Retrofitting Equipment for Efficient Use of Variable Feedstock in Metal Making Processes - REVaMP

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1. About REVaMP

The main objective of the project "Retrofitting Equipment for Efficient Use of Variable Feedstock in Metal Making Processes" (REVaMP) is to develop, adapt and apply novel retrofitting technologies to cope with the increasing variability and to ensure an efficient use of the feedstock in terms of materials and energy.

For this purpose, existing metal production plants shall be retrofitted with appropriate sensors for scrap analysis and furnace operation. Furthermore, the selection of the optimal feedstock in terms of material and energy efficiency shall be improved by application of appropriate process control and decision support tools. Also, a solid scrap preheating system operated with waste derived fuel shall increase the energy efficiency of the melting processes. To monitor and control the process behaviour in an optimal way, model-based software tools will be developed and applied.

The retrofitting solutions will be exemplarily demonstrated within three different use cases from the metal making industry, namely electric and oxygen steelmaking, aluminium refining and lead recycling. The performance of the different technologies will be assessed, and the benefits will be evaluated in terms of economic and ecological effects, as well as cross-sectorial applicability in other process industries.

2. Introduction and Summary (to Deliverable)

This deliverable D8.4, "Report on cross-sectorial transferability of retrofitting solutions", is included in the work package WP 8 "Evaluation of retrofitting solutions at industrial scale" of the project. Specifically, the deliverable relates to the activities developed within Task 8.4: "Cross-sectorial applicability of developed retrofitting solutions" by the project partners who developed technologies and software tools for retrofitting, i.e. NCBJ, SYS, POL, ILT, LSA (sensors for scrap analysis); AZT (Alu-Q® equipment for evaluating the quality of liquid aluminium alloys); GHI (scrap preheating equipment); and BFI, EUT, AZT and CAR (models, optimisation strategies and advanced control techniques).

Deliverable D8.4 is a PUBLIC Report which consists in a series of assessment matrices which gather how well each retrofitting solution will be transferable to other industrial sectors, like other metal making processes (cast iron, copper, silicon, ferro alloys, etc.) and other process industries (such as minerals, cement, chemical industry, etc.). The adaptation requirements for replication of the retrofitting solutions in each case are identified.

It should be noted that both the opportunities for applicability and the limitations and adaptation needs are evaluated by REVaMP partners based on their expertise and competence in the corresponding technologies and AI tools. In most cases, the authors are lacking a deep knowledge of the industrial processes of industries out of the scope of REVaMP project (e.g., non-ferrous metals other than aluminium and lead recycling, cement, ceramics, chemical…) Their assessment is then built on general assumptions, on the description of the processes and flows provided by industry associations and the BREF reference documents available from the European IPPC Bureau and on the consultation of technical and scientific literature.

3. Assessment of the transferability of the proposed retrofitting solutions

The following retrofitting solutions are assessed by the partners who have been involved in their development/application in REVaMP:

- ILT, LSA: LIBS (*Laser Induced Breakdown Spectroscopy*) for in-line chemical characterisation of scrap (surface analysis)
- NCBJ, SYS, POL: neutron sensors incorporating PGNAA (*Prompt-Gamma Neutron Activation Analysis*), i.e., Large Sample Sensor (LSS) and TRuck Sensor (TRS), for chemical characterisation of scrap (bulk analysis)
- AZT: Alu-Q® for quality evaluation of aluminium alloys in the melt
- GHI: aluminium scrap pre-heater
- BFI, EUT, AZT, CAR: models, optimisation strategies and advanced control techniques for steelmaking, aluminium refining and lead recycling

The process industries considered as potential users of the retrofitting solutions which were developed and tested in REVaMP are other metal making/recycling industries, such as ferrous and non-ferrous foundries, zinc and copper smelters, precious metal refineries, ferroalloys producers, silicon producers… but also other sectors participating in the SPIRE Public-Private Partnership, like minerals, ceramics, cement, chemicals, etc. (see Figure 1). The full list of industries proposed for the study of transferability of results is included in the ANNEX.

Figure 1. Sectors represented in the A.SPIRE European Association, which implement the Processes4Planet co-programmed Partnership, successor of H202 SPIRE PPP (image source: https://www.aspire2050.eu/aspire/the-association)

The cross-sectorial transferability assessment carried out comprises the evaluation of the following points, per solution and sector in process industries:

- Opportunities for applicability
- Limitations of applicability
- Adaptations required

LIBS Scrap Sensor (ILT, LSA)

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
Other metal making /recycling industries	Ferrous foundries	Detection of scrap impurities (e. g. lead, zinc), and high-value alloying elements (Co, Cr, Mn, Ni, …)	S, P, B detection only in vacuum and/or process gas environment	High-resolution spectrometer required because of large quantity of Fe-lines in the spectrum
	Non-ferrous foundries	Scrap feedstock monitoring; for high-value scrap (e.g. Al) also single particle sorting of pure alloys	For sorting: mass throughput [t/h] for high-added value of the product, lower for small particle size	Increased measurement frequency required to increase throughput
	Zn, Cu smelters	Monitoring of high-value content and detection of scrap impurities	WEEE scrap monitoring complicated by complex material structure.	-
	Precious met. refineries	Determination of material value, detection of impurities, single-particle sorting		-
	Ferroalloys	Continuous monitoring of composition of primary raw materials and product		High-resolution spectrometer required because of large quantity of Fe-lines in the spectrum
	Silicon	Continuous monitoring of composition of primary raw materials and product		-
Other Process Industries	Cement	Quality assurance of produced cement types; raw material monitoring and sorting	Detection of chlorine from waste derived fuel limited in typical industrial environment	Adaptation of spectral line selection due to typically high concentrations of Ca, Mg, Si, Al

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
	Ceramic	See cement		
	Minerals	Determination of ore grade (Cu-, Ni-, etc.) in a running process: continuous monitoring or sorting	Inhomogeneity of the material may limit accuracy/response time; limited throughput for sorting; measurement of stoichiometry but not mineralogy	Adaption of data evaluation to consider inhomogeneity and varying humidity
	Chemicals		Only chemical elements and not molecules detectable	Extension to Raman-spectroscopy by adaptation of the optical setup
	Others	Detection of contaminations and process-related chemicals, e.g. heavy metals, in product or wastewater	Limit of detection may to very low.	Several industries would require an adaptation of measurement system for use on liquids.

