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Summary

The overall objective of REProMag is to develop and validate a manufacturing route for the Shaping, Debinding and Sintering (SDS) method of Rare Earth (RE) magnet processing. This method must consider both economic and resource efficiency whilst producing a net-shape magnet with complex geometric structures. It must also be 100% waste free. WP7 aims to support the design of the SDS route from an environmental and economic perspective by conducting a Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). The LCA and LCC will be carried out on the SDS method of magnet production and a state-of-the-art method before directly comparing the two for polluting emissions, resource usage, energy consumption per kg of magnetic material and cost. The analysis will be carried out over the whole life cycle (cradle to grave).

This deliverable aims to investigate the costs associated with the manufacture and processing of RE Magnets via the SDS production route.

1. LCC Background and Methodology

The energy and materials use by a system depend on the design of the system in question, how it is installed into a facility and how the system is operated by the user. These factors are interdependent and moreover in the most productive and cost effective facilities, they are carefully matched to each other. They remain so throughout their working lives ensuring the lowest energy cost, lowest maintenance cost, longest equipment life and other benefits. The initial purchase price of equipment is often seemingly high, however, it is a small part of the life cycle cost for high-usage machinery. Operating requirements may - in some cases - override energy cost considerations an optimum solution is still possible.

A greater understanding of all the components that make up the total cost of operation will provide an opportunity to reduce energy, operation and maintenance costs. Reducing energy consumption and waste also has important environmental benefits which will be discussed in other related deliverables.

The above is the basis for carrying out a Life Cycle Cost (LCC) assessment. It allows end users to identify expensive aspects/areas of a production process and reduce them. In the case of REProMag however this is slightly different. For REProMag the LCC will provide an insight to the cost of production for a recycled rare earth NdFeB magnet which can then be compared to international markets whilst also considering the environmental impact. It should also be noted that the facility in question in this LCC is a virtual one and based on a probable scenario for production - not the one that currently exists.

Life cycle cost analysis is a management tool that can help companies minimise waste and maximise energy efficiency for many types of systems or production routes including forming processes such as the ones used in REProMag.

The life cycle cost of any piece of equipment is the total lifetime cost to purchase, install, operate, maintain and dispose of that equipment. Determining the LCC involves the following methodology to identify and quantify all of the components of the LCC equation.

When used as a comparison tool between possible design or to overhaul alternatives the LCC process will show the most cost-effective solution within the limits of the available data.

The components of a life cycle cost analysis typically include initial costs, installation and commissioning costs, energy costs, operation costs, maintenance and repair costs, down time costs, environmental costs and decommissioning and disposal costs.

2. Reasons for Considering LCC

Many organisations only consider the initial purchase and installation costs of a system. It is in the fundamental interest of the factory designer or manager to evaluate the LCC of different solutions before installing new equipment or carrying out a major overhaul. In this case we will be evaluating the production method of NdFeB magnets in a new facility importing scrap material, recycling and creating new magnets in one factory. As national and global markets become more competitive organisations must continually seek cost saving that will improve the profitability of their operations. Machine equipment operations are receiving particular attention as a source of cost savings especially minimising energy consumption and machine downtime.

In addition to the economic reasons for using LCC, many organisations are becoming increasingly aware of the environmental impact of their businesses are considering energy efficiency as one way to reduce emissions and preserve natural recourses.

LCC analysis, either for new facilities or renovations requires the evaluation of alternative systems. For a majority of facilities the lifetime energy and/or maintenance costs will dominate the life cycle costs. It is therefore important to accurately determine the current cost of energy, the expected annual energy price escalation for the estimated life, along with the expected maintenance labour and material cost. Other elements, such as the life time costs of down time, decommissioning and environmental protection can often be estimated based on historical data for the facility. Depending upon the process, down time costs can be more significant than the energy or maintenance elements of the equation. Careful consideration should therefore be given to productivity losses due to down time. In applying the evaluation process or in selecting equipment the best information concerning the output and operation of the machine must be established. The process itself is mathematically sound but if incorrect or imprecise information is used then an incorrect or imprecise assessment will result. The LCC process is a way to predict the most cost-effective solution; it does not guarantee a particular result but allows the machine designer or manager to make a reasonable comparison between alternative solutions within the limits of the available data.

This analysis is concerned with the developing an overall cost for producing NdFeB magnets through the SDS production route developed within REProMag. To create a fair assessment certain assumptions will have to be made again within the limits of the available data from partners in the REProMag consortium. Therefore only machinery used by partners will be used, however the recycling process that is currently a laboratory process will be scaled up. All of these processes will be housed within a single factory importing the scrap waste.

