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Review

Sensor-Based Ore Sorting Technology in Mining—Past, Present and Future

Christopher Robben [1,*] and Hermann Wotruba [2]

1 Tomra Sorting Solutions Mining, Feldstrasse 128, 22880 Wedel, Germany
2 AMR Unit of Mineral Processing, RWTH Aachen University, Lochnerstrasse 4–20, 52064 Aachen, Germany
* Correspondence: christopher.robben@tomra.com; Tel.: +49-4103-1888-1429

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Abstract: While the deposit qualities for mineral raw materials are constantly decreasing, the challenges for sustainable raw material processing are increasing. This applies not only to the demand for minimizing the consumption of energy, water, and reagents, but also to the reduction of residual materials, especially fine and difficult-to-landfill materials. Sensor-based ore sorting can be used as a separation process for coarser grain sizes before the application of fine comminution and separation technologies and is applicable for a large variety of mineral raw materials. Sensor-based ore sorting applies at various points in the process flow diagram and is suitable for waste elimination, for material diversion into different process lines, for the production of pre- and final concentrates, as well as for the reprocessing of coarse-grained waste dumps and other applications. The article gives an overview of the development and state of the art of sensor-based ore sorting for mineral raw materials and introduces various applications.

Keywords: sensor-based sorting; ore sorting; dry processing; XRT sensor; NIR sensor; laser-scattering detection; waste elimination

1. Introduction

Sensor-based ore sorting is gaining increased attention both within and outside the mining industry, as it is leaving the state of pilot plant scale and technology road-mapping, and an increasing amount of equipment is installed in high-capacity production scale environments. In this manuscript we review the last decade of developments, benchmarked against the state ten years ago. We put the development into perspective, in relation with the requirements stated by a major mining house, and see where it stands today on a technology roadmap.

To describe the current state of the art, we use exemplary lighthouse projects to highlight the versatility, differences, and similarities in multiple mineral applications.

Sensor-based ore sorting across all segments of mineral production is an extensive topic, and each segment or specific application deserves its own analysis. This article aims to give a general overview of the topic but is not exhaustive.

The following table summarizes the detection systems that have been applied in mineral processing applications. In general, the following requirements need to be met be the respective sensing system to be applied in sensor-based ore sorting:

- (Near-)real-time measurement
- Non destructive
- Contactless
- Adequate spatial resolution to deliver the position of each single particle

- Adequate spectral resolution to deliver information about material properties/composition of each particle
- Reasonable costs

For some technologies with low spatial resolution, supporting detection systems have been added. Table 1 summarizes the detection systems applied in mining operations. The systems, which are currently being brought into production are highlighted in bold.

Table 1. Detection systems for sensor-based sorters and exemplary applications in mining (productized systems in italic letters).

Detection Type	*Industry Abbreviation*	*Material Property*	*Mineral Application*
Radiometric	RM	Natural gamma radiation	Uranium, precious metals
X-ray transmission	*XRT*	*X-ray attenuation coefficient*	*Base/ precious metals, coal, diamonds, etc.*
X-ray fluorescence	*XRF*	*Elemental composition*	*Base/precious metals*
X-ray luminescence	*XRL*	*Visible luminescence under X-rays*	*Diamonds*
Visual spectrometry	VIS	Reflection/absorption of visible radiation	Metals, industrial minerals, gem stones
Color	*COLOR*	*Color, reflection, brightness, transparency*	*Base/precious metals, industrial minerals, gem stones*
Photometric	*PM*	*Monochromatic reflection, absorption*	*Industrial minerals, gem stones*
Near-infrared spectrometry	*NIR*	*Reflection/absorption of NIR radiation*	*Base metals, industrial minerals*
Thermal infrared	TIR	Microwave excitation and thermal infrared detection	Base Metals, Precious Metals
Laser triangulation	3D	Hull detection (shape and form)	Base metals, precious metals, ferrous metals
Prompt gamma neutron activation analysis	PGNAA	Absorption and emission of prompt gamma rays	Ferrous metals
Laser induced breakdown spectrometry	LIBS	Evaporation of matter and	Industrial minerals
Laser induced fluorescence	LIF	Absorption of laser light and spontaneous emission of light	Industrial minerals

2. Historic Development and State of the Art in 2008

With principally the same technology and equipment available for processing of various mineral bulk materials, the degree of successful implementation was hugely different for different commodities. When attempting to introduce the sensor-based ore sorting, only a few plants found repetition in other facilities. Either the conditions were unique and favored implementation in this niche, or the installation had pilot plant character and was eventually abandoned. Table 2 shows a timeline of publications on technology development.

Table 2. Timeline on sensor-based ore sorting publications.

Commodity	Sensor	Year	Region	Reference
Diamonds	XRL	1928	USA	[1]
Coal	XRT	1928	UK	[2]
Uranium	RM	1946	Canada	[3]
Nickel	EM	1950	Canada	[4]
Coal	PM	1952	UK	[5]
Uranium	PM	1959	Canada	[6]
Coal	XRT	1966	UK	[7]
Manganese	PGNAA	1966	-	[8]
Coal	XRT	1975	UK	[9]
Gold	PM	1974	South Africa	[10]
Silver	PM	1974	-	[11]
Copper	EM	1974	US	[12]
Uranium	PM and RM	1975	Canada	[13]
Magnesite, Wolframite, Gold	PM	1976	Australia	[14]
Gold	PM	1977	-	[15]
Uranium	RM	1979	-	[16]
Wollastonite	PM	1979	Finland	[17]
Copper-Zinc	RM	1984	Finland	[18]
Fluorite et al.	UV	1985	US	[19]
Kimberlite	TIR	1989	USA	[20]
	XRF	1996	Russia	[21]

The only segment with widespread implementation was the Diamond history with the application of X-ray-luminescence (XRL)-based sorting machines, which were operated independently and in-house by the main Diamond producers. Due to confidentiality, there are no publications in the table.