Large Sample Sensor (LSS) based on PGNAA for scrap (NCBJ, SYS, POL)

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
Other metal making /recycling industries	Ferrous foundries Non-ferrous foundries Zn, Cu smelters Silicon Ferroalloys	Neutron activation techniques applied in the LSS system, developed in the REVaMP project, can be also applied in other industrial branches as long as the material under study has similar, physical form to the samples used for the LSS validation. The method sensitivity depends strongly on the material form, in particular on the density (or bulk density) and the total weight of the tested material (the higher the better). The expected chemical composition is also crucial and here the opportunities for applicability should be considered for elements already analysed by the LSS system. In particular the elemental content at the level of 1% and below, is extremely hard to measure with good accuracy. As long as the industrial conditions in other process industry are similar to the conditions during the test campaigns of LSS, application	The method sensitivity depends strongly on the form of the material —the sensitivity for light materials in small volumes can be too low for practical usage of such systems. It is preferable to have access to a number of industrial calibration samples with a well-known composition, which is not always possible. The samples should also cover a wide range of compositions. The application of the neutron sources requires radiation safety procedures and safety zones to be introduced at industrial sites. In rare cases, the long lived radioactive activation of the material under study can be induced (not present in the case of aluminium and iron).	Licenses, authorisations and procedures for application of neutron/gamma sources at industrial site. Radiation safety procedures, safety zones and staff training required to introduce at industrial site. Change or adaptation of a part of the industrial line for a Neutron System installation. In rare cases, change of the materials used for mechanical structures due to content of materials such as Cl or B with high neutron capture probability (e.g. exchange of conveyor belts with Cl). Preparation of the calibration samples dedicated to a given installation. The final LSS or similar system design has to be always dedicated to specific conditions at a given industrial site.

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
		of the similar neutron techniques can be considered with high chance of success.		
	Precious met. refineries	Unknown: possible but not yet verified during this and other projects. According to some OEMs of PGNAA analysers, PGNAA is a candidate for Bulk Ore sorting (cross-belt, chute) for precious metals operations		PGNAA analysers must be calibrated using reference standards containing a range of elemental concentrations representing the choice of materials to be analysed. The LSS system must be dedicated to a single material type - the aluminium scrap in the case of REVaMP project. The system however can be easily modified towards other scrap types/raw materials.
Other Process Industries	Cement	The method is widely used with systems working online on conveyor belts transporting raw materials. Cross-belt neutron analysers are used in cement industry to quantify elements (Si, Al, Fe, Ca, Mg, S, Na, K, Ti, Mn, H, Cl) and to determine cement parameters (LSF, C_3S, C_2S, C_3A, iron modulus, silica modulus), for stockpile optimisation and raw mix control.		
	Ceramic	Some OEMs of PGNAA analysers claim they have customers in the refractory industry		

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
	Minerals	The method is widely used for coal and lignite analysis with systems working online on conveyor belts transporting raw materials. For instance, neutron analysers are applied for measuring critical parameters for coal industry such as analysis of C, S, H and O concentration, moisture, total ash and ash elemental concentration, for monitoring and control during load out of truck and rail receipted coal and at power plants (bunker feeds).		

TRuck Sensor (TRS) based on PFTNA for scrap (NCBJ, SYS, POL)

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
Other metal making /recycling industries	Ferrous foundries Non-ferrous foundries Zn, Cu smelters Silicon Ferroalloys	All the comments from the Table above, regarding the applicability of the LSS systems (*LSS based on PGNAA*), are valid also for the potential use of the TRS setup in other process industries. Application of neutron activation methods for analysis of chemical composition of a whole volume of the materials directly on trucks is a very challenging task. In general, the LSS approach in more compact measurement geometry is preferable. However, in case of the TRS success, the applied neutron methods can be also applied in other industrial branches as long as the material under study has similar, physical form. Moreover, in other areas of application, the materials under study can have a form better suited for this kind of measurements (higher bulk density and higher fragmentation).	The limitations from the Table above, regarding the applicability of the LSS systems (*LSS based on PGNAA*), are valid also for the potential use of the TRS setup in other process industries. The additional limitations could be: • More extensive requirements for licenses, authorisations and procedures for application of neutron generator at industrial site. • Larger radiation safety zones and more restrict conditions due to higher intensity of neutrons • Extended measurement time and lower sensitivity due to extremely large volume of the material under study (whole truck) • Extreme temperature variations could strongly affect the performance of the neutron generator and detection system • Increased system costs due to requirement of high number of scintillation detectors and	Licenses, authorisations and procedures for application of a neutron generator at industrial site. Radiation safety procedures, safety zones and staff training required to introduce at industrial site. Proper selection of the TRS system installation place at industrial site, which assures: • lack of interference with other equipment present in vicinity of TRS (e.g. radiation portals, rails, entrances) • space to create the safety zone around the TRS system with supervised, restricted access

