being collected; all mechanical processes required to prepare the scrap for input must be completed; and hazardous waste such as electricals and electronics shall have gone under treatment, cables be chopped off, CFC's shall have been captured, barrels and containers shall be cleaned.
iii. The scrap generated from recovery processes shall be graded in accordance with a customer specification, and industry specification or a standard for direct use in production of metal substance; the amount of foreign material shall be less than 5% by weight [41].

The 2008 directive was created in order to decrease the environmental impact of waste and to encourage resource efficiency through the 3 R's of Reduce, Reuse and Recycle. It had ambitious targets such as separate collection of plastics, paper, glass and metals in all households by 2015 and 50% of all these types of waste be recycled or reused by 2020.

In March of 2020, the European Commission adopted a new circular economy action plan in aid of achieving its goal of climate neutrality by 2050 and decoupling of economic growth from resource use. This plan introduces a future oriented plan for the purpose of achieving a cleaner and more competitive Europe. There are mentioned a set of interrelated initiatives to establish a healthy product policy framework so as to make sustainable products, services and business models the norm and evolve patterns of consumption so that there is no waste produced in the first place. This plan also considers a global role and not just of the EU to achieve a circular economy at a worldwide level [42].

3.2 Netherlands

The ministry of infrastructure and water management came up with the National Waste Management Plan (LAP) to set out the policy for waste management in the country. The latest is the LAP3. It describes the policy for traditional waste activities such as collection, recycling, incineration and landfill. It also discusses topics such the relationship to circular economy, the available instruments, aspects of importance when granting permits, consideration of whether a material is waste or not and also the policy on capacity regulation. The first two LAP's were very successful but they lacked incentives for shifting towards a circular economy. LAP 3 focuses more on transition to a circular economy which has become a priority in the Netherlands. LAP3 sets out objectives for the next planning period, it is a starter to differentiate between more and less high grades of recycling, devotes attention to innovation contributing to waste policy and circular economy, development of policy where very high concern substances are handled and give a structure to LAP with each step being well defined. Governments are required by law to keep all their waste related decisions in touch with the LAP [13].

3.3 Rest of the World

Some other countries which should necessarily be considered when discussing about aluminium scrap recycling have been mentioned in this section.

China is the largest producer of primary aluminium in the world. Recently, it has put sanctions on the import of aluminium scrap from other countries citing environmental concerns. China has multiple companies which make use of secondary aluminium. The Chinese government has recognised this and encouraged other companies to increase the use of secondary aluminium by offering VAT rebates which are a first for such recycled aluminium companies. There have been new emission standards of pollutants which have been laid down which are estimated to cost companies around $2 Million to upgrade to required environmental protection equipment. Their 13^{th} 5-year plan aims to increase domestic aluminium scrap usage and due to this there is an expectation from companies to upgrade to new technologies. [43]

Brazil had an aluminium can recycling rate of around 98.4% which was the highest in 2014 in the world and hence made Brazil world leaders in this field for over 13 years. Due to tremendous coordination between all the involved parties including manufacturers to consumers, Brazil has maintained its position as world largest aluminium can recycler. The government played a huge role by educating and raising awareness for this purpose. Due to a pre-existing recycling market, ease of collection and transport and high value of the metal, aluminium recycling has changed consumer behaviour in the country and is a healthy source of employment and income in the country. [44]

4. METHODS

The aim of the work done was to produce a time series for the input of aluminium particles coming from a screen after shredding and then test the singulation process using various equipment such as an input conveyor, a vibrating feeder, a customised chute and a sorting belt as explained below. The experimental setup and numerical modelling methods are explained below.

4.1 Experimental Setup

The experiment was setup in the Reukema campus in Harderwijk where all the experiments were done. In the eventual setup, the aluminium scrap would go through a shredder to be shredded into pieces of 50-100 mm and 100-180 mm size fractions. These size fractions were selected since they were the most abundant from the aluminium scrap which went through screening tests done at a German company named Spaleck.

Tests at Spaleck:
Spaleck is a German company which builds various machines to solve various problems related to recycling of metals and other industrial problems. Metal processing and separating machines are some the machines they build.
At Spaleck, Reukema tested their aluminium scrap for screening. In the first round of testing, aluminium scrap having size fractions from 0-300+mm was put on screens so as to separate the materials of size fractions of less than 50 mm and of greater than 300 mm and reject them. It was then determined that the highest number of particles were in between size ranges of 50-180 mm (Table 4)

Size Fraction (mm)	Percentage Weight of Total
0-50	3.3%
50-100	30%
100-180	50%
180-300	12%
300+	4.5%

Table 4. Weight of each size fraction in the total by percentage

In the next round of testing, aluminium pieces within size fraction of 50-100 mm were screened out separately and aluminium pieces within size fraction of 100-180 mm were screened out separately.


Figure 7. A still from a test at Spaleck

From these tests, a time series was derived of the particles falling from the screen to a feeding belt below the screens which carries the particles forward. The time series (Section 4.2.1) was used as the pattern of input of particles for the vibrating feeder.
In this section, there is also a description of how an aluminium particle travels through the setup for process of singulation. The mentioned mathematical description is a model which can be used to further investigate the process in detail but here it is mentioned to get an idea of the process and not in detail since it is out of the scope of work in this project.

4.1.1 Feeding Belt

The feeding belt is where the particles enter the process of singulation. Here, the belt feeds material which falls from the screens after shredding to the vibratory feeder. The feeding belt has a certain speed which is the feeding rate. It is based on the capacity of the process.
Here, the particle falls from the feeding belt, which is inclined at a certain angle, onto the vibratory feeder. The speed of the particle and the time it takes to fall on the feeder are mentioned below and figure 8 is a sketch of the process.

The speed of the particle can be expressed in two directions since the belt in inclined at angle ‘θ’.

The horizontal speed is V_x and vertical speed is V_y.

$$V_x = V * Cos\theta$$
$$V_y = V * Sin\theta$$

Where, V is the belt speed.

Using these, the time taken by the particle to fall on the feeder (t_i) is calculated by:

$$L = V_y * t_i + ½ * g * t_i^2 \quad (1)$$

Where L is the distance from the point of release of particle from the feeding belt to the point of contact of the vibrating feeder.

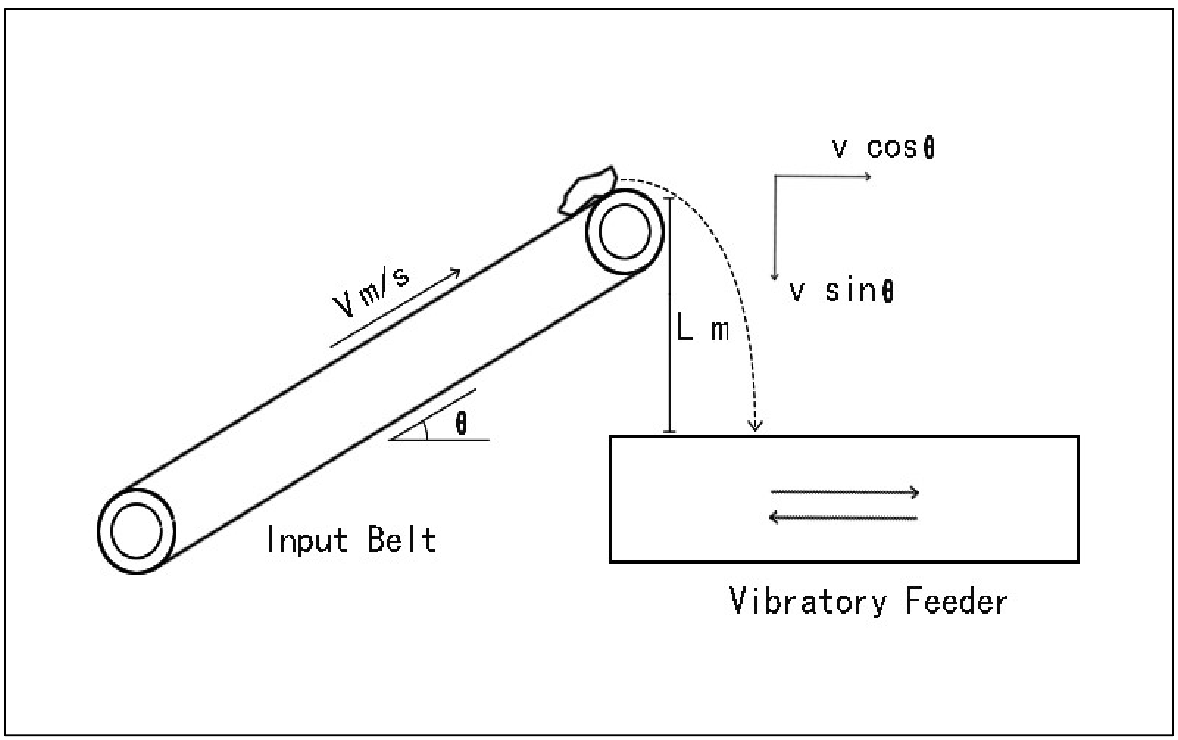

Figure 8 Path of an aluminium particle from the feeding belt

4.1.2 Vibrating Feeder

The vibrating feeder (Fig. 3) is the second phase of the test. The main task of the vibrating feeder is to act as a buffer and absorb large-scale fluctuations of the scrap particle output flow of the screens. The feeder should arrange the aluminium scrap particles such that when they emerge from the feeder, they should be in a monolayer. The used feeder had dimensions of 2 m x 2 m but only one half of the feeder (2m x 1m) was used.