The timeline shows that the peak in ore sorting popularity and R&D efforts in non-Diamond segments was reached in the late 1970s. This period was followed by the 1990s reluctance to sorting [22], when three main strains of developments occurred. The booming development of color-based sorting technology in the recycling industry spilled over to this segment of mineral production, resulting in the installation of a growing number of this type of sorters in industrial mineral applications. The second strain relates to the development and installation of low-tonnage, channel-based X-ray fluorescence (XRF)-based sorters in the Russian federation [21].

This short description of sensor-based ore sorting technologies, while far from exhaustive, aims to show that, despite the developments and efforts spent, it is only a decade ago that sensor-based ore sorting had a widespread implementation in Diamond concentration using XRL and industrial mineral sorting using COLOR-based ore sorting systems. In the following two paragraphs we summarize the state of the art in 2008.

2.1. Optical Sorting in Minerals Processing

Optical sorting for the upgrading of industrial minerals had been standard for producing white fillers, such as calcium carbonate, magnesite and burnt magnesite, and quartz for ferrous silicon production. Plant designs and equipment had been continuously optimized with about 200 installed machines since the end of the 1980s. If a sorter produces a finished product that no other process can match, such as the sorting of magnesite in Greece [15], then the benefit is obvious [22].

Expertise on successful plant design and operation around optical sorting machines was developed and retained, but mainly kept in the relatively small industry segments with limited to no successful technology transfer into other segments. Publications were limited, but there is, for example, one covering the implementation of an optical-based ore sorter at the Danielskuil operation in South Africa [23].

2.2. X-Ray Luminescence-Based Concentration of Diamonds

The first and most widely applied sensor-based sorting technology for minerals is the concentration of diamonds using X-ray luminescence (XRL)-based sorters, and the first patent on Diamond sorting was registered in 1928. Automation of the final diamond concentration stage eliminated the security risk of diamonds being stolen from the previously-applied grease-tables [24]. In addition, it eliminated the necessity for attrition milling to remove the surface coating before the grease table, as well as the unwanted risk of diamond breakage [17]. Most diamonds, apart from the highly pure Type IIa diamonds, fluoresce in the exposure of X-ray radiation and mechanical flaps are applied to divert the recovered stones. The position in the flow-sheet is after the concentration stage using dense–medium separation. The mechanical discharge results into high yields and cascades of sorters are necessary to recover Diamonds in a hand-sortable concentrate for the manual recovery and classification stage in the gloveboxes. XRL machines have been systematically applied since the 1960s [25].

In other segments, than diamonds, the technology development was very much a spillover from the food processing industry, where available technology was adopted for the requirements of a mineral bulk material. This was different in the Diamond segment, where the two main diamond producers, DeBeers and Alrosa, developed in house their own XRL-based sorting equipment: DebTech and Bourevestnik, respectively. Another supplier was the RioTintoZinc technology development, which was followed by UltraSort and is now part TOMRA. Another producer of XRL equipment, but for small- to medium-scale miners is FlowSort. Due to the low capacity and the need for cascading flow-sheets, there are an estimated 1500 to 2000 XRL-based diamond machines installed in total.

2.3. Conclusion

Generally, there is agreement across multiple authors in the literature that sensor-based ore sorting is widely applicable, contributes to increasing the productivity, and addresses the main challenging megatrends of declining head-grades, the increasing difficulty to access process support resources, such as land, energy and water, and increased environmental liability [26–32]. However, apart from industrial minerals and Diamond processing, sensor-based ore sorting can still be considered to be in market entry stage for the minerals industry.

3. Working Principle

The term "sensor-based sorting" (SBS) is an umbrella term for all applications where particles are singularly detected by a sensor technique and then rejected by an amplified mechanical, hydraulic or pneumatic process [33]. Other terminologies used in the industry are "ore sorting", "automated sorting", "electronic sorting", "particle sorting", or "optical sorting".

Sensor-based ore sorting systems inspect single particles to determine the value of some property using contactless and real-time measurements that obtain both the location (to control the latter ejection process) and material properties. The detection process; therefore, requires a fast integration time as well as appropriate spatial and spectral resolution.

Sensor-based ore sorting is the only mechanized mineral processing where the separating force is detached from the separation criterion—a unique characteristic that makes it more difficult to imagine and understand for people not familiar with the topic. The variety of industrially-available sensors, as well as the flexibility in programming different sorting algorithms, make the technology very complex, but also extremely versatile in its application.

The working principle of sensor-based ore sorting can be subdivided into sub-processes, all of which contribute to the overall separation efficiency of the equipment. Salter and Wyatt have divided the main process into four sub-processes in 1991 [22]. Robben described the characteristics of the technology in 2013 by dividing it according to the efficiency contribution of multiple factors [34]. Table 3 shows the division into the sub-processes and efficiency contributions and how they relate to each other.

Table 3. Sensor-based ore sorting process sub-division.

Sub-process [23]	Efficiency Contribution to the Overall Process Efficiency [34]
n.a.	Platform efficiency
	Preparation efficiency
Particle presentation	Presentation efficiency
Particle examination	Detection efficiency
Data analysis	
Particle separation	Separation efficiency

The history of sensor-based sorting is rich in innovative experiments on equipment configurations, which include:

- Chutes or slides [1];
- Flat-belts [3];
- Bucket-wheels [35];
- Rotary disks [36];
- Jet-slinger belts [22];
- Pinched rolls [22];
- Cones [37];
- Channels [21];
- And probably more.

As physical separation mechanism, there are principally two setups that have been applied to introduce the kinetic energy to the particles that are ejected.