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
			application of the neutron generator with associated particle imaging feature (including NG service costs connected with finite lifetime of the target inside)	
	Precious met. refineries	Neutron Activation Analysis may be valid for determining the contents of elements of interest and impurities in ores and process slurries.	Limited applicability of the TRS setup for measuring composition of loads directly on the trucks: • inherent limitations of the TRS set-up, as explained for the sectors above; • truck may be not the most pertinent measuring stage for the logistics/operation of the plants	
Other Process Industries	Cement Ceramic Minerals	As it was mentioned in the Table above, regarding the applicability of the LSS systems (LSS based on PGNAA), OEMs of PGNAA/PFTNA analysers offer these technologies to cement, minerals, sintering and other bulk materials applications (limestone; iron, copper and nickel ores, phosphates, refractories...) to determine the elemental composition.	Proven analyser for measuring bulk raw materials in truck loadouts, the use of the TRS setup for measuring loads directly on the trucks (before unloading) may be challenging.	Calibration with reference standards (appropriate for the type of materials and process requirements) is essential

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
		However, the above-mentioned industries use the Neutron Activation Analysis (NAA) mainly on conveyor belts or in sample streams. The innovative TRS approach proposed in the REVaMP project is desired by many plants, but it is a very demanding configuration, mostly due to physics of NAA, that to our knowledge has not been built yet. The project results and conclusions may be the guidelines for the possible future application of TRS-similar solutions in other industrial branches.		

Alu-Q® melt quality prediction equipment (AZT)

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
Other metal making /recycling industries	Steelmaking	The concept of a portable analyser of a molten alloy, based on the analysis of some physical metallurgy characteristics is transferable to the secondary metallurgy (ladle furnace) in steelmaking. Such an analysis can enhance the control of the LF process supplied by periodical offline analysis of slag or can supplement real-time slag analysis monitoring.	Rapid cooling of the molten steel may limit the thermal analysis of the solidification.	• Sampling-analysis procedure in thermal cups (as with aluminium and iron) may be not valid. • Equipment materials to withstand higher temperatures than in cast iron (thermocouples type S, cups). • Database of thermal, metallographic and other metallurgical parameters of steel alloys.
	Aluminium recycling	Alu-Q® is designed for assisting industries, either producing aluminium alloys from scrap (remelters, refiners), or casting components made of Al alloys (foundries).		Enlargement of the database of Thermolan-Al® to include more casting and wrought alloys
	Ferrous foundries	• The concept of Alu-Q® is totally transferable to IRON foundries. Actually, the development of the Alu-Q® and Thermolan-Al® analysis application is built on the knowledge gained by a previous solution developed by AZTERLAN for iron foundries: Thermolan® is a Thermal Analysis System for spheroidal, lamellar and compact graphite cast	• STEEL foundries: due to the rapid cooling of the molten steel, the liquidus part of the solidification curve is missing at the time the analysis of the sample (taken from the ladle) starts in the thermal cup.	• IRON foundries: ✓ equipment materials to withstand higher temperatures than in aluminium (thermocouples type K, cups). ✓ Resolution and sample rate (number of measured T data per second) for plotting the solidification curve: lower

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
		iron. With a single sample it can monitor over 300 parameters, offering key information regarding the predicted quality of castings in less than 60 s. Possibility of analysing several types of quick cups at the same time. • Transferability to STEEL foundries possible (under study by AZTERLAN).		sample rate than for aluminium. ✓ Database of thermal, metallographic and other metallurgical parameters of cast iron alloys • STEEL foundries: ✓ Sampling-analysis procedure in quick cups (as with iron) is not valid. Immersion sampling. ✓ Equipment materials to withstand higher temperatures than in cast iron (thermocouples type S, cups). ✓ Database of thermal, metallographic and other metallurgical parameters of cast steel alloys
	Non-ferrous foundries	Alu-Q® is designed for evaluating the quality of manufactured (aluminium) alloys based on the analysis of some physical metallurgy characteristics. As such, the assessment principles are transferable to foundries of other NON-FERROUS ALLOYS (bronzes. brasses, Zn alloys, Mg alloys, Ti alloys, Ni alloys…).	• Mg ALLOYS foundries: a protective gas is needed to prevent Mg from reacting with the oxygen and moisture in the air in the thermocouple set-up used to record the cooling curve. Conventionally, SF_6, a gas with a high GWP, has been	• Type of thermocouple and materials of crucibles, cups, samplers, etc. appropriate to reactivity and temperature of each molten alloy. • Adequate resolution and Temperature sampling rate for

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
			employed as the cover gas for the prevention of magnesium flaring (combustion) during melting and casting. That makes it complex and costly to measure the temperature of solidification using portable equipment like Alu-Q® • Ti ALLOYS foundries: Titanium reacts readily with oxygen and nitrogen and requires melting and pouring under vacuum or under a protective inert gas atmosphere. Molten Ti is also reactive with all ceramic oxides. That makes it complex and costly to measure the temperature of solidification using portable equipment like Alu-Q®	plotting the solidification curve of the specific alloy • Databases of thermal, metallographic and other metallurgical parameters of the specific alloys
	Zn, Cu, Pb smelters	Alu-Q® is designed for evaluating the quality of manufactured (Al) alloys by analysing some physical metallurgy characteristics. Therefore, it is NOT APPLICABLE in pyrometallurgical processes aiming at producing concentrates and pure metals.	N.A.	N.A.