The most important aspect of the particles on the feeder is their speed. The surface of a vibratory feeder oscillates along a line at an angle of approximately 30 degrees with the horizontal. In the first quarter of the cycle of oscillation, the surface both accelerates and moves forward-upward, so that the particles are pressed towards the surface and the combined gravity and acceleration creates enough friction to make the particles move forward with the surface. In the next quarter of the cycle, the acceleration is backward-downward while the movement of the surface is still forward-upward. In this phase, the particle comes loose from the surface and keeps flying close to its speed obtained in the previous phase. If the maximum acceleration of the feeder is well chosen, the particle remains flying in the third quarter of the cycle when the movement of the surface changes to backward-downward. In the fourth and final quarter of the cycle, the particle falls back to the surface and the process is repeated.

The speed of the particle on the feeder was calculated during the experiments by observing the time it took from the point it fell on the feeder to the point where it was released onto the chute.

Once the particle falls from the feeding belt to the vibrating feeder, it is assumed that the particle is at rest when it falls. The distance from the end of the feeder to the spot where the particle falls (d) is expressed as:

$$d = V_x * t_i$$

From here, the actual average moving velocity of the particle on the vibrating feeder (v_m) is expressed as:

$$V_m = C_a * C_h * C_m * C_w * V_d \tag{2}$$

Here, C_a is coefficient influenced by the inclined angle of the feed trough;

C_h is coefficient influenced by thickness of material layer;

C_m is coefficient influenced by material properties;

C_w is coefficient influenced by sliding motion;

V_d is the average velocity of the particle without the influence of inclination of feed trough, thickness of material layer, material properties and sliding motion. [45]

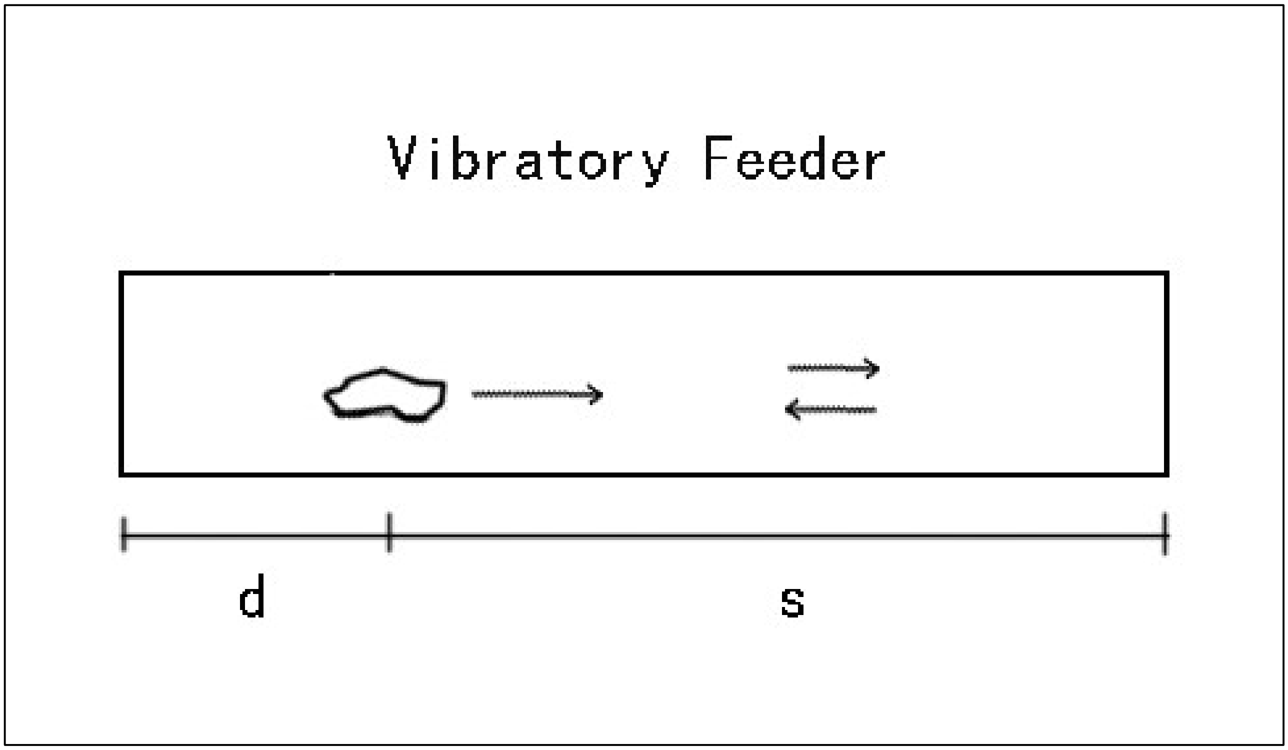

Figure 9 Path of particle on the vibrating feeder

Using the speed of the particle, the acceleration and distance travelled, time taken to reach to the end of the feeder can be calculated.

At the end of the feeder is the chute which is the next step of the singulation process.

4.1.3 The Chute

Particles flowing from a feeder typically have velocities of 0.1 - 0.3 m/s. On the other hand, conveyor belts transporting scrap along sensors and pickers have typical speeds of 2 – 3.5 m/s. If the scrap particles would tumble directly from the feeder onto the conveyor, they would jump and roll in unpredictable ways. This is not practical when the particles should be presented in a single file to sensors and pickers. Another point is that aligning scrap particles in a single file at feeding velocity means low capacities. Therefore, a wide flow of particles will fall from the feeder. For these reasons, the scrap particles falling from the edge of the feeder

are accelerated on a converging chute, to transform a wide flow of slowly moving particles into a single file of fast-moving particles.
The chute is a “wear” part that needs to be replaced every now and then. Therefore, it must be cheap. A good option is to make it from a sheet of stainless steel that is folded into a convenient shape. Folding a single sheet is cheaper than welding several parts together or deforming a sheet into a specified form. However, sheet cannot be folded into just any prescribed shape: the only shapes that are possible are parts of generalized cones or cylinders.
In this case the shape is a part of a generalized cone. The most important factors in the chute are its slope i.e., angle with horizontal, its radius of curvature, the movement and behavior of particles on it once they arrive from the vibrating feeder, the effect of friction on the movement of particles and the transition to the deaccelerating gutter.

As an extended part, there is a deaccelerating gutter. present at the end of the chute to deaccelerate the outgoing particle for a smooth transition to the sorting belt.

Figure 10. The Chute

The shape of the chute is such that it is used to accelerate particles. Generally, chutes consist of a straight part, followed by a curved path i.e. the deaccelerating gutter to make the particles end at approximately horizontal speed. The scrap particle has friction coefficient ‘f’ with the trough of length ‘L’ at an angle ‘φ_0’ with the horizontal, then it accelerates from 0 m/s at the top to speed:

$$V_0 = g[\sin(\varphi_0) - \mathrm{f}\cos(\varphi_0)]t_0 \quad (3)$$

Where,

$$t_0 = \sqrt{\frac{2L}{g[\sin(\varphi_0) - \mathrm{f}\cos(\varphi_0)]}} \quad (4)$$

Which is the time of flight in the straight part of the chute.

At the end of the curved part of radius R, the speed reduces to:

$$V_e = \sqrt{V_0^2 e^{-2f(\varphi_0-\varphi_e)} + \frac{6fgR}{1+4f^2}\left[\sin\varphi_e + \frac{1-2f^2}{3f}\cos\varphi_e - \left(\sin\varphi_0 + \frac{1-2f^2}{3f}\cos\varphi_0\right)e^{-2f(\varphi_0-\varphi_e)}\right]} \quad (5)$$

Where, φ_e is the end angle of the curved path with horizontal.