- Water jets [38];
- Mechanical flaps [1];
- Pneumatic valves [22];
- Suction nozzles [22].

The compressed air ejector with pneumatic valves [22] became the industry standard as far back as three decades ago and remains so to this day for effective ejection on high-capacity sensor-based ore sorting machines. Mechanical ejectors are installed in low-throughput units, for example, single-particle XRL diamond sorters or XRF sorters [39].

Mechanical Platforms

Two main mechanical platforms are currently being installed in mining operations: belt-type and chute-type machines, as shown in Figures 1 and 2.

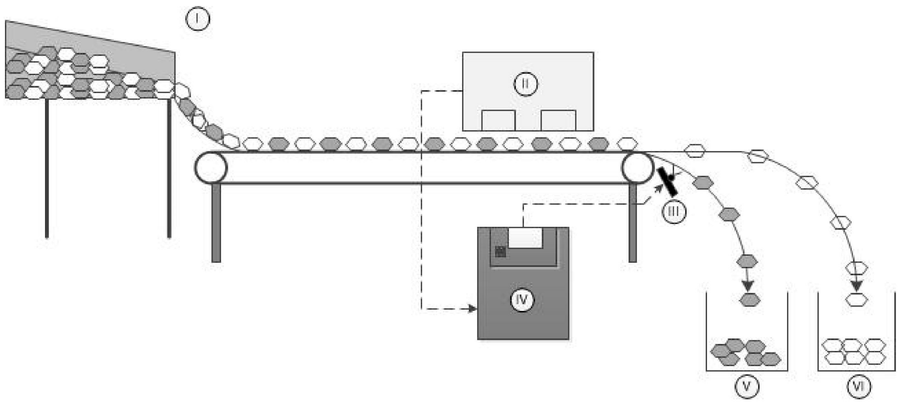

Figure 1. Belt-type sorter: (I) Material presentation by vibrating feeder and belt; (II) sensors; (III) ejection nozzle array; (IV) central processing unit (CPU); (V) drop fraction; and (VI) ejected fraction.

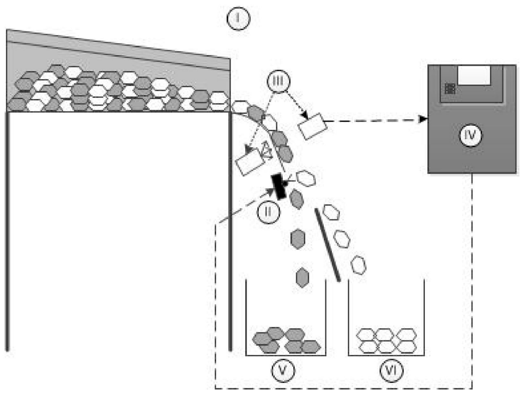

Figure 2. Chute-type sorter: (I) Material presentation by vibrating feeder and sliding chute; (II) sensors; (III) ejection nozzle array; (IV) CPU; (V) drop fraction; and (VI) ejected fraction.

4. Reasons for Implementing Sensor-Based Ore Sorting

There are multiple motivations and possibilities for the implementation of sensor-based ore sorting into the production flow sheet of mineral processing.

The technical and financial feasibility depends mainly on the type of mineralization, because sensor-based ore sorting exploits heterogeneity at relatively large particle sizes.

Financial benefits and characteristics are well described by many authors, and the main drivers behind the application of the coarse particle separation technology of sensor-based ore sorting have not changed in the last decade [17,23,25,34,40]. They include megatrends such as decreasing head-grades of existing mines and the increasing difficulty to obtain a social license to operate in times of dam failures and water scarcity, which are becoming increasingly important. It is; however, difficult to quantify them in financial terms, for example, with a social license, the costs are the usual market costs, while without the costs is closing down the operation.

4.1. Increased Productivity

One of the main motivations for brownfield operations is to improve productivity by clearing bottlenecks and increasing the mining production rate by the amount of waste ejected downstream through the implementation of sensor-based ore sorting. The more waste that is discarded, the higher the grade of values in the feed to the downstream processes. As a result, additional production can be achieved with little investment into increased extraction and haulage processes.

This is the most important driver during times of insufficient market supply, high demand, and high production margins—assuming the additional production achieved is marketable at the same price as the production of the base case scenario.

There are two main bottlenecks that limit production rates in mining operations. These are the two units that can only be expanded to a very limited extent or not at all, the shaft and mill. They also account for most of the total capital expenditure of mining operations.

The sensor-based ore-sorting step practically never reaches 100% recovery, and this has to be regarded while evaluating a project and has to be accounted for as costs for lost production. The implementation of sensor-based ore sorting into mineral processing flow-sheets introduces an additional recovery factor that contributes to the overall recovery on the whole process, which results in additional product volume, creating revenue. (If the overall recovery, consisting of the recovery of the waste rejection step multiplied by the recovery of the conventional process treating pre-concentrated material, is higher than the recovery of the conventional process, additional product volume is created.) The additional revenue must justify the investment and operation of a waste rejection step. But still the standard project evaluations, net-present-value (NPV) and internal-rate-of-return (IRR), underline the economic viability of this scenario. Generally, the waste created, if not discarded on a rock dump or used underground as backfill, can be either sold as aggregate (inside or outside the own organization), stockpiled for cheaper (e.g., heap leaching) processes, or processed later in the operation.