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
	Precious met. refineries	Alu-Q® is designed for evaluating the quality of manufactured (aluminium) alloys based on the analysis of some physical metallurgy characteristics. Therefore, it is NOT APPLICABLE in refining processes aiming at producing high purity metals.	N.A.	N.A.
	Ferroalloys and other master alloys	Alu-Q® is designed for evaluating the quality of manufactured (aluminium) alloys based on the analysis of some physical metallurgy characteristics. The manufacturing process of ferroalloys can be achieved by smelting processes (metallothermic or carbothermic reduction of oxides) or by melting iron scrap and metal scrap. When the performance of ferroalloys and other master alloys (Al base, Cu base) depends on their microstructure characteristics or on the inclusions (oxides) present, apart from their chemical composition, testing molten samples by Alu-Q® equivalent equipment during the manufacturing process of the master alloys may be of use. Testing on molten samples may avoid remelting and the limitations stemming from sample preparation procedures, due to the different		• Type of thermocouple and materials of crucibles, cups, samplers, etc. appropriate to reactivity and temperature of each molten alloy. • Adequate resolution and Temperature sampling rate for plotting the solidification curve of the specific alloy. • Databases of thermal, metallographic and other metallurgical parameters of the specific alloys

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
		physical presentations of the ferroalloys. Phase equilibrium diagrams can make it possible to predict the phases formed and how they influence the physical properties and segregation tendencies.		
	Silicon	Alu-Q® is designed for evaluating the quality of manufactured (aluminium) alloys based on the analysis of some physical metallurgy characteristics. Therefore, it is NOT APPLICABLE in silicon metal production.	N.A.	N.A.
Other Process Industries	Cement	NOT APPLICABLE. Alu-Q® is designed for evaluating the quality of manufactured metal alloys. Although cement is a multi-phase material and its quality control is based on chemical and crystallographic characterisation, the processes involved are too different from metallurgy.	N.A.	N.A.
	Ceramic	NOT APPLICABLE. Alu-Q® is designed for evaluating the quality of manufactured metal alloys based on metallurgy characteristics. Although ceramics are mixtures of compounds with phase diagrams that	N.A.	N.A.

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
		work in a similar way to those of metal alloys, the phase composition and transformations and their effects on properties are far from metallurgy.		
	Others: Minerals, Carbon & Graphite, Chemicals, Refining, Pulp&Paper, Water, Engineering	NOT APPLICABLE. Alu-Q® is specifically designed for evaluating the quality of manufactured metal alloys	N.A.	N.A.

Scrap pre-heater fuelled by WDF (GHI)

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
Other metal making /recycling industries	Ferrous foundries	Applicable for preheating scrap	BATs for WDF combustion (esp. BAT 30) must be applied (Commission Implementing Decision (EU) 2019/2010)	The scrap preheating chamber system must be redesigned, using the ladle as the scrap preheater chamber
	Non-ferrous foundries	Applicable for preheating scrap		
	Zn, Cu smelters	Applicable with copper scrap, the loading procedure is very similar to the aluminium case Limited application with Zn smelters	Limitation with Zn smelters, loading systems, depending on the type of load. BATs for WDF combustion (Decision (EU) 2019/2010)	Preheating chamber and loading must be redesigned for zinc cathodes, depending on the loading system of the smelter
	Precious met. refineries	Applicable	Melting point temperature of different materials must be considered. BATs for WDF combustion (Decision (EU) 2019/2010)	Redesign of the preheating chamber to ensure no losses on the scrap or the material to be melted.
	Ferroalloys	Applicable as in ferrous foundries.	BATs for WDF combustion (Decision (EU) 2019/2010)	
	Silicon	Not applicable	NA	NA
Other Process Industries	Cement Ceramic Minerals	Not applicable, only designed for preheating load to melt	NA	NA
	Others		NA	NA

Model-based optimisation and control techniques (BFI approach for steelmaking)

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
Other metal making /recycling industries	Ferrous foundries	The tool for scrap characterisation and charge mix optimisation can be applied at ferrous foundries are operated with similar charge materials. The process models for the melting furnaces can be applied also for the furnaces of ferrous foundries, as they are partly the same (EAF) or similar (Induction furnace) as in steelmaking	Limitations of applicability of the scrap characterisation and optimisation tool might occur if no liquid metal analysis is available. Regarding the process models and the process control tools, limitations may occur when the melting process is too different to the Electric Arc Furnace which is used for scrap melting in steelmaking (e.g., cupola furnaces)	The software tools used for data pre-processing to feed the scrap characterisation tool have to be adapted. The model structure has to be adapted to the used furnace technology, and the model parameters have to be determined by validation of modelling results. The control set-point algorithms will have to be adapted to different process targets.
	Non-ferrous foundries	The tool for charge material characterisation and charge mix optimisation can be applied at non-ferrous foundries, as long as they are operated with a mix of secondary raw materials with varying composition. The process models for the melting furnaces can be applied also for the furnaces of non-ferrous foundries, as long as they are similar to the EAF used in steelmaking	Limitations of applicability of the scrap characterisation tool might occur if no analysis after melt production is available. Regarding the process models and the process control tools, limitations may occur when the melting process is too different to the Electric Arc Furnace which is used for scrap melting in steelmaking (e.g., cupola furnaces)	The software tools used for data pre-processing to feed the scrap characterisation tool have to be adapted. The model structure has to be adapted to the used furnace technology, and the model parameters have to be determined by validation of modelling results. The control set-point algorithms will have to be adapted to different process targets.