3. The LCC Equation

The following section examines each element and of the LCC equation. Also included is the consumption of raw materials in producing the NdFeB magnets.

Life cycle cost equation (LCC) = $C_{ic} + C_{in} + C_e + C_o + C_m + C_S + C_{Env} + C_d$		
C_{ic}	Initial Cost/Purchase Price	[€]
C_{in}	Installation and Commissioning	[€]
C_e	Energy Cost	[€]
C_o	Operating Cost (Normal System Use)	[€]
C_m	Maintenance cost	[€]
C_S	Down time, loss of production	[€]
C_{Env}	Environmental Costs	[€]
C_d	Decommissioning and disposal	[€]

Table 1 - Life cycle cost equation.

C_{ic} - Initial Cost/Purchase Price

The machine designer or plant manager must decide the layout of the system. There will be other choices to, which may be made during the design stage that can have an impact on the initial investment costs. One important choice is the quality of the equipment being selected. There may be an impact regarding materials having improved wear characteristics, heavier duty bearings or seals which will increase the overall working life of the machine. More expensive control software may be employed which will have an impact on the overall cost of the machinery but may reduce the overall LCC costs.

- The initial costs will also usually include the following:
- Purchase of the machine and other admin
- Testing and inspection
- Inventory of spare parts
- Training
- Drawings and regulatory documentation
- Auxiliary equipment

C_{in} - Installation and Commissioning

Installation and commissioning costs can include the following.

- Foundations - design, preparation, concrete and reinforcing, etc.
- Setting of equipment on foundation
- Connection of process piping
- Connection of electrical wiring and instrumentation

- Connection of auxiliary systems and other utilities
- Performance evaluation at start-up

Installation can be carried out by an equipment supplier, contractor or by own personnel. This decision depends on several factors including the skills, tools and equipment required to complete the installation. Contractual procurement requirements, work rules governing the installation site and the availability of competent installation personnel. Machine supplier or contractor personnel should coordinate site supervision with the supplier. Care should be taken to follow the installation instructions carefully. A complete installation includes transfer of equipment operation and maintenance requirements via training of personnel responsible for system operation.

Commissioning requires close attention to the equipment manufacturer's instruction for initial start-up and operation. A checklist should be used to ensure the equipment and the system are operating to the manufacturers recommendations. A final sign off typically occurs after a successful operation is demonstrated.

C_e - Energy Costs

Energy consumption is often one of the larger cost elements and may dominate the LCC. Energy consumption is calculated by gathering data on the pattern of the system output. If the output is steady (or reasonably steady) the calculation is simple. If the output varies over time then a time-based usage pattern needs to be established.

The plant designer or manager needs to obtain separate data showing the performance of each machine/system being considered over the output range.

Performance can be measured in terms of the overall efficiencies of the unit or of the energies used by the system at the different output levels. Driver selection and application will affect energy consumption. For example, more electricity is required to drive a pump with an air motor than with an electric motor. In addition, some energy use may not be output dependent. For example, a control system sensing output changes may itself generate a constant energy load, whereas a variable speed electric motor may consume different levels of energy at different operating settings.

The efficiency or levels of energy should be plotted on the same time base as the usage values to show their relationship to the usage pattern. The area under the line represents the total energy absorbed by the system being review over the selected operating cycle. The result will be in kilo watt hours (kWh). If there are differential power costs at different levels of load then the areas must be totalled within these levels.

Once the charge rates are determined for the energy supplied they can be applied to the total kWh for each charge band (rate period). The total cost of the energy absorbed can then be found for each system under review and bought to a common time period.

Finally the energy and material consumption costs of auxiliary services need to be included.

C_o - Operation Costs

Operation costs are the labour costs related to the operation of a machine or a group of machines. These vary wildly depending on the complexity and duty of the system. For example, a hazardous duty machine may require daily checks for hazardous emissions, operational reliability and performance within a desired range of operating conditions.. On the other hand, a fully automated non-hazardous system may require very limited supervision. Regular observation of how a machine is functioning can alert operators to potential losses in system performance. Performance indicators include changes in vibration, shock pulse signature, temperature, noise, power consumption, flow rates and pressure.

C_m - Maintenance and Repair Costs

Obtaining optimum working life from a machine requires regular and efficient servicing. The manufacturer will advise the user about the frequency and the extent of this routine maintenance. Its cost depend on the time and frequency of the service and the cost of materials. The design can influence these costs through the materials of constriction (does this make sense?), components chosen and the ease of access to the parts that need to be serviced.

The maintenance program can be comprised of less frequent but more major attention as well as the more frequent but simpler servicing. During maintenance time the unit is unavailable to the wider plant, there can be loss of product or a cost from a temporary replacement. These costs can be minimised by programming major maintenance during annual shutdown or process change-over.