It is difficult to make generalizations about the increase of recovery in downstream processes for different cases, but Cresswell notes that there is the potential to improve the product recovery and grade and reduce the specific reagent consumption [41], while Bamber generalizes the improvement using the two-product formula and fixing the tailings grade in the equation [34,42]

4.2. Decreased Capital Expenditure and Specific Operating Costs

Sensor-based ore sorting in waste rejection has an effect on both the cost structure and the productivity of a mining and mineral processing operation. The two factors influence the determination of the cut-off where resources turn into reserves. This is especially interesting for retreatment of old waste dumps to eliminate an environmental liability, and also because they can be mined at very low costs [43]. But it can also mean that the cut-off grade in the mine is lowered, as in the case of the Mittersill tungsten mine [44]. In both cases, the life of mine can be extended with relatively low investment, and the capacity to continue production with a depreciated asset is especially interesting.

Different economic assessments show that the value added by sensor-based ore sorting is highest when treating marginal ore, just below cut-off [34,43,45].

4.3. Reduction of Specific Fine Tailings Generation

Past and recent catastrophic tailings dam failures, such as Brumadinho in Brazil [46], have increased difficulty to obtain the social license to operate wet fine tailings dams. This has resulted in technical developments towards dewatered stockpiling, so called dry stacking. Dewatered tailings disposal is a safer alternative to tailings dams [47]. Reducing the specific amount of fine tailings generated per ton of produced product is; therefore, an increasingly important incentive for the implementation of sensor-based ore sorting. This is especially important for brownfield operations with limited tailings dam capacity and outstanding dam license extension.

In general, coarse waste separated with sensor-based ore sorting is easier to store due to the geotechnical stability, lower moisture content and the lower reactive surface. Coarse discard has a lower surface area than fine tailings. This has two main positive effects. The first is related to dewatering and tailings handling. Mill tailings streams with a particle size of the solids of around 100 μm usually have moisture contents of 70 wt.% while coarse discard (>10 mm) usually has a moisture content of 5 wt.% [48]. This results in decreased effort for water handling, recirculation, and purification. Although the coarse waste stockpiles have higher permeability, the reactive surface for oxidization is smaller resulting into less acid mine drainage potential. Under certain circumstances the ejected coarse particles can be saleable by-product (e.g., aggregates for construction applications). An industrial example for the implementation of SBS for simplified tailings disposal is the Mittersill Mine operated by Wolfram AT in Austria [49]. The sales of aggregates are highly dependent on the local market for this low value commodity. The discard can also be a commodity traded within the mining operation, for example, when being applied as functional backfill, for road construction, etc. [33].

4.4. Sustainable Development

Sensor-based ore sorting has the potential to increase productivity through greater efficiency, also in terms of the input resources, such as water, energy, and process reagents per ton of product. In an environment where competition for resources with other stakeholders such as communities and agriculture is increasingly fierce, this can become a driver to obtain the social license to operate.

4.5. Reduction of Transport Costs

Waste rejection close to the extraction face was reported as far back as the sixteenth century, when hand-sorting was applied underground close to the face in order to reduce the load on transport and cut costs in the mill, as well as for direct backfilling, thus saving wood for rock support [50]. Salter and Wyatt also mentioned the widely-held perception that sensor-based sorting is especially well suited for underground or in-pit scalping [22].

The flexibility and mobility of sensor-based ore sorting installations, together with the relatively low effort for legislation, allows the application of separation close to the mining face [30,40,51–53]. This can apply to an operation located on arid territory, in an area lacking sufficient power supply, or in an environmentally sensitive area. Close-to-face waste rejection is also a viable option in the case of a central plant being fed by several smaller satellite mining operations at distances of more than 30km from it. [34].

5. Positions in the Flow-Sheet

Sensor-based ore sorting, as a unit process, can be located in any position in the flow-sheet that offers applicable size range. It is applicable for rougher, scavenger, and cleaner configurations. The most common combination tested is the rougher–scavenger to obtain maximum recovery. Usually, only the rougher stage is installed for reasons of flow-sheet/plant operation complexity.

5.1. Run-of-Mine Sorting

The most common position of sensor-based sorting is either the run-of-mine or run-of-dump position. The latter can be just regarded as a run-of-mine stream from a low-grade, marginal mining block at low mining costs. To obtain suitable particle sizes as feed to the machines, in most cases primary crushing and secondary crushing are applied.

5.2. Pebble Circuit Sorting

Many mines use pebble ports in their autogenous mills to remove critical or near-critical size material, which is then crushed and returned to the mills. If this material was sorted before crushing, then only the value-bearing material need to be crushed and sent to the mill and the barren material could be discarded. The work of Freer [54], following on from Bohme and Kilian [55], showed how successful this route is for optimizing the mill power draw and throughput of a gold ore mill. Given the breakage characteristics of most ore waste systems and widespread use of autogenous and semi-autogenous mills, the potential for this type of sorting appears enormous. [22]. Further work has been published on successful pebble sorting on a copper ore [56].

5.3. Portable Production Plants

The relatively low footprint of a single-sorter installation enables portable installations. This is further supported by the availability of portable peripheral equipment, such as crushers, screens, and compressors. The idea of a semi-mobile or portable installation is first mentioned for a small, trailer-mounted sorting plant [22]. Specific interest has been paid to locating parts of the mineral processing activities underground. Increasing environmental constraints and growing competition for land, water, and energy resources have supported the idea of the invisible mine, which has been explored mainly by research but also in the industry [24,30,34,51,57–62]. The concept for the implementation of portable systems underground is still years ahead on the development roadmap.

On the other hand, surface implementation is today's state of the art. The main reasons driving towards portable installations are the flexibility they offer for relocating production or their being used as a pilot in preparation for a full-scale production plant.