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
	Zn, Cu smelters	The tool for charge material characterisation and charge mix optimisation can in principle be applied for Zn and Cu smelting processes, as long as they are operated with a mix of secondary raw materials with varying composition. The process models for the melting furnaces can be applied also for the Zn/Cu smelting furnaces, as long as there are similarities to the EAF used in steelmaking. An application to electrolytical processes is not possible.	Limitations of applicability of the scrap characterisation tool might occur if no analysis after melt production is available. An application becomes very difficult when the smelting processes are operated continuously and not in batch mode. Regarding the process models and the process control tools, limitations may occur when the melting process is too different to the Electric Arc Furnace which is used for scrap melting in steelmaking (e.g., Submerged Arc Furnaces)	The software tools used for data pre-processing to feed the scrap characterisation tool have to be adapted. The model structure has to be adapted to the used smelting furnace technology, and the model parameters have to be determined by validation of modelling results. The control set-point algorithms will have to be adapted to different process targets.
	Precious met. refineries	No application possible, as precious metals are gained from chemical or electrolytical processes using ore materials.		
	Ferroalloys	The tool for charge material characterisation and charge mix optimisation cannot be used, as Ferroalloys are not produced from secondary raw materials, but from metal ores.	Regarding the process models and the process control tools, limitations may occur when the melting process is too different to the converter which is used for steelmaking.	The model structure has to be adapted to the used converter technology, and the model parameters have to be determined by validation of modelling results. The control set-point algorithms will

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
		The process models for the refining furnaces can be applied also for the ferroalloy production converters, as they are similar to the converter used in steelmaking.		have to be adapted to different process targets.
	Silicon	The tool for charge material characterisation and charge mix optimisation cannot be used, as Silicon is not produced from secondary raw materials, but from Silicon oxides. The process models for the melting furnaces can be applied also for the Silicon production in smelting furnaces, as long as there are sufficient similarities to the EAF used in steelmaking.	Regarding the process models and the process control tools, limitations may occur when the melting process is too different to the Electric Arc Furnace which is used for scrap melting in steelmaking (e.g., Submerged Arc Furnaces), so that only parts of the modelling approaches can be transferred.	The model structure has to be adapted to the used smelting furnace technology, and the model parameters have to be determined by validation of modelling results. The control set-point algorithms will have to be adapted to different process targets.
Other Process Industries	Cement	No application possible, as minerals, cement, ceramics, chemicals, fuels and Pulp & Paper production is too different to liquid steelmaking.		
	Ceramic			
	Minerals			
	Chemicals			
	Refining (fuels)			
	Pulp & Paper			

Model-based optimisation and control techniques (EUT approach for aluminium recycling)

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
Other metal making /recycling industries	Ferrous foundries	The model-based optimisation tools developed by EUT for optimizing the feedstock material usage based on the alloy grade to be produced can be transferred to Ferrous foundries to optimize their feedstock material usage based on their production and their final ferrous products. The Process control model of the Gas furnace defines an ML pipeline that can be a foundation for new developments in other metal making industries for equipment monitoring.	The main model, based on feedstock material optimization can be largely transferred/used to ferrous foundries The process control model has been trained and designed for gas furnace operation of a rotative furnace for remelting of aluminium scrap and chips.	Boundary conditions and restrictions of the optimization model as well as cost function should be adapted to the ferrous foundries use case. Models for elements evolution and composition correction should be adapted or newly developed taking into account the constraints and characteristics of the new materials and production process. The process control model defines a pipeline that can be reused for other equipment monitoring solutions. New feature engineering as well as model training would be required to adapt the defined ML pipeline to new applications
	Non-ferrous foundries	The model-based optimisation tools developed by EUT for optimizing the feedstock material usage based on the alloy grade to be produced can be transferred as well to other non-ferrous industries.	The main optimisation model can be easily applied in the optimisation of the production process of other non-ferrous alloys.	In order to apply the optimisation model, differences between the new processes and the ones of GRU should be evaluated and the model should be modified accordingly, in order to adapt it to the new process conditions and restrictions.

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
		The Process control model of the Gas furnace, can also be applied in furnaces of other non-ferrous industries different than aluminium	The process control model can also be largely applied in other gas furnaces, different than the rotative gas furnace used in aluminium remelting of scrap and chips	An adaptation of the process control model will be also required, taking into account the differences in both processes and furnaces
	Zn, Cu smelters	The applicability in Zn, Cu and other metal industries of the optimisation models can be applied when the final product is an alloy with a given composition. The process control model can be used as basis for other gas furnace applications and target industries with the required modifications.	The optimisation models and tools cannot be applied in industries that want to produce metal with the maximum purity as possible, without desired alloying elements. The limitation of applicability of the process control model are the same as in the previous target industries.	The adaptations requirement will depend on the particularities of each industry, as already explained for the previous cases. An adaptation of the process control model will be also required, taking into account the differences in both processes and furnaces
	Precious met. refineries	The process control model can be used as basis for other gas furnace applications and target industries with the required modifications.	The optimisation models and tools cannot be applied in industries that want to produce metal with the maximum purity as possible, without desired alloying elements. The limitation of applicability of the process control model are the same as in the previous target industries.	The adaptations requirement will also depend on the particularities of each industry, as already explained for the previous cases.
	Ferroalloys	The model-based optimisation tools developed by EUT for	The main optimisation model can be easily applied in the optimisation	The adaptations requirement will depend on the particularities of each

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
		optimising the feedstock material usage, based on the alloy grade to be produced, can be transferred as well to Ferroalloys industries. The Process control model of the Gas furnace can also be applied in furnaces of other non-ferrous industries different than aluminium.	of the production process of other ferrous alloys. The process control model can also be largely applied in other gas furnaces, different than the rotative gas furnace used in aluminium remelting of scrap and chips	industry, as already explained for the previous cases. An adaptation of the process control model will be also required, taking into account the differences in both processes and furnaces
	Silicon	The process control model can be used as basic pipeline for arc furnaces and other furnaces different than gas furnaces. However, larger changes and adaptation in the initial model will be required.	A thorough analysis of the process and industry will be required in order to define the model applicability and its limitations.	The adaptation requirements will also depend on the particularities of the industry and process, and data availability
Other Process Industries	Cement	The process control model can be used as basis for other gas furnace applications and target industries with the required modifications.	The limitation of applicability of the process control model are the same as in the previous target industries.	The adaptations requirement will also depend on the particularities of each industry, as already explained for the previous cases.
	Ceramic			
	Others			