C_s - Downtime and Loss of Production Costs

The cost of unexpected downtime and lost production is a very significant item in the total LCC and can rival the energy costs and replacement parts cost in its impact. Despite the design or target life of a machine and its components, there will be occasions when an unexpected failure occurs. In those cases where the cost of lost production is unacceptably high a spare machine may be installed parallel to reduce the risk. If a spare machine is used the initial cost will be greater but the cost of unscheduled maintenance will only include the cost of the repair.

The cost of lost production is dependent on downtime and differs from case to case.

C_{env} - Environmental Costs

The environmental costs take into account the embedded CO_2 in a process or product. This is measured in kgCO_2 equivalent. For example, using a machine that is based in the UK the use of steel from a distant source - due to transportation - may carry a higher embedded CO_2 content.

This is of particular interest in the case of REProMag and will be developed more later. However with the current production route which relies on partners from all over Europe and third party contractors the CO_2 footprint of the final magnet (and consequently the cost) is high. This is why a different scenario for this evaluation will be created.

C_d - Decommissioning/Disposal Costs

In the vast majority of cases, the cost of disposing of a machine/equipment will vary little with different designs. This is certainly true for non-hazardous materials. Toxic, radioactive or other hazardous materials will have legally imposed protection requirements, which will be largely the same for all system designs. A difference may occur when one system has the disposal arrangements as part of its operating arrangements. Similar arguments can be applied to the costs of restoring the local environment. When disposal is very expensive the LCC becomes much more sensitive to the useful life of the equipment.

C_{ma} - Material Costs

This covers the materials invested into the products on a production line and included this into the overall running costs of the equipment this resulting in a true inclusive product cost.

Total Life Cycle Costs

The costs estimated for the various elements making up the total life cycle costs needs to be aggregated to allow for a comparison of the designs being considered. This is best done by a means of a tabulation which identifies each item and asks for a value to be inserted. Where no value is entered an explanatory comment should be added. The estimated costs can then be totalled to give the LCC values for comparison and attention will also be drawn to non-quantitative evaluation factors.

Overall Equipment Effectiveness (OEE)

OEE is an abbreviation for the manufacturing metric Overall Equipment Effectiveness. OEE takes into account the various sub components of all the manufacturing process - availability, performance and quality. After the various factors are taken into account the result is expressed as a percentage. This percentage can be viewed as a snapshot of the current production efficiency for a machine, line or cell.

4. LCC Background for REProMag

The LCC for in this deliverable will follow the production route developed on the REProMag project - the Solvent, Debinding and Sintering or SDS process. The production route is shown in Figure 1 below.