The decision to start with a pilot operation instead of proceeding directly to a full-scale production plant is based on various factors. The most important are the mitigation of fundamental sampling error and grouping and segregation error when higher masses are treated. Secondly, liberation characteristics in different particle sizes and different separation strategies can be tested taking short- and long-term fluctuation into account. It is advisable at this stage to define the sampling strategy to limit efforts required and maximize precision of the assay results, which then is the basis for further optimization of the sensor-based ore sorting machine. Since containerized full-scale production machines are applied for pilot testing, an early application to production mode is possible and advisable in order to achieve a return on the investment. Furthermore, operational factors such as training and adapted practices are easier to evolve in a free-standing pilot plant. However, in the case of a clearly financially viable case, where the technical risks and the material heterogeneity are limited, a project is advised to proceed directly to the stage of a full production plant [63].

6. Technology Requirements and Roadmap

At the Sensor-Based Sorting Conference in Aachen 2008, Robert Crosby and Dr. Mike Buxton summarized the experiences they gained in their sensor-based ore sorting program and stated the technology requirements that would govern its applicability, specifically in base and precious metal mining [64]. The requirements they mention are in line with those stated by Salter and Wyatt [22].

The following paragraphs elaborate on the requirements specified and set them in relation to the state of the art today.

6.1. Detection of a Significant Unique Mineralogical Property or Significant Mineral

Sensor-based ore sorting is a physical separation technology where the mechanical platform contributes to the overall process efficiency. The primary factor for technical feasibility is the sub-process of detection. The detection efficiency describes the chance of misclassification in dependence of the cut-off grade. One way for calibration and validation is the so-called bench-scale test which correlates single particle assays with the sorting index, which is the output of the software. Figure 3 shows an example for a copper ore. It is important to note that the results of the detection efficiency are described in an allocation table, which determines the chance of true classification (waste-to-waste; product-to-product) or misclassification (waste-to-product; product-to-waste). The correlation expressed as R^2 is of interest but not of significance for a high detection efficiency and reliable classification into product and waste fractions.

The detection efficiency depends both on the signal-to-noise ratio of the sensor and on the principle of detection in combination with the feed particles' properties. It also includes the accuracy of the multivariate calibration applied. For the surface detection technologies, the detection efficiency also includes the representativeness of the surface in relation to the content. If the primary valuable species cannot be detected and relations to markers are used, the detection efficiency also describes the relation of the detected analyte to the valuable species. Last but not least, detection efficiency also depends on the size of the particles in relation to the spatial resolution of the sensor [34].

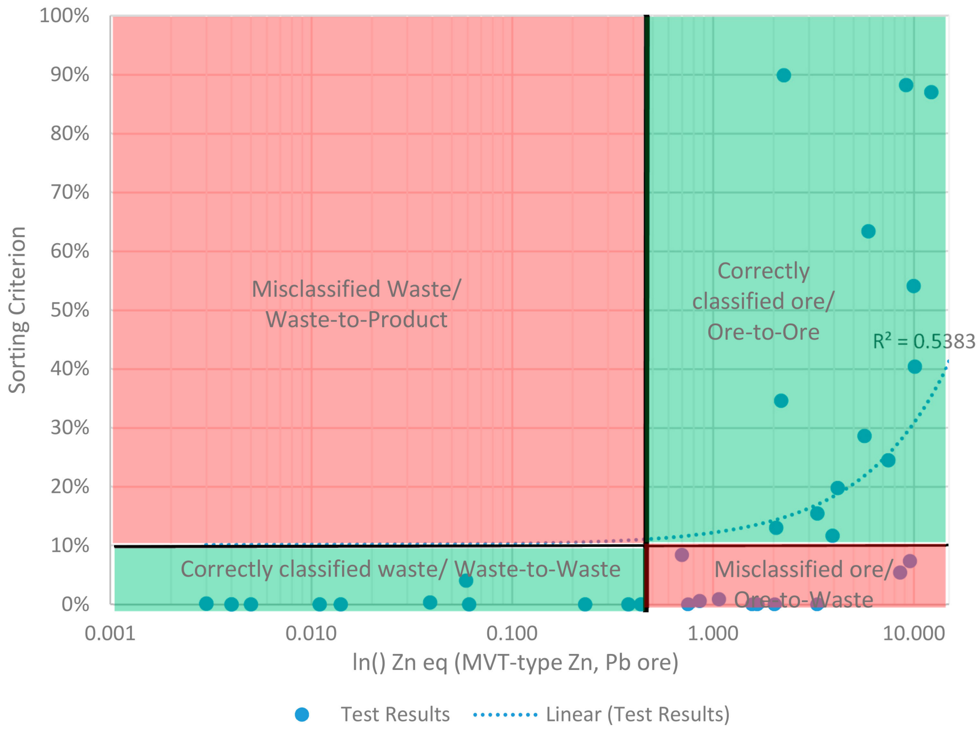

Figure 3. Example of bench-scale test results to describe detection efficiency, modified after Crosby and Buxton [64].

It is important to have a significant and unique mineralogical or elemental property to detect, to understand the separation criterion, and to evaluate if this separation criterion can be extrapolated over the volume of the reserve, and hence the life-of-mine. Extensive work with color-based separation of gold ores showed that the association of gold with certain color features is not reliable, and equipment installed was taken out of operation [65].

The guidelines that the theory of sampling present for calibration and validation activities apply to the setup (during test work) and operation of sensor-based ore sorters [66]. It is essential to ensure that the calibration of the sensor-based ore sorter accommodates for the operation and supports a high process efficiency, which is required for the financially viable operation of the plant. A lack of understanding of the fundamental sampling principles and the failure to call on an engineer for their expertise on how to apply calibration to the future sorter feed are the primary reasons for sensor-based ore sorting plant failures and shutdowns.

This requirement expressed by the fundamental sampling principle explains the dominance of X-ray transmission (XRT)-based ore sorting today. The mineralogical property of elemental composition is primarily the atomic density as this dominates the attenuation of hard X-rays applied. The presence of matter with high elemental composition and; therefore, X-ray attenuation is easy to understand and extrapolate. The XRT-based principle images a planar projection of the attenuation. Since the radiation passes the particle, it also respects the fundamental sampling principle that all components shall have the same probability of being detected.