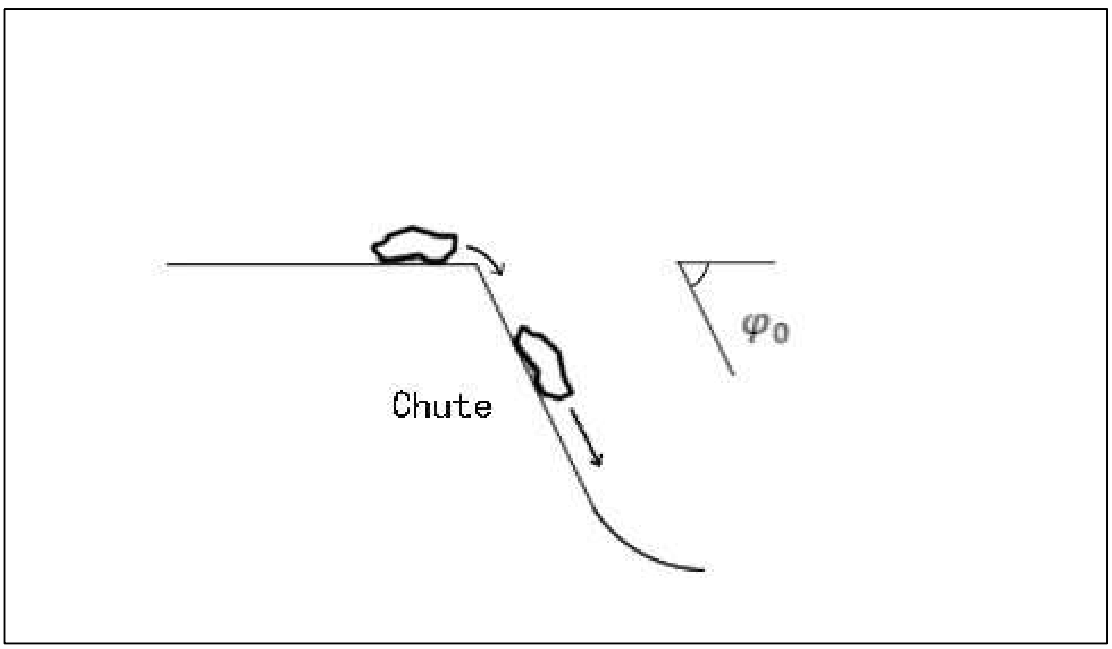

Figure 11 Path of particle on the Chute

4.1.4 Sorting Belt

The sorting belt is where the particles finally end up from the chute. Here, the speed of the belt is between 2 - 3.5 m/s and this high speed helps in a smooth transition of particles arriving from the chute. If the speed of the particles arriving is greater than the speed of the sorting belt, the particle might jump and fall off the sorting line. The particles from here go for other separation processes.

Once the particles complete their journey on the chute, they end up on a sorting belt with much higher speed. The distance between successive particles determines whether the particles are singulated or not. To know whether the distance between successive particles is more than the determined distance, the use of time interval between successive arrivals and the belt speed is used which is expressed in mathematical terms below:

$$d_s = \tau_i * z \tag{6}$$

Here, d_s is the distance between two particles
τ_i is the interval between arrival on the belt
z is the belt speed.

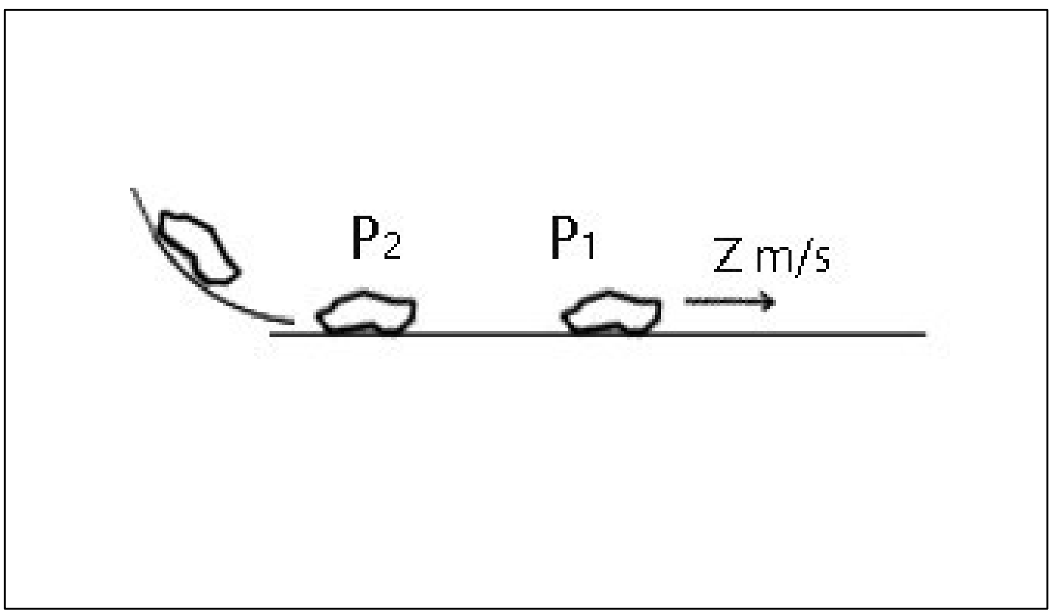

Figure 12 Distance between successive arrivals on the sorting belt

4.2 Dynamic Model

Here, the method used to develop a time series to compare with the experimental time series is explained. Also, a model for comparison with singulation experimental results was made which doesn't include the detailed effects of the vibrating feeder and the chute.

4.2.1 Time Series

From what would be the actual setup of a shredder output to a conveyor (input belt) for further process, this section explains the time series of the arrival of aluminium particles from the screens onto the conveyor belts at Spaleck which mimics the desired process. The time series of the particles arriving from the screen is essential for the calculation of next steps in the singulation process.

The homogeneous, fully random (HR) distribution can be regarded as a neutral reference distribution. In principle, it can always be generated by proper random feeding from a buffer.

But the actual arrival distributions are often less efficient for sorting lines than the HR reference. Yet, a well-conditioned process flow has a more efficient probability distribution. The physical mechanisms that change the distribution of the flow can be grouped into three different categories:

i. Mechanisms that "clump", i.e., mechanisms that act just as if particles have a short-range attraction to each other. An example is a stagnation point in a conveyor: particles build up behind some obstruction until they suddenly become released as a group.
ii. Mechanisms that "regularize", i.e., mechanisms that act as if the particles have a short-range repulsion to each other. An example is when particles are forced in a row without the possibility to be on top of each other. Then the time between arrivals of successive particles becomes very regular: equal to the size of a particle divided by the transport speed.
iii. Mechanisms that are "diffusive", i.e., processes that move individual particles fully randomly forward or backward along the time axis. This mechanism tends to restore clumpy or regularized flows back to the HR condition.

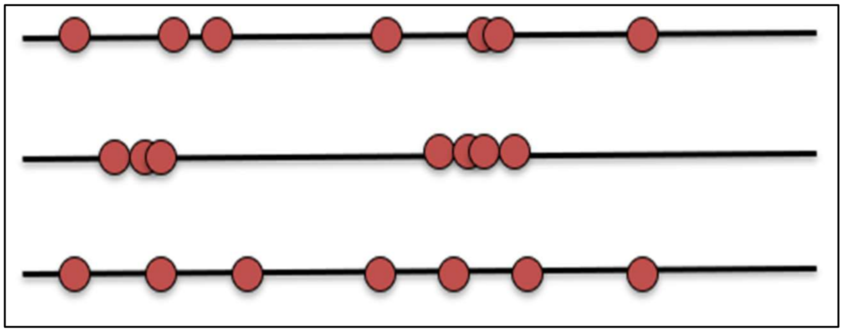

Figure 13. Particles flowing in HR condition (Top), Clumpy flow (Middle) and Regularised flow (Bottom)

Screening has a diffusive mechanism, unless the screens have bars in between them, which act like stagnation points. The diffusive mechanism is due to the fact that two particles arriving on the screen at the same time, will pass at unpredictable moments, and so each particle may be shifted a fraction of a second forward or backward on the timeline with respect to the other particles.
Once a time series of arrival times of particles is measured, we evaluate whether it is HR, clumpy or regular.

The distribution of the time between successive particles arriving should be plotted. If the time series is HR, this should be an exponential distribution. If the actual distribution lacks data at the low end and the high end, then the flow is more regular than HR. If, on the other hand, it is heavier at the low end, then the flow is clumpy. An HR series of times between successive particles can be generated using:

$$\tau_i = -\frac{1}{N_S}\ln(R_i) \tag{7}$$

Here, τ_i is time interval between 2 particles.
N_s are the average no. of particles in one second.
R_i is the random number between 0 and 1 with a homogenous probability distribution.