Model-based optimisation and control techniques (AZT approach for aluminium refining – melting step)

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
Other metal making /recycling industries	Steelmaking	The multivariable optimisation algorithm based on the 4 models can be applied for recommending operation conditions towards an overall optimum: best quality of the product achievable in the shortest batch time, with the lowest possible environmental impact and energy consumption.	Possible limitations are (i) the nature of the problem, giving the possibility to not achieve a possible result (it can be solved with the calculation of a suboptimal solution) and (ii) the inputs to be able to make this kind of calculations must be digitalised (with no input data the optimisation cannot be done).	Constraints and list of variables in every model should be adapted to the specificities of the system (feedstock, liquid steel, melting furnace operation). In addition, the base scenario to detect when the optimisation must be run have to be adapted.
	Aluminium recycling	Optimisation in aluminium refining is based on simultaneous optimisation of 4 predictive models: energy consumption, metal behaviour, productivity and environmental impact.		
	Ferrous foundries	The multivariable optimisation algorithm based on the 4 models can be applied for recommending operation conditions towards an overall optimum: best quality of the product achievable in the shortest batch time, with the lowest possible environmental impact and energy consumption.	Current prediction models and the desired moments to make this optimisation are not created to handle this manufacturing process. However, it can be adapted, giving the opportunity to be deployed in this new domain. Furnace technologies and process flows in smelting may be completely different from the rotary furnace considered in the developed optimisation algorithm. Straightforward applicability in smelting may be limited to specific	Constraints and list of variables in every model should be adapted to the specificities of the system (feedstock, molten metal alloy or metal, melting furnace operation)
	Non-ferrous foundries			
	Zn, Cu, Pb smelters			

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
			steps in the pyrometallurgical routes, such as the fire refining step in primary Cu smelting or secondary Pb smelting in rotary furnaces (scrap batteries).	
	Precious met. refineries	No application foreseen, as the precious metal refining are complex multi-steps processes not exclusively pyrometallurgical. Nevertheless, the base optimisation architecture can be applied.	Current prediction models and the desired moments to make this optimisation are not created to handle this manufacturing process. However, it can be adapted, giving the opportunity to be deployed in this new domain.	Keeping the general algorithm, the input data and models (maybe the combination of prediction models) must be adapted to face this new domain.
	Ferroalloys & master alloys Silicon	The multivariable optimisation algorithm based on the 4 models can be applied for recommending operation conditions towards an overall optimum: best quality of the product achievable in the shortest batch time, with the lowest possible environmental impact and energy consumption.	Current prediction models and the desired moments to make this optimisation are not created to handle this manufacturing process. However, it can be adapted, giving the opportunity to be deployed in this new domain.	Constraints and list of variables in every model should be adapted to the specificities of the system (feedstock, molten metal alloy or Si metal, melting furnace operation). Moreover, the anomaly detection method to detect the calculation moment must be adapted too.
Other Process Industries	Cement	The theoretical thermal (fuel) energy demand for cement clinker production is determined by the energy required for the chemical/mineralogical reactions of the clinker burning process and the	Applicability of the full development. However, as in other kind of AI applications, the models are totally focused on the original problem. Hence, they should be adapted (inputs, ranges, among others) to	'Metal behaviour' model should be replaced by a model predicting the quality of the clinker. Constraints and the lists of variables in every other model should be

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
		thermal energy required for raw material drying and preheating. Keeping the quality of the clinker within acceptable range requires the measurement, from time to time, of some quality parameters (e.g., Lime Saturation Factor (LSF), tricalcium silicate or alite (C3S) concentration, tricalcium aluminate (C3A) concentration, etc.). The multivariable optimisation algorithm based on the 4 models can be applied for recommending operation conditions towards an overall optimum in furnace processes: best quality of the product achievable in the shortest batch time (rejection/recycling of clinker), with the lowest possible environmental impact and energy consumption.	meet the new objectives and domains. Maybe the selected models are not the most accurate for this manufacturing process, so, again, these algorithms could be changed.	adapted to the specificities of the system (feedstock, clinker, cement kiln operation). The anomaly detection method to detect the calculation moment must be adapted too.
	Ceramics	NOT APPLICABLE. The firing kiln process produces stable solid phases: an irreversible ceramic structure for the product is reached in the kiln. That is a completely different situation than the furnace processes producing	N.A	N.A

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
		liquid metal for which the optimisation algorithm was designed. In this case, only the optimisation base architecture could be applied, not the rest of the solution.		
	Others: Chemicals, Refining, Pulp&Paper…	No application foreseen, as production processes are quite different from the “furnace-centred” processes in metal making. Therefore, the only part that can be reutilised is the main optimisation architecture without the application of the original prediction models	N.A.	N.A

Model-based optimisation and control techniques (CAR approach for lead recycling)

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
Other metal making /recycling industries	Ferrous foundries	The temperature control model in lead melting process can be applied in different furnaces of other ferrous industries	It would be necessary to analyse the different stages of the process to study the evolution of the temperature and the variables that affect it.	An adaptation of the process control model will also be required, considering the differences in both processes and furnaces
	Non-ferrous foundries	The furnace charging model could also be applied to predict the aluminium content from scrap as long as it was homogeneous.	The limitation is determined in case aluminium has to be added if some of the impurities exceed the limits since that amount of aluminium added could not be predicted.	To calculate the parameters of the model, laboratory tests should be carried out to calculate the amount of aluminium for each type of scrap.
	Zn, Cu smelters	In the pyrometallurgical process for copper recovery, a furnace is used in which several stages take place. The temperature control tool could be used to evaluate the different phases of the process with the evolution of temperature.	A thorough analysis of the process and industry will be required in order to define the model applicability and its limitations.	It will be necessary to study the process to analyse the phase changes to later reprogram the algorithm.
	Precious met. refineries	The application of optimisation and control methods is not possible because the methods used in this industry are far from the pyrometallurgy methods used in the lead recovery industry		