6.2. Ability to Cover a Relevant Portion of the Mass Flow

Coverage of a relevant proportion of the mass flow is a function of the size distribution combined with the technically and economically feasible sizes to be fed onto a sensor-based ore sorter.

With the increasing specific operating costs per ton of feed to the machine, the lower size limit is usually an economic barrier where sorting of fines becomes unfeasible. The fines fraction is then bypassed either to the product or to the waste fraction. The upper size limit is determined by three factors. First of all, the technical feasibility of the detection system applied. Here, XRT-based detection has a limitation to the possible penetration depth whilst still maintaining a good signal to noise ratio at about 75 mm (depending on the atomic density). Reliable penetration is necessary for at least one of the two fractions that the machine shall classify into. A ferrous metal application is limited to about 75 mm, while carbon-based coal or diamond separation is possible up to 150 mm.

The second technical limit may be the degree of liberation present in the range of coarse particles. It may be necessary to crush the ore further to obtain a suitable, thus economically exploitable, degree of liberation.

The third technical limit is the mass flow in the coarse particle size. Due to the necessary size-range-coefficient of about 3, the upper size cut of the feed fraction cannot just be lifted to accommodate for a few percent of the particle size distribution, as this would decrease overall process efficiency. The solution is either to reduce the opening of the crusher, or to bypass the coarse fraction around the sensor-based ore sorters.

The relevant portion of mass flow may not only be meant in terms of percentage of the mass flow, but also as the selection of a size range in which natural concentration of a wanted or unwanted proportion occurs. An example is the placement of sensor-based ore sorting in the pebble circuit, where there is usually an increased occurrence of hard waste due to preferential breakage.

6.3. Constant/Discardable Tails Grade

The requirement for a constant, discardable tails grade defines the rejection of a sub-economic waste fraction in a waste rejection flow-sheet. Here, the waste grade does not carry enough value to pay for the costs of recovering it. It was once stated that the elimination of waste at any cost lower than the total milling cost will show profit [11]. However, how to account for fixed and variable costs of a concentrator remains a heated discussion in the industry. A generally accepted conclusion is that the waste grade of a sensor-based ore sorting stage may be equal or lower than the grade of the final process tailings.

It is interesting to note that all cases where operating data for waste rejection stages has been published show a very similar pattern. The graph in Figure 4 of process data from the X-ray transmission-based sorting plant at the Mittersill tungsten mine shows, that a constant waste grade at about 0.03% WO_3 is achieved over the course of the period analyzed. The product grade varies as all feed variation is reported to the product fraction. Consequently, waste rejection has a valuable function with (planned and unplanned) mining dilution control, but also acts as an amplifier for all feed variation which is now reporting to the main plant.

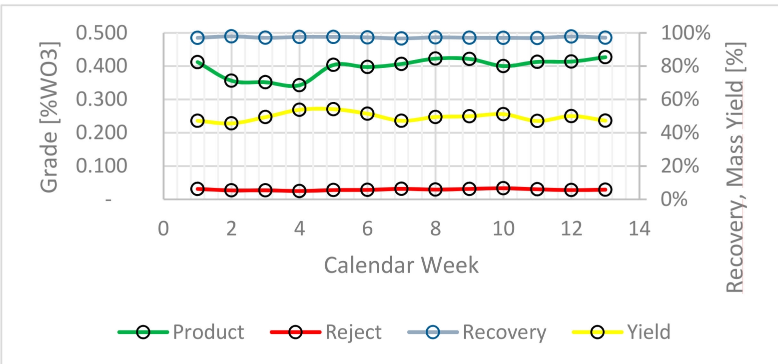

Figure 4. Process data from the waste rejection stage using XRT-based ore sorting [44].

6.4. Competitive Capital Cost/High Throughput

Because any coarse particle separation technology cannot achieve a high separation efficiency (apart from minerals, where liberation of final product occurs in the sensor-based ore sorter feed size), it must add its value through low capital and operation costs. Due to the disproportional link of capacity and specific capital and operating costs, capacity is the main lever to reduce costs and reduce footprint.

Further, for high tonnage applications, multiple streams should be used rather than attempting to sort in megalithic machines [22].

6.5. Robust, High Quality

The design of a sensor-based ore sorter must accommodate for the realities in mineral processing plants, and high availability is a necessity. This is not always a given, as the developments in sensor-based sorting technology nowadays are largely transferred from neighboring and much bigger markets such as food processing and recycling. This ties in with the requirement in the next paragraph.

6.6. Ability to Operate in Remote Locations under Adverse Operational and Environmental Conditions with Minimal Supplier Intervention

The mining industry expects easily maintained sorters with a high level of technical support [22]. Ad-hoc spare part delivery may be a challenge in remote locations; suitable service schemes and spare part handling strategies must be in place and tie in with the appropriate machine design. Machine design must also meet the skills available locally and the safety and operational procedures at the site.

7. Recent Developments

7.1. Procedures and Project Development

In 2006, Wotruba encouraged the mining industry to consider sensor-based ore sorting in the earliest planning and flow-sheet design stages in project development [28]; and it seems that the industry has heard this call. During the last decade, hundreds of projects have been tested regarding their technical feasibility and the data has made it possible to assess the economic feasibility of these projects. This is a sign of acceptance of sensor-based ore sorting as a standard tool for minerals processing. It also means that an increasing number of projects in the development pipeline has sensor-based ore sorting in their flow-sheet, and that upon implementation it will be an integral part of the project design with impacts both upstream and downstream: Upstream, with reserve estimation and mine plan based on applicability of a sensor-based ore sorting machine; downstream, with adequate mill and circuit design based on the properties of a sorted material stream.