For the purpose of calculating the probability that the time interval between successive arrivals of particles is between τ and $\tau + d\tau$ for the HR time series, the formula below was used.

$$N_S e^{-N_S \tau}\, d\tau \tag{8}$$

Where, N_s are the average no. of particles in one second.

The following figures show examples of clumpy, regularized and HR data sets.

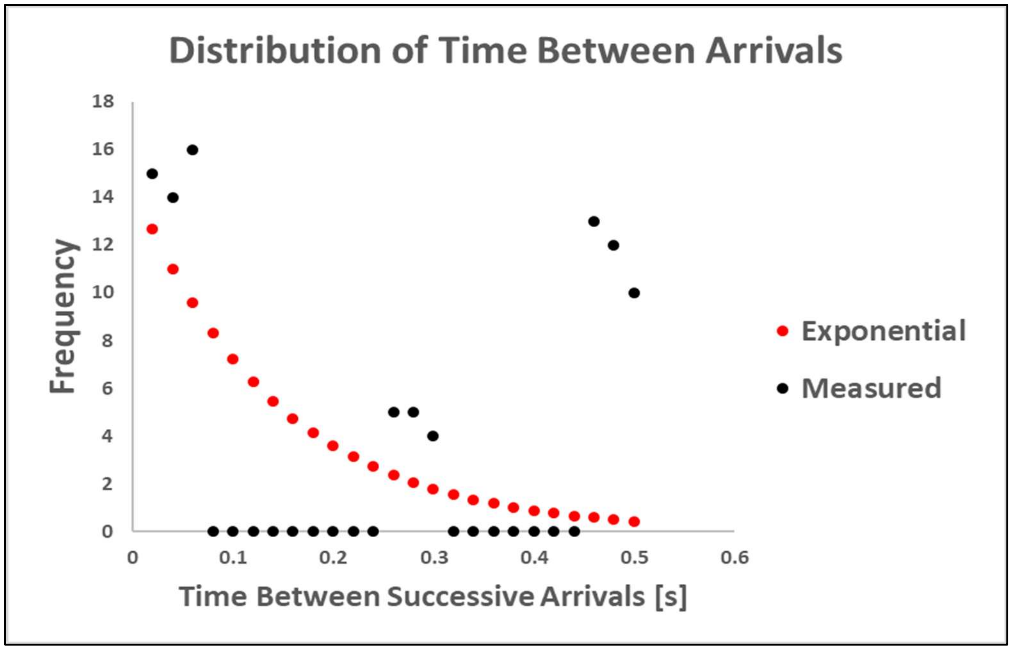

Figure 14 Example of a Clumpy Time Series

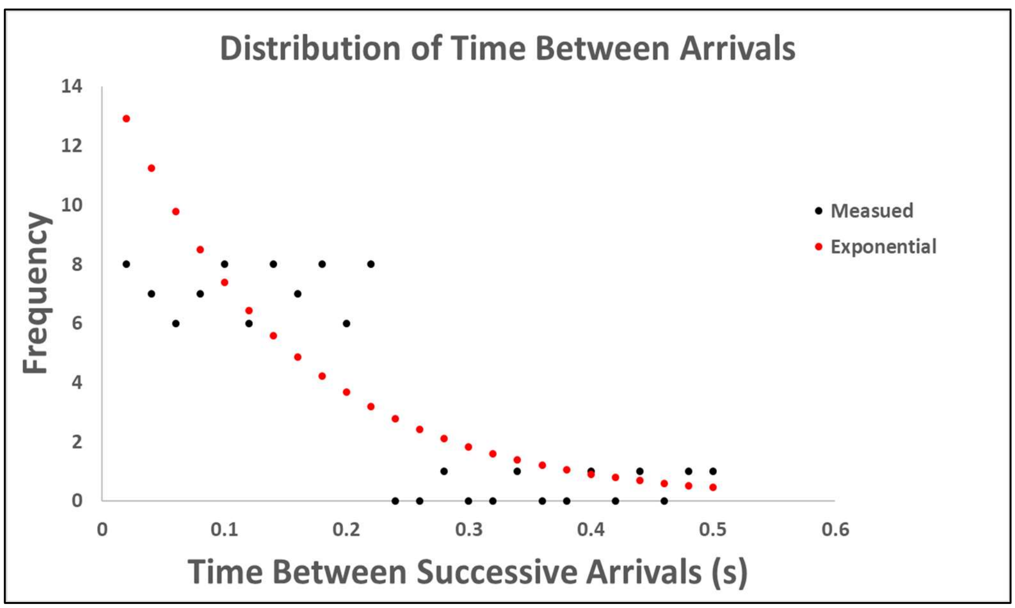

Figure 15 Example of a Regularized Time Series

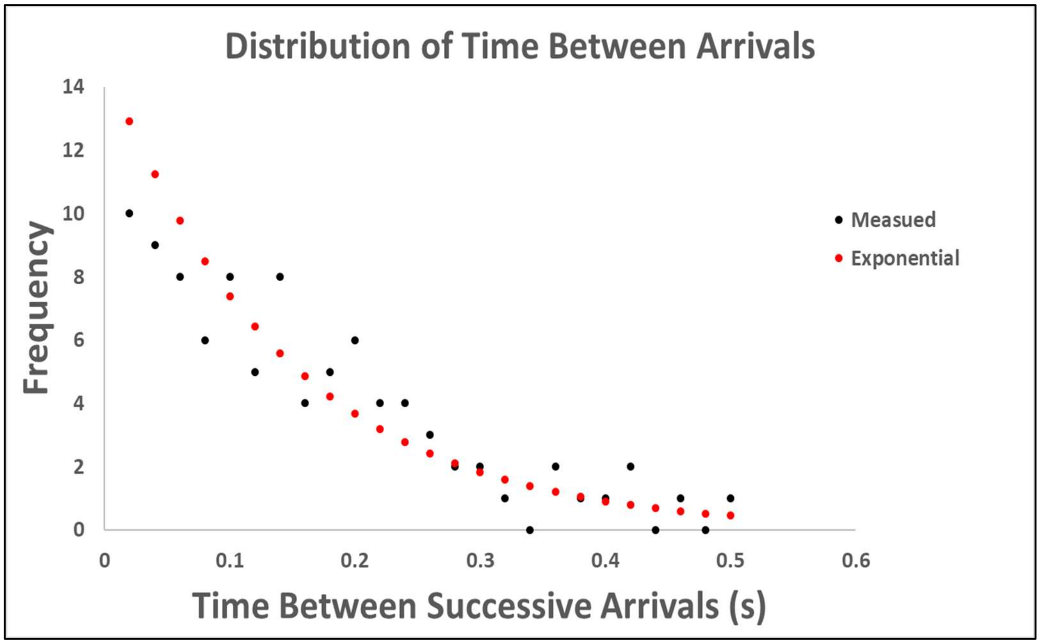

Figure 16 Example of an HR Time Series

4.2.2 Singulated Material Simulation

Singulated material simulation is essential in this project since it will be the benchmark for comparison of results of the experiments.

Simulation, here, is done by creating a homogenously random time series of arrivals of particles and put them on the sorting belt. Using Microsoft Excel, random numbers were generated and then these were used to develop a homogenously random time series. The time intervals of the particles were used with the speed of the sorting belt to calculate distance travelled until the exact moment when the next particle just arrives at the sorting belt (Using Equation 6). If the particle distance is less than 5 cm, which is calculated by subtracting each distance by 5cm and the size of the particle itself, and if that value is found positive, the material is counted as singulated and if negative, the particle is rejected. This was done for 2000 particles with throughput/s range from 1 to 12 particles per second. The results of this are mentioned in the next section.

$$d_{singulated} = (\tau_i * z) - singulation\ distance - particle\ length$$

If $d_{singulated} > 0$, the particle is singulated.

5. RESULTS

In this section, the time series and outcomes of the experiments are mentioned and then discussed. First, the comparison between the experimental and a computed time series is done. Then the experimental results for singulation success rate is shown.

5.1 Time Series

Since, Reukema aims to process 30,000 tonnes of aluminium scrap per year, taking into account Dutch working hours, that leads to 16.3 tonnes/hr of material to be processed. Out of the 16.3 tonnes, 30% of the scrap particles fall under 50-100mm and 50% are 100-180 mm size fractions i.e., the 50-100 mm size fraction is 4.89 tonnes and 100-180 mm is 8.15 tonnes.

As measured on site with more than 200 pieces each, the average weight of each particle for smaller size fraction was 58.5 g and 293 g for the larger size fraction.