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
	Ferroalloys	The applicability of the optimisation models can be applied when the final product is an alloy with a given composition.	The alloys will have to have a number of alloying elements to be able to apply the algorithm as well as limits on their quantities.	Reprogramming of the different phases of the genetic algorithm must be carried out to comply with the restrictions of the process
	Silicon	The temperature control model in lead melting process can be applied in furnaces of silicon industry.	It would be necessary to analyse the different stages of the process to see the evolution of the temperature and the variables that affect it.	An adaptation of the process control model will be also required, considering the differences in both processes and furnaces
Other Process Industries	Cement	It is not applicable because the processes are different from lead melting, although genetic algorithms can be used to find the optimal combination of different materials (such as cement, sand, water, aggregates, etc.)		
	Ceramic	It is not applicable because the processes are different from lead melting, although the genetic algorithms can be used to find the best combination of raw materials that result in improved mechanical, thermal, and chemical properties of ceramic products.		
	Minerals	It is not applicable because the processes are different from lead melting		

Process industry		Opportunities for applicability	Limitations of applicability	Adaptations requirements
	Chemicals	It is not applicable because the processes are different from lead melting, although the genetic algorithms have been used to optimise recipes for the production of chemical compounds		
	Pharmaceutical	It is not applicable because the processes are different from lead melting, although in the pharmaceutical industry, genetic algorithms have been used to optimise drug production recipes.		

4. Conclusions

The cross-sectorial transferability of the REVaMP project's developments in a range of industries belonging to the sectors represented in the *A.SPIRE European Association* is summarised in the synoptic Table 1 enclosed on the next page. The table compiles the detailed analyses per retrofitting solution included in the matrices of Section 3. It covers the industries that have been the target users for some of the retrofitting solutions in the project (but that have not been specifically addressed by other developments tested in REVaMP); as well as other process industries, with special exhaustiveness for metal making/recycling industries. The extent of the transferability is rated using a three-level scale, using the following colour code:

(green)	Applicable/Transferable with proper adaptions
(yellow)	Limited applicability/transferability
(white)	Non applicable

Additionally, when the transferability/applicability is limited for certain industries, some text added to the yellow code clarifies the general constraints:

exc.charge	optimisation not applicable to the charge
Sec.	applicable only to secondary smelting

The retrofitting solutions of the REVaMP project that are represented in the Table 1 are listed below, indicating their corresponding retrofitted metal industries during the project's use cases and experimental developments:

- **LIBS (scrap sensor):** demonstrated with feedstock for EAF and BOF steelmaking, aluminium chips recycling, aluminium scrap refining and lead recycling
- **LSS (PGNAA):** Large Sample Sensor based on PGNAA for scrap, demonstrated with aluminium chips recycling, aluminium scrap refining.
- **TRS (PFTNA)**: TRuck Sensor (TRS) based on PFTNA demonstrated with feedstock (ferrous scrap) for BOF steelmaking
- **Scrap preheater (WDF)**: Scrap pre-heater fuelled by Waste Derived Fuel, demonstrated with the aluminium old scrap feedstock for aluminium refining in a rotary furnace
- **Alu-Q® melt quality**: Alu-Q® melt quality prediction equipment demonstrated at aluminium recycling and refining plants
- **Model-OCT (steel)**: Model-based optimisation and control techniques (BFI approach for steelmaking), demonstrated for EAF and BOF
- **Model-OCT (Al/01)**: Model-based optimisation and control techniques (EUT approach for aluminium recycler) demonstrated for aluminium chips recycling in a rotary furnace
- **Model-OCT (Al/02)**: Model-based optimisation and control techniques (AZT approach for aluminium refiner – melting step), demonstrated for aluminium refining in a tilting rotary furnace
- **Model-OCT (Pb)**: Model-based optimisation and control techniques (CAR approach for lead recycler), demonstrated in process based on a lead-refining kettle.

The use cases which were successfully demonstrated in the project are also green coded in Table 1, but with a red frame.

Table 1. Summary table of cross-sectorial transferability of retrofitting solutions studied in REVaMP project.

PROCESS INDUSTRIES			LIBS (scrap sensor)	LSS (PGNAA)	TRS (PFTNA)	Scrap preheater (WDF)	Alu-Q® melt quality	Model-OCT (steel)	Model-OCT (Al/01)	Model-OCT (Al/02)	Model-OCT (Pb)
Metal making/recycling	Iron & Steel making	Iron making (BF)									
		Steel making (BOF,EAF)									
	Aluminium	Al smelting									
		Al remelters & refiners									
	Ferrous foundries	Iron									
		Steel									
	Non-ferrous foundries	Al & Al alloys									
		Mg & Mg alloys									
		Cu & Cu alloys									
		Other NF metals &alloys									
	Smelters (primary & secondary)	Lead smelters						Sec.	Sec.	Sec	Sec.
		Zinc smelters						Sec.	Sec.		
		Copper smelters						Sec.	Sec.		
	Precious metals refineries										
	Master alloys producers	ferroalloys						exc.charge			
		other master alloys						exc.charge			
	Silicon producers		unknown					exc.charge	exc.charge		
	Carbon and graphite		unknown								
Other Process Industries	Minerals										
	Ceramics										
	Cement								exc.charge		
	Chemicals		unknown								
	Pulp & Paper										
	Refining (Fuels)										
	Water		unknown								
	Engineering		unknown								

To sum up, reasonable chances of transferability of the hardware and software retrofitting solutions, beyond the specific metal making/recycling processes for which they have been developed, are expected, provided that the adequate adaptations are implemented.