This means that the technology is not retrofitted in a sub-optimal manner, but truly integrated. Combined with the increasing number of operating machines, it also means that there is an increasing number of engineers across multiple disciplines both in project development and plant operation, who now represent a critical mass to discuss, develop, and share expertise.

Within this developing community, standard test methodologies and project development strategies are evolving and refined with each successfully implemented project [63]. Considering the long project development lead time, which is in the order of five to seven years, it may be a decade until the full result of the projects developed today becomes evident.

7.2. Equipment

The main technology development in equipment can be seen in the field of XRT-based sorting. This detection principle has proven to be widely applicable in all segments of mineral production. Ten years ago, only a few pieces of equipment were operated in coal, tungsten [49] and gold [67]. Today, production machines are operating in tungsten, tin, coal, gold, copper, iron ore, chromite, diamonds, phosphate, and limestone processing.

Development efforts have been invested in sensors, detection efficiency, capacity, and availability.

7.3. Sensors

Detection systems applied for sensor-based ore sorting must fulfill the following requirements of spatial and spectral detection and near-real-time in a production environment at a reasonable price. New systems, in addition, need to add information, decrease costs, present higher availability, or decrease plant complexity in comparison to existing technologies. Only two new technologies have presented additional benefits and emerged in minerals processing in the last decade: near-infrared spectrometry (NIR)- and LASER-based sorting, which we introduce in the following paragraphs in chronological order.

7.3.1. Near-Infrared Spectrometry

NIR spectroscopy has been used in remote sensing for nearly 40 years. Remote sensing is the acquisition, processing, and interpretation of information about a target like the Earth surfaces or other surfaces in the solar system in the absence of physical content with this target. Remote sensing in the NIR region can, for example, be applied for mapping, exploration (also on mine and pit-scale), and environmental control. Different examples of remote sensing projects for exploration are described by, for example, Agar and Sabins [68,69]. Examples of environmental control and monitoring by remote sensing are impact detection of mine tailings and the detection of acid mine drainage [70]. Landform, lithology, mineralogy, vegetation stressed by metals, expansive soils [71], alteration, and faults and fractures can be mapped with remote sensing [69,72–74].

NIR-based sorting was first systematically assessed for applicability in mining in 2008 [75]. The system originates from sensor-based sorting of plastics and paper, where many thousands of machines are in operation. It quickly became evident that the direct and positive detection of (near-infrared active) minerals known from mineral exploration would be features exploitable for coarse particle separation. NIR is a vibrational spectrometric method and near-infrared minerals include the following molecular bonds in their crystal structure or intercrystallite. The most common diagnostic features in the spectra of geogenic material are due to the presence of unfilled orbitals of transition elements (Mn, Cu, Ni, Cr, Co, Fe, etc.) and the molecular bond incorporating OH, CO_3, NH_4, and H_2O. Understanding the variables that affect spectral response is not only critical for the interpretation of a data set (e.g., during test work), but also for the estimation of the repeatability and thus robustness of this technique during the life of the mine [74]. The surface detection principle requires both clean particle surfaces and the implementation of a chute-type sorter for double-sided recognition to minimize shadowing effects. NIR spectrometry, as vibrational spectrometry, excites about 30 µm thickness of the surface, thus is partly able to tolerate thin dust layers. Surface moisture from wet-screened and dewatered particles needs to be considered in the multivariate calibration but does not negatively affect separation efficiency.

The first projects applying NIR-based sorting, which followed soon after the first tests, proved technical feasibility. These projects included the processing of zinc-oxide ore from the Scorpion Mine in Namibia [76]. Technical feasibility was also shown for the concentration of talc ore and machines implemented in the field [77]. Another successful application proved to be the concentration of Kimberlite ore. A study on the performance test work and pilot operation was published in 2016 [78]. The work has further resulted in the installation of NIR-based sorting for Kimberlite concentration at the Renard Mine in Canada [79]. The project is described in some detail in Section 8.

7.3.2. Multi-Channel LASER

The multi-channel LASER-based detection principle was developed and matured in the food processing industry. It detects the reflection and diffraction of multi-channel laser light from the particles' surfaces, and in the case of translucent minerals, from diffraction within the volume of a particle. The first test work campaigns showed that the principle of detection is especially suited for positive recognition of quartz. Both lumpy quartz, quartz veining and other quartz structures in the size of about 500 µm are positively detected. The setup also allows limited color-detection functionality when choosing laser sources in the visible spectrum of electromagnetic radiation. As for NIR-based sorting, LASER requires clean surfaces and double-sided detection implemented on a chute-type sorting system.

With mineral Quartz being the main target, two possible applications were identified and systematically developed. The first one is the Quartz-associated Gold ore, where a high recovery of (surface visible) Quartz leads to a high Gold recovery. It showed that the detection of small Quartz veinlets was especially important for a high Gold recovery because of the Gold mineralization in close vicinity to the veining—even more than in the Quartz veins themselves. As a high Gold recovery is a condition for the economic feasibility of a sensor-based ore sorting installation, it becomes clear why previous COLOR-based gold ore sorting attempts have often failed [80]. The development has led to two pilot installations: one at Björkdals Mine in Sweden [81], and the other one, in combination with an XRT-baser sorter, at Corrego do Sitio Mine in Brasil [82].

The second application is the concentration of high-purity Quartz pebbles for high-purity applications, such as ferrous silicon. The main advantage of the LASER-based sorting principle of the COLOR-based sorting principle is a 15% to 20% increase in yield at the same product quality [83].