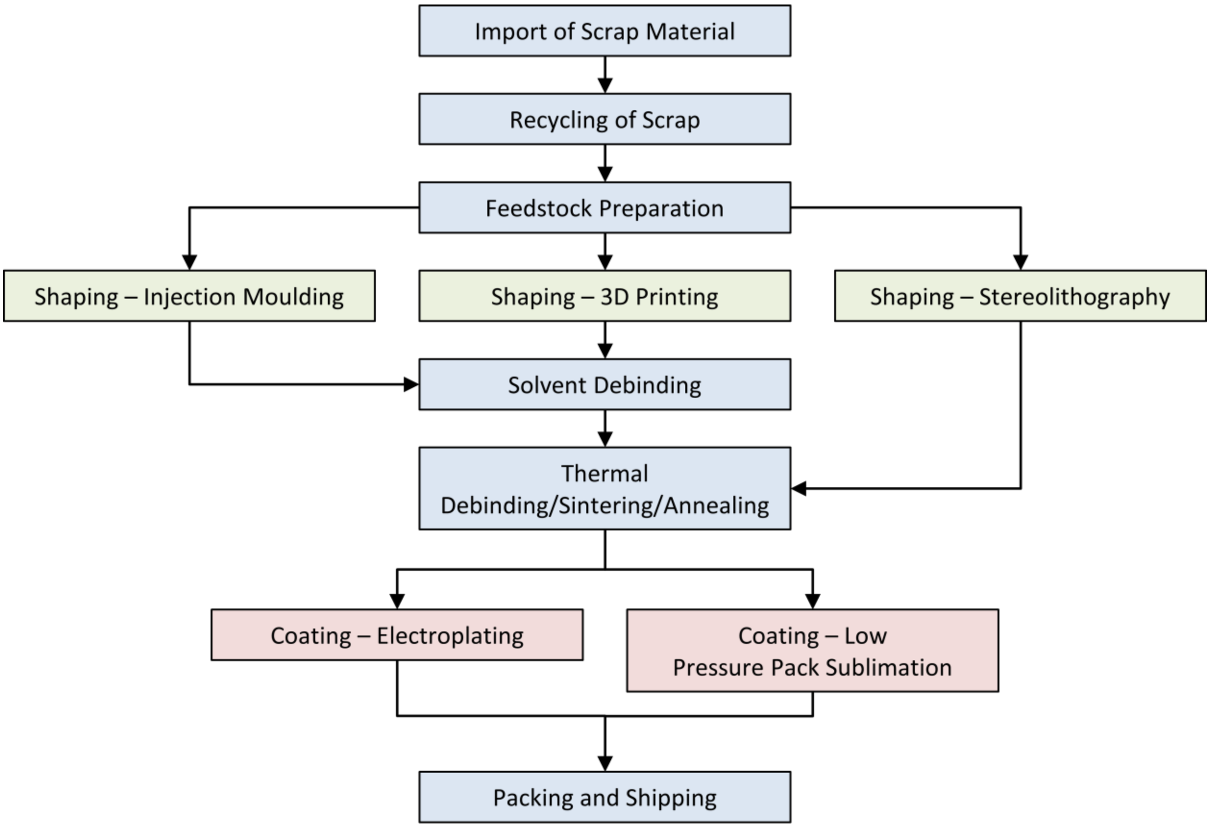

Figure 1 - The REProMag production route.

Like the LCA the LCC will follow different scenarios. As it is shown in Figure 1 there are three different shaping processes and two different coating processes. This creates a total six different means of production.

In the model, we will import scrap from Stena Technoworld (Halmstad, Sweden) to OBE (Ispringen, Germany) where it will then be crushed before the hydrogen decrepitation takes place. Finally, the flakes will be sieved. Next the feedstock is prepared - the particles are covered with additives and blended with a binder before being granulised. The recycled powder is then ready to be shaped. There are three ways of doing this the first being injection moulding. The cavity in the injection moulding machine is filed and then aligned in a magnetic field before being ejected.

The other shaping methods are quite similar. 3D printing is the extrusion of filament building the part up layer by layer. The parts are then left to cool before being removed. Another 3D printing technique, stereolithography, uses a moving laser beam to build up the required structure, layer by layer, from a liquid polymer that hardens on contact with ultraviolet laser light. The parts are cleaned and handled at the end.

If the parts have been injection moulded or 3D printed they move on to solvent debinding where the parts are loaded into the vat, debinded and unloaded. Thermal debinding is the next step and is the same for all shaping methods. The NdFeB magnets are thermally debinded and sintered.

Next the parts are coated. If they are electroplated they undergo activation before plating and cleaning alternatively they undergo low pressure pack sublimation.

The associated costs with the above production route have been provided by partners or found from literature.

The following table gives the related life cycle costs for the REProMag process broken down via manufacturing process. The table below is for production of 50,000 parts via metal injection moulding.

REProMag LCC (MIM)	
Process	Cost Per Part (€)
Transport	0.01
Recycling	0.01
Feedstock	0.20
Shaping	0.03
Debinding	0.17
Sintering	0.48
Heat Treatment	0.02
Personnel	0.22
Coating	0.02
Overhead inc. Profit	0.34
Total	1.50

Table 2 - LCC process data for metal injection moulding.

All data for the above has been provided by consortium partners. The transport and recycling costs are too small to measure in. This gives a total annual production cost (based on the production of 50,000 parts) of €75,000.

REProMag LCC (3D Printing)	
Process	Cost Per Part (€)
Transport	0.01
Recycling	0.01
Feedstock	0.20
Shaping	0.42
Debinding	0.17
Sintering	0.48
Heat Treatment	0.02
Personnel	0.22
Coating	0.02
Overhead inc. Profit	0.34
Total	1.89

Table 3 - LCC process data for 3D printing.

As previously mentioned the production is taking place in one factory the above scenario simply removes the metal injection moulding machines and replaces them with 3D printers. The total cost for this (based on 50,000 parts) is €94,500.

5. LCC Conclusions

An in-depth conclusion will not be provided in this deliverable. However, a retrospective of all of the deliverables in WP7 will be provided in D7.6 - *Final Environmental and Economic Report: Considerations and Future Guidance*. It is however worth noting that the current production route with partners based around Europe would be much higher due to the cost incurred by transport and an increase in production time. This is not sustainable and not comparable with any current process hence the simplification and combination of all processes within one facility - a true representation of an industrial process. This has been done for several reasons but mainly to serve as a good basis of comparison to the state-of-the-art Chinese production route.