In principle, LIBS sensors for sorting of feedstock materials (scrap, ores) and online monitoring of primary raw materials and products seems to be the most versatile technology, applicable in a range of metal industries apart from the steelmaking, aluminium recycling and lead recycling; but also in other process industries such as cements, ceramics and minerals and others in which the determination of chemical contamination in process streams or products plays a role. It should be pointed out that LIBS technology has been evaluated as scrap sensor according to the concept of REVaMP, comprising two different approaches that have been tested in steel, aluminium and lead uses cases for different types of feedstock materials, regarding composition, morphology and physical state (metal scrap pieces and chips, powders, paste): as a cross-belt sensor for characterisation of conveyed material streams and as a gantry crane mounted sensor for inspection of truck/container loads. LIBS in general has a much broader applicability than LSA's and ILT's developments for the project.

The same holds true for PGNAA and PFTNA sensors. Applicability as scrap(/feedstock) neutron analysers is assessed in the present deliverable report not only on the basis of the capabilities of the sensing technology, but also on the basis of the transferability of the proposed system set-ups for positioning and irradiating the samples in the neutron sensors' field (online large sample analysis system; direct analysis of truck loads before dumping/unloading). Thus, it is concluded that neutron sensing technologies can be applied to monitoring and sorting bulk raw materials and products in stockpiles and in the feeds to the core process step (melting furnace, kiln), in some metal industries, but also in coal, minerals, cement and refractory industries. However, presently, chute, cross-belt and loadouts systems appear as more convenient designs than the setup for direct measurements on trucks. As such, the LSS design sems to be more adaptable than the TRS system. Nevertheless, the innovative TRS approach proposed in the REVaMP project is desired by many plants, yet it is a very demanding configuration mostly due to physics of Neutron Activation Analysis (NAA). To our knowledge, the NAA-based TRS for ferrous scrap designed and tested in REVaMP project is the first try of building such a system. The project results and conclusions are the guidelines for the possible future application of TRS-similar solutions in other industrial branches.

Regarding the Alu-Q® melt quality instrument, the solution can be transferable to other metal alloy making and casting processes, by developing the specific correlated databases of the thermal, metallographic and other metallurgical parameters of the selected alloys.

The transferability of the scrap pre-heater based on WDF combustion would make sense only to metal industries with furnaces fired by fossil fuels and within a broader circular economy approach, when non-recyclable non-halogenated wastes with calorific content are generated as rejects of the main industrial process in large volumes. Anyway, the applicability must observe the Best Available Techniques (BATs) for waste combustion established in the *Commission Implementing Decision (EU) 2019/2010* and should be supported by an environmental impact study demonstrating the positive balance of energy, emissions and final residues. Scrap preheating systems using residual heat might be preferred.

The transferability of the developed analytical process models and control concepts is limited to similar processes, as they are based on fundamentals and knowledge on the involved processes. However, AI techniques, such as the application of genetic algorithms, could be used to optimise the feed of raw materials and the process variables of any industry. For the transferability assessment, the particular approaches in the optimisation of pyrometallurgy processes have been considered. For instance, in the use case of lead recycling, the different tools developed in the project in relation to the optimisation and control of the lead smelting and refining process could be applied to the rest of the ferrous and non-ferrous foundry industries. To do this, it would be necessary to analyse in detail the processes and stages that take place in the smelting furnaces of these industries and adapt the models and tools to achieve their applicability. In the rest of the industries, it is more complicated for the developed applications to be adaptable to their processes.

5. Acronyms and Abbreviations

BATs	Best Available Techniques
BF	Blast Furnace
BOF	Basic Oxygen Furnace
BREF	BAT Reference documents (European IPPC Bureau)
EAF	Electric Arc Furnace
IPPC	Integrated Pollution Prevention and Control
LIBS	Laser Induced Breakdown Spectroscopy
LSS	Large Sample Sensor
Model-OCT	Model-based Optimisation and Control Techniques
NAA	Neutron Activation Analysis
NF	Non-Ferrous (metals)
PFTNA	Pulsed Fast Thermal Neutron Activation
PGNAA	Prompt-Gamma Neutron Activation Analysis
TRS	TRuck Sensor
WDF	Waste Derived Fuel

ANNEX - Process sectors (Process Industries)

Metal making/recycling	Iron & steel making	Iron making (BF)
		Steel making (BOF,EAF)
	aluminium	Al smelting
		Al remelters & refiners
	ferrous foundries	Iron
		Steel
	non-ferrous foundries	aluminium
		magnesium
		copper
		zinc
		Other NF metals and alloys (bronze, brass, nickel, lead, tin, titanium…)
	(secondary) smelters	Lead smelters
		Zinc smelters
		Copper smelters
	precious metals refineries	
	Masteralloys/ferroalloys producers	
	silicon producers	
	carbon and graphite	
Other Process Industries	Minerals	https://ima-europe.eu/about-ima-europe/sections-members/
	Ceramics	https://cerameunie.eu/members/sectors/
	Cement	
	Chemicals	https://cefic.org/about-us/organization/
	Pulp & Paper	
	Refining (Fuels)	
	Water	
	Engineering	

Bibliography: BAT reference documents (BREFs) available from European IPPC Bureau (https://eippcb.jrc.ec.europa.eu/reference)