With the above information, the weight to be processed per second of each size fraction would be 1.358 kg for the smaller size fraction and 2.263 kg for the larger size fraction hence, the no. of scrap particles to be processed per second for each size fraction is 24 and 8 respectively. But since there would be 2 chute lines for smaller size fraction and 4 chutes for larger size fraction, the pieces to be processed per chute per second are 12 and 2 respectively.

But, according to the tests done at Spaleck, the average particles to be processed per second came to be 2 and 1 respectively for each size fraction. This value was way less than the desired value hence, to meet the required amount, the experimental time series was first folded for one set of experiments and then the folded time series was doubled for another set of experiments.

Since the folded and doubled time series had the nearest number of particles per second to the desired amount, the time series is mentioned below.

The experimental time series was of 36 seconds since that represented the flow of particles most suitably.

Using information in 4.2.1, a time series for both the size fractions is developed.

For 50-100 mm size fractions, the N_s = 6 and the no. of particles is 194. The time intervals for which frequencies were measured was taken as 0.02 s.

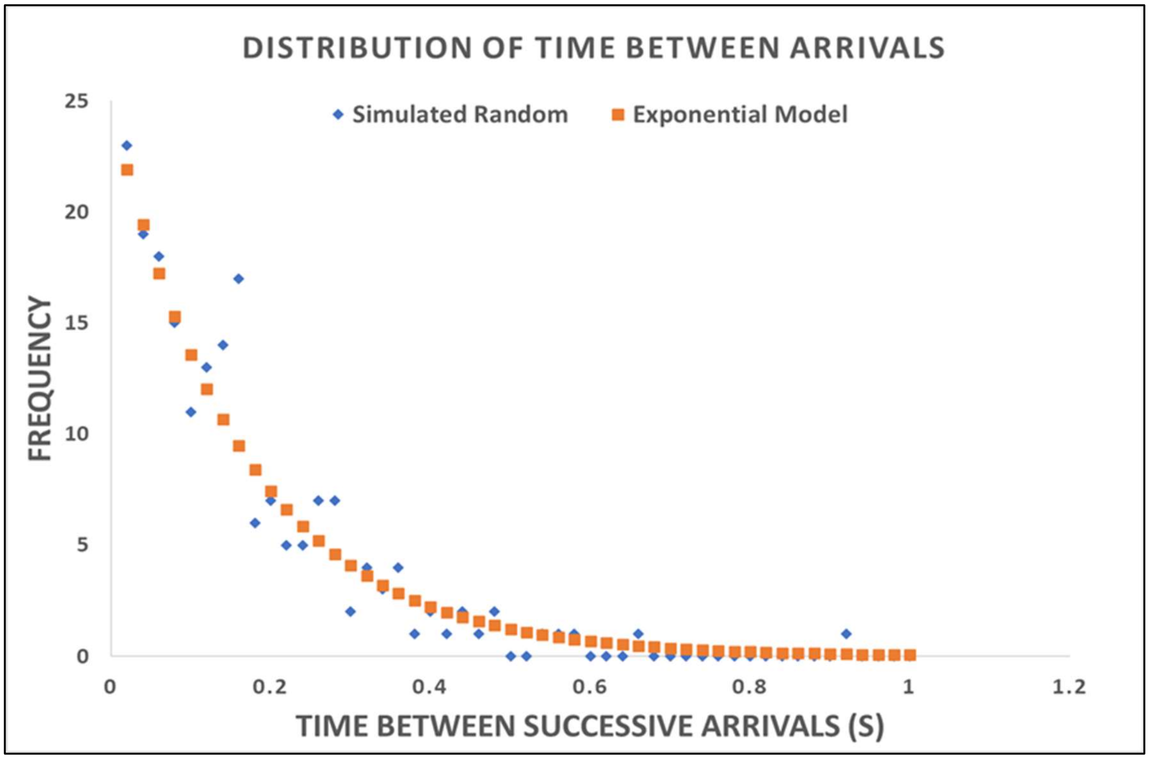

Figure 17. Exponential time distribution for folded and doubled time series (50-100mm)

It is clearly seen when referred to fig.12 that the distribution of the smaller size fraction for the folded and doubled time series is close to homogenous, fully random. This is the desired distribution as this perfectly describes the situation which is expected and would give the most accurate output results.

For 100-180 mm, the no. of particles per second, N_s= 3 and the no. of particles is 88. The time intervals for which frequencies were measured was taken as 0.02 s.

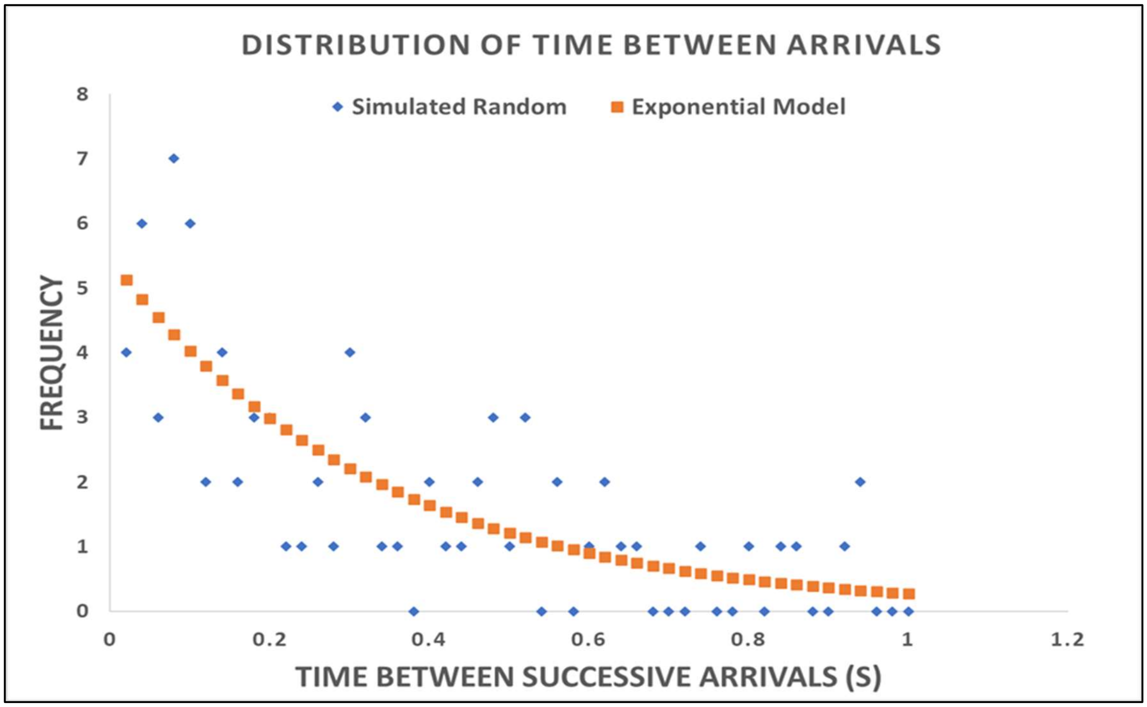

Figure 18. Exponential time distribution for folded and doubled time series (100-180mm)

For 100-180mm size fraction, it is clearly visible that the flow of particles here is not homogenous, fully random but more towards the regularized flow.

The above-mentioned analyses are direct experimental results for the few particles involved. Since there will be much greater number of particles involved in the eventual process, a simulation for 1000 and 2000 particles is done for both size fractions and shown as below.

For 1000 Particles:

For 50-100 mm size fractions, the $N_s = 6$ and the no. of particles is 1000. The time intervals for which frequencies were measured was taken as 0.02s.

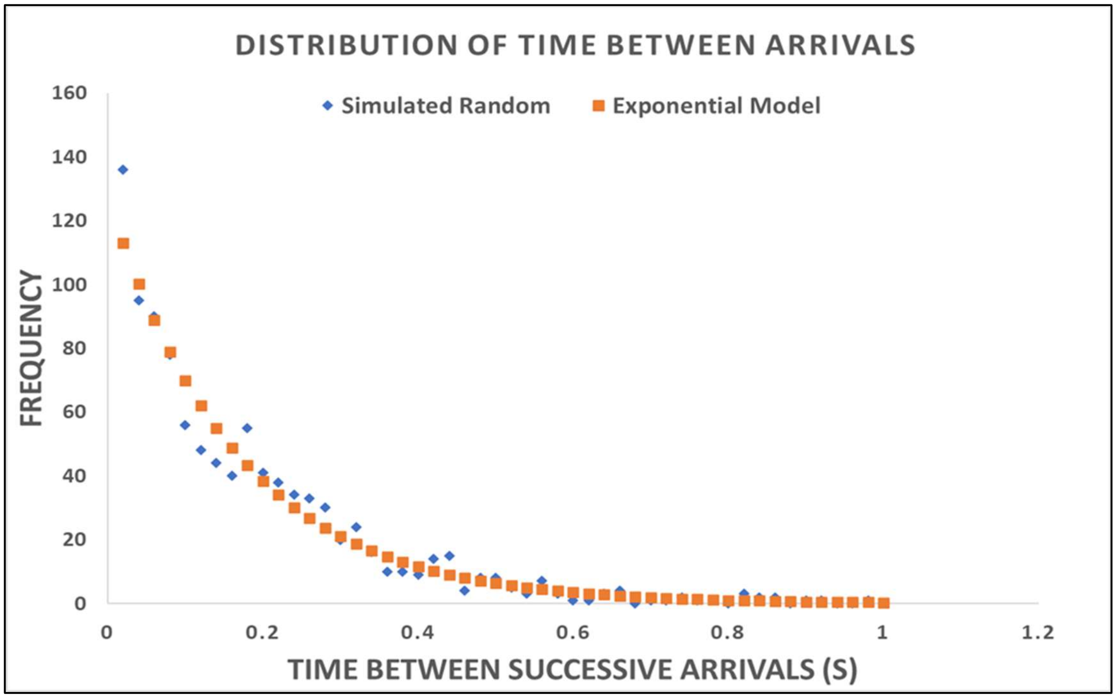

Figure 19 Exponential time distribution for 1000 pieces (50-100mm)

For 100-180 mm, the no. of particles per second, N_s= 3 and the no. of particles is 88. The time intervals for which frequencies were measured was taken as 0.02.

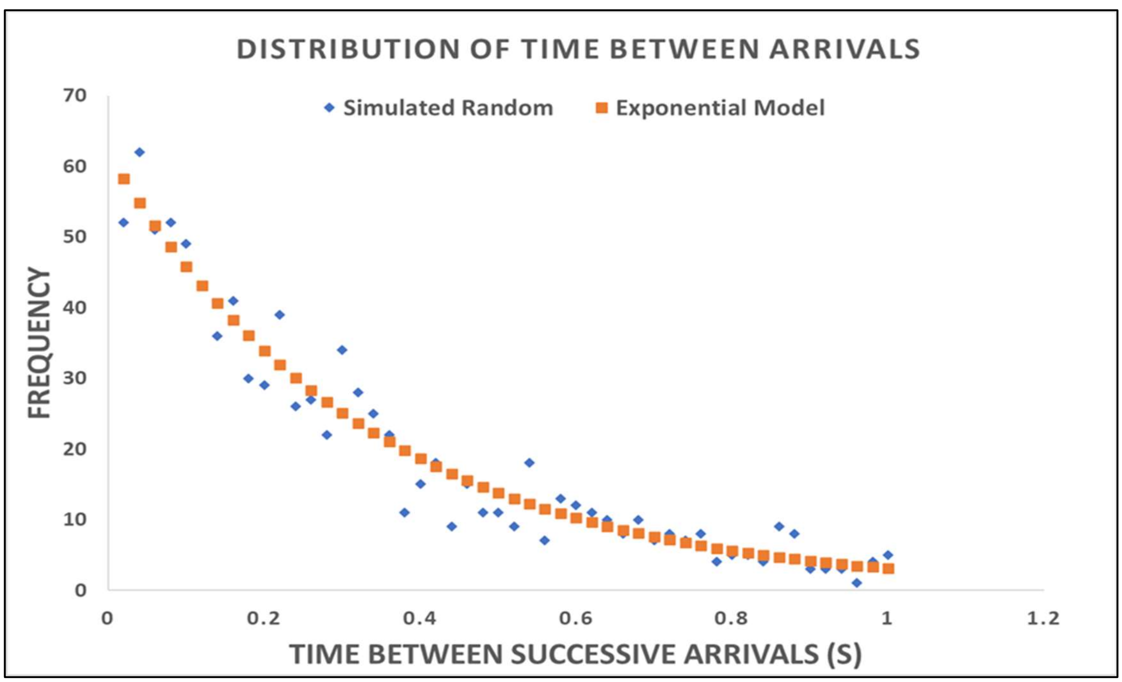

Figure 20 Exponential time distribution for 1000 pieces (100-180mm)

For 2000 Particles:

For 50-100 mm size fractions, the N_s = 6 and the no. of particles is 2000. The time intervals for which frequencies were measured was taken as 0.02 s.

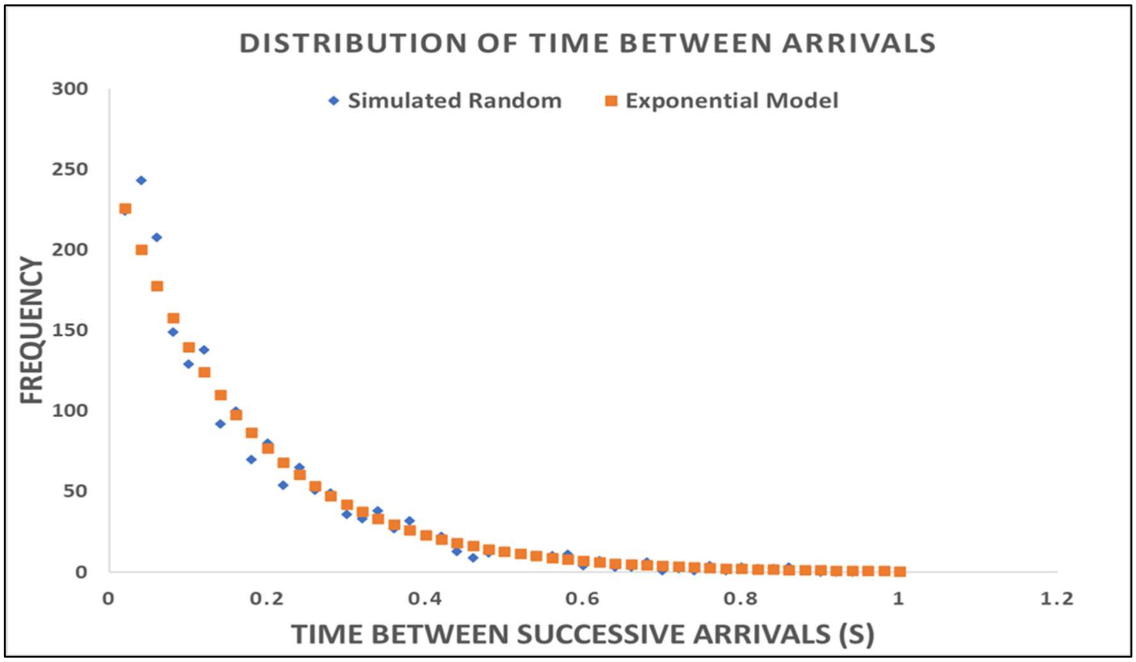

Figure 21 Exponential time distribution for 2000 pieces (50-100mm)

For 100-180 mm size fractions, the Ns = 3 and the no. of particles is 2000. The time intervals for which frequencies were measured was taken as 0.02 s.

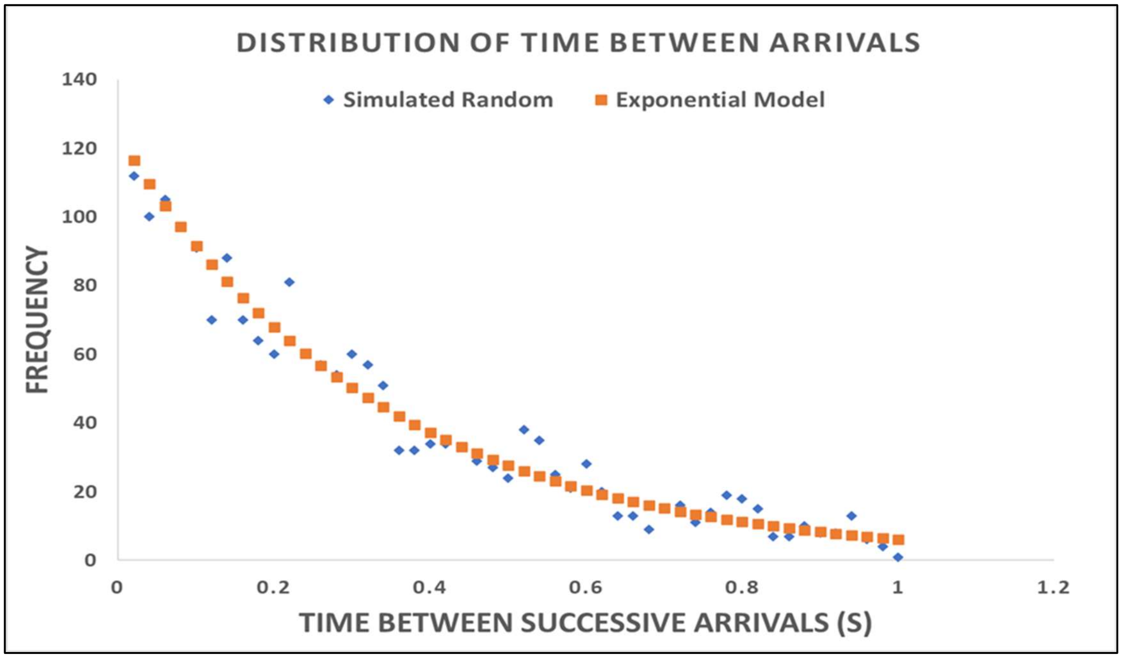

Figure 22 Exponential time distribution for 2000 pieces (100-180mm)

For both size fractions, it is clearly visible that as we increase the number of particles, the input more and more resembles the exponential distribution, which is the expected curve. This is what is required since a homogenous, fully random input is what is required to receive the best possible output.

5.2 Singulation

Due to time constraints, not many experiments could be conducted but the ones which were conducted are mentioned and explained here.
The experiments were done with 2 size fractions, 50-100 mm and 100-180 mm. The experiments were done with the initially measure time series, folded time series and a folded and doubled time series. The vibrating feeder could vibrate with different frequencies so the frequencies were also varied to know the speed of a particle on the feeder with different size fractions. The speed of sorting belt was not changed much since the results achieved in the initial experiments showed efficiency. The table below shows the parameters used for different experiments.

Experiment no.	**Frequency (Hz)**	**Particle Speed (m/s)**	**Size Fraction (mm)**	**Time Series**	**Speed of Sorting Belt (m/s)**
1	26.4	0.11	50-100	Initial	2.8
2	26.4	0.11	50-100	Folded	2.8
3	30	0.14	50-100	Folded	2.8
4	35	0.18	50-100	Folded	2.8
5	35	0.18	50-100	Folded	2.96
6	35	0.18	50-100	Folded & Doubled	2.8
7	26.4	0.11	100-180	Initial	2.8
8	26.4	0.11	100-180	Folded	2.8
9	30	0.14	100-180	Folded	2.8
10	35	0.18	100-180	Folded	2.8
11	35	0.18	100-180	Folded	2.96
12	35	0.18	100-180	Folded & Doubled	2.8

Table 5. Specifications of each experiment

The singulation percentage was calculated by observing the particles on the sorting belt and spotting whether they were in clusters or separated (Figure 23).
Two particles were considered singulated if they had enough evident space between them (>5 cm end to end). The clustered particles are rejected and the particles with more than 5 cm in between them are counted as singulated.

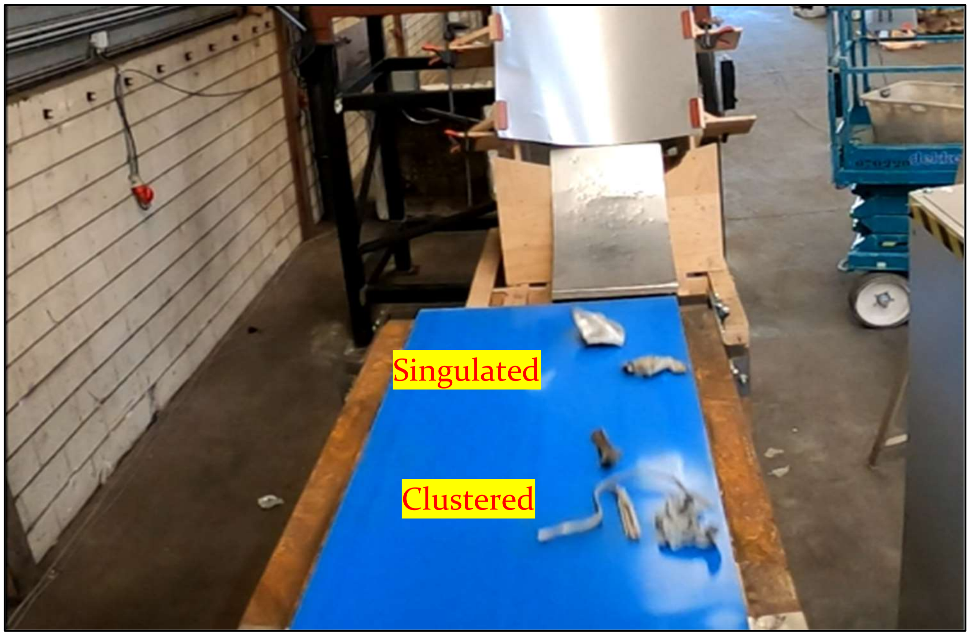

Figure 23. Singulated and Clustered pieces

A comparison of average no. of particles per second (throughput/s) vs acceptance (Singulation %) was done.

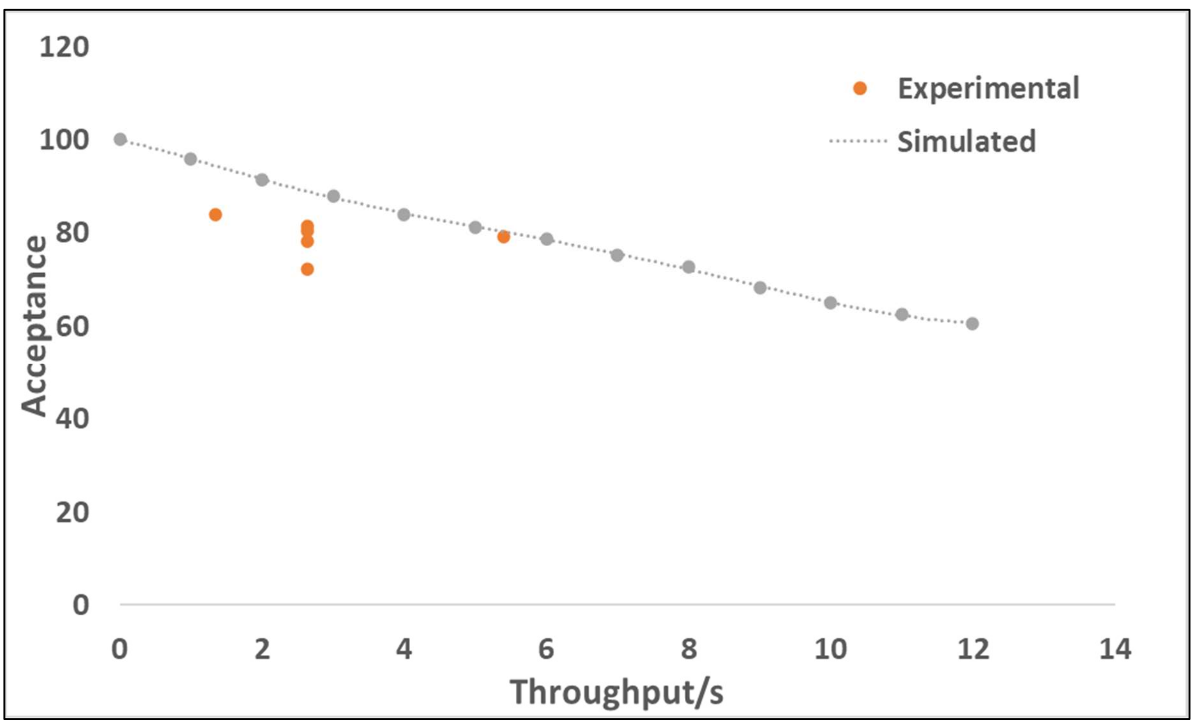

Figure 24. Throughput vs Acceptance (50-100 mm)

For the smaller size fraction, the average no. of particles per second were 1.35, 2.64, 5.4 for initial, folded and doubled time series respectively. The range of singulation percentage was from the range of 72.2 to 84%. The experiment with least singulation was experiment 2 and the most was experiment 1 (Table 5).

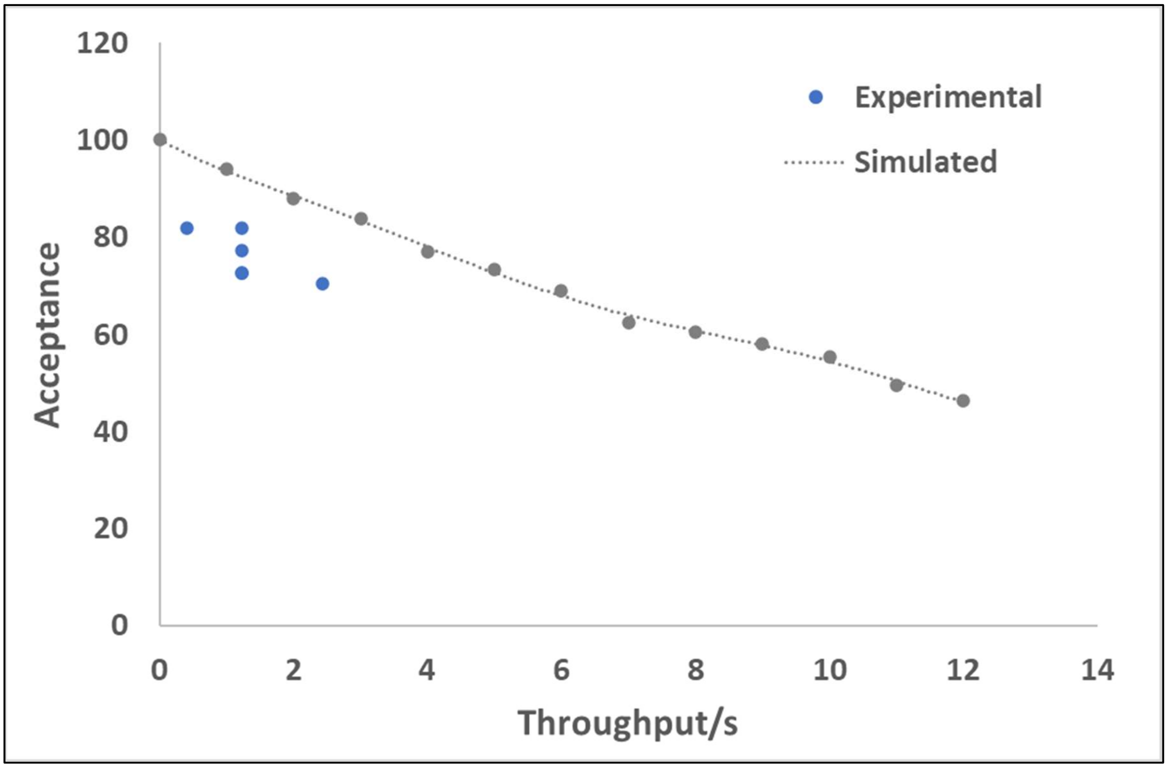

Figure 25. Throughput vs Acceptance (100-180 mm)

For the larger size fraction, the average no. of particles per second were 0.4, 1.22, 2.64 for initial, folded and doubled time series respectively. The range of singulation percentage was from the range of 70.4 to 81.8%. The experiment with least singulation was experiment 12 and the most were experiment 7 and 9 (Table 5).

6. DISCUSSION

This section discusses the results obtained from the above section and a viewpoint on aluminium recycling after conducting the whole study.

6.1 Time Series

When we review the results obtained in the time series section of the work, it is understood that the particles are arriving on the feeder at a homogenously random time intervals for the 50-100 mm particles size range. This is a desired result and it can be seen that when the time series is developed for 1000 and even 2000 particles, the result is the same that is the time series is homogenously random.

For the larger particles size range i.e., 100-180mm, the problem with initial number of particles used is that the time series is highly regularized. This is due to folding of time series since the nature of initial time series was such that this caused the folded time series to be regularized. But when the time series is extended to 1000 and 2000 particles, it is visible that the time series is homogenously random hence, giving the desired result.

It is important to note that these homogenously random time series are what are desired for a result which would be much closer to the actual process. Once a homogenously random time series of arrivals is achieved, the further process can be investigated.

6.2 Singulation

While discussing the results of singulation, it is essential that we discuss the two facets, experimental and simulated singulation together as a comparison.

For the smaller size fractions, we can see similar trend to the one of larger size fractions as the singulation percentage decreases as average number of particles per second (throughput) increases although it is steeper for larger size fractions. A difference in size causing different results is clearly seen here.

In the simulated singulation process, the throughput/s is an important parameter. As visible, the simulated singulation process gives less acceptance when the number of particles per second arriving is getting higher. This is an expected result. It is important to note that the effect of vibrating feeder and the effect of the chute are not considered in the simulations as using a homogenously random time series would give similar results since this is close to ideal case.

For the experimental results, let us first consider the smaller (50-100mm) size fraction. The input of this size fraction was according to a homogenously random time series. It is seen that the highest singulation is achieved in the first experiment which has the least number of particles per second which is expected but it is interesting to note that the frequency of the feeder is also the least hence here, the smaller number of particles per second was dominant against the lesser vibrating speed. The least percentage of singulation was given by experiment two which consisted of the same frequency as the first experiment but the throughput had increased to almost double. Again, this result is expected as the throughput is higher and the frequency is still low. In other experiments, the results obtained are somewhat similar. The increase in frequency in experiment 3 to experiment 4 seems to have very little effect and the change in sorting belt speed in experiment 5 from experiment 4 also gives similar results. But it is interesting to note that even after the increase of throughput in experiment 6 is double that of experiment 4, the singulation achieved is similar. This can be attributed to the high frequency of the feeder.

Now, considering the larger (100-180mm) size fractions, the input of which in experiment 9 was a highly regularized, and the results obtained give the highest singulation along with experiment 7. This can be attributed to the fact that even though the feed was regularized, the feeder with vibrating speed compensated for it. But that is again contradicted in experiments 10 and 11 where the vibrating speed is higher in experiment 10 and the sorting belt speed is higher in experiment 11 but still the singulation is less than experiment 7 and 9. This is a contradictory result to the expected results. But the results of experiment 12 were very much anticipated as the throughput is almost doubled that of the previous experiments and hence the singulation produced is the least.

These results which are achieved as discussed above have less meaning when we consider the effects of the chute. The chute is an essential part of the singulation process and no conclusions should be made on these results before considering the effects of the chute in great detail. Also, a vibrating feeder with a higher vibrating capacity would provide much better results.

After studying, analysing and working on aluminium recycling and the process of singulation, it is understood that a lot of progress has been made in understanding and the usage of technology since the commencement of the process of recycling. In this work, aluminium has been positioned as an essential metal for the much-desired circular economy. Aluminium waste, due to being enormous, has a huge potential to be a cornerstone for achieving a circular economy since it is highly recyclable and has a relatively high value even after getting recycled. The processes used to make aluminium are age old and reached almost maximum efficiency so not much can be changed there. Aluminium metal can be used to make a lot of alloys which makes it a very useful metal. The alloys are made to fit different purposes and are used in a plethora of industries. And once they reach their end-of-life stage, recycling them is highly possible. Recycled aluminium is very high in demand as giants in the commercial world are starting to use such metals to benefit the environment. When it comes to the role of authorities, the EU and the Netherlands have tried their best to formulate rules which encourage aluminium recycling and have been quite successful as well. Future programs to move towards a circular aluminium industry and a circular economy as a whole have motivated countries and corporates to adopt aluminium recycling. The collection of such waste is still an issue which requires focus. As far as case at Reukema is concerned, their aim to become an aluminium recycling company is quite a possibility. The setup they have needs some improvements but the aim to recycle their own aluminium for trading is highly achievable. Singulation processes have been applied before based on specific uses and this case is no different. The tests at Reukema have shown results which can be built upon.

7. CONCLUSIONS

Aluminium recycling is an integral part of the metal recycling industry and many nations have recognised this especially the European Union. The emergence of circular economy concepts has played a major role in this purpose. Circularity and sustainability are the way forward for this and future generations to survive.

Singulation is an age-old problem which is solved based on the industry it is being used. For aluminium scrap of such large size fractions, the problem still needed a solution. This section talks about what was achieved during this work i.e., the conclusion.

The following are the conclusions:

1. The Bayer's and the Hall-Heroult processes which are quite old and efficient are used for aluminium production with the alloys being made based on the usage. Once at the end-of-life stage, aluminium, being a highly recyclable material is recycled via various techniques, both mechanical and chemical. Although, there is high efficiency in aluminium recycling processes, the rising demands of aluminium cannot be met by just the secondary aluminium available at present, hence, to compete with primary aluminium, secondary aluminium industry should focus more on increasing efficiency of collection of such waste.
2. Sorting based on alloys should be adopted as it is ecologically and economically beneficial.
3. Singulation occurs at similar trends for both size fractions. The experiments where the speed of particles on the feeder were highest didn't produce the most singulation but the experiments with least vibrating frequency or highest throughput did produce the lowest singulation. The speed of sorting belt didn't produce much difference in the singulation results.
4. Singulation experimental setup could be optimised better so as to get better results. The vibratory feeder and the positioning of sorting belt being the equipment of focus here.
5. A screen with bigger dimensions than that of Spaleck is required at Reukema.
6. When the effect of feeder and chute are considered, the results obtained here could be very different.

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