7.4. Detection Efficiency

Most business cases for the application are driven by the recovery of the pay-component of the bulk material treated with a sensor-based sorter, and the detection efficiency is the biggest lever for the value that can be created with this machine. For this reason, efforts have been taken to lower the detection limit. This is achieved by optimizing the spatial and spectral resolution according to the ore properties treated, as well as the signal-to-noise ratio of the detection system applied.

On the software processing side, there is no bottleneck in the interpretation of the data. Most of the efforts are funneled in understanding the mineralogical features detected and converting them into reliable sorting criteria. An example is reported on methodologies for the most challenging example of a Gold ore [82]. The difficulties and approaches described are an effective development from the procedures described on a copper ore a decade ago [64].

7.5. Capacity

On the cost side, specific capital expenditure (total capital expenditure/design-feed capacity) is directly linked to the feed design capacity of the equipment. Considering that the total capital expenditure is the investment for a complete plant—and not just the sensor-based ore sorting machine—which is four- to 10-fold of the main equipment value, and with capital costs for sensor-based ore sorters stagnating, the design capacity has more than doubled during the last decade. In specific applications, such as diamond concentration with XRT-based sorting, the design-feed capacity has increased almost five-fold in relation to what was specified ten years ago [84]. This means that the specific capital expenditure is less than half.

Additionally, on the operating costs side, increasing the design capacity of the equipment will decrease the specific operating costs almost proportionally. Wear components in contact with the material flow account for about 20% of the total hourly costs and 30% of the total spare part costs [85]. The wear of the components rises with increasing particle size, specific density, and abrasiveness of the ore more than it does with increasing design-feed capacity.

In summary, the two-fold increase in design capacity on the belt-type XRT-based sorting machines has almost halved the specific capital costs and specific operating costs and is one of the main achievements in equipment development during the last decade.

7.6. Availability

The productivity of a system is a factor of both the above-mentioned design-feed capacity and availability. Availability can be achieved by increasing the mean time between failures, as well as by easing maintainability to accelerate care and maintenance activities. With the increasing importance of belt-type XRT-based sorters, most of the development in the last decade have focused on this equipment. This type of machines has operated in arid, desert, tropical, and arctic conditions and collected a few million operating hours. It has been applied for the high abrasiveness of a 50–150 mm lump chrome ore as well as on coal in the size range 10–100 mm, which tends to cake in the presence of moisture. The combined experience about the lifetime of components, as well as about the processes and activities involved in care and maintenance, has formed the basis for maturing the equipment and developing new generations. This evolution needed the climatic, ore specific, and cultural conditions under full operation load in order to happen.

The availability also depends on maintainability, and in this respect, Stone identified the real problem of obtaining and retaining skilled maintenance, especially in remote and small operations [86]. Probably the biggest achievement in the last decade was bringing equipment into operation and maintaining its operation. This development included efforts from the suppliers, but even more on the operator's side. From the suppliers, apart from the equipment itself, a high contribution was given in terms of service strategies, training, and implementing suitable spare-part supply strategies. Tailored service strategies respecting the site conditions and location have been implemented as preventive regular site support and—for larger installations—also full operating contracts. For the operators' side, it meant the development of operational and maintenance procedures. Four factors have been essential for this success:

- Suitable equipment;
- Training and service support;
- Defined and dedicated ownership within operation;
- Position in a critical stream of the process.

A typical and successful example is the ramp-up of the XRT-based ore sorting plant at the San Rafael tin mine in Peru. Figure 5 shows that stabilization above design capacity of 3000 tons per day was achieved after six months, after which it successfully performed at up to 3600 tons per day. Challenges overcome include caking in material handling, undersize material above specification, and development of operational procedures. This development is truly a good example of what it takes to bring a new technology and plant into operation and it has been highly rewarded as an extraordinary profitable operation [43].

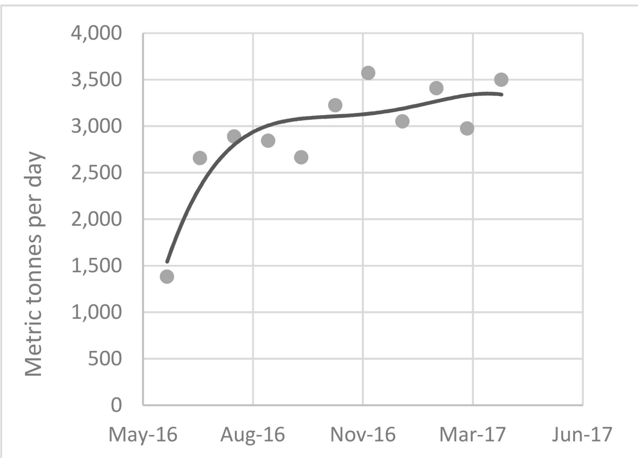

Figure 5. Feed tonnage to ore sorting plant during ramp-up phase of an XRT-based ore sorting plant at San Rafael Mine [43].

8. Plant Design

The sensor-based ore sorting plant design remains a novelty in some regions and for some engineers, in spite of the fact that this technology is generally held in favorable regard in the industry. There is a limited number of proven designs ready for implementation in specific environmental or process conditions, or regional legal requirements. Dry material handling systems are not familiar, nor is the intent to create a coarse particle size distribution to increase the mass-flow fed to sensor-based ore sorting. The particle size distribution and the resulting benefits can generally be controlled [87]. A case study shows that by changing the operation of the secondary crusher to closed circuit, the mass-flow in the applicable size fraction for sensor-based ore sorting—in this case, 12–45 mm—can be increased from 60% to about 85% [88].

A trend is slowly emerging, so that with each plant commissioned, there is a greater understanding in the industry of the specific system requirements that govern the operability and the bottom-line result of a plant.

9. Lighthouse Installations

In this chapter we describe a number of selected installations—all of them publicly reported references—that have reported successful operation, some having also published very detailed operational data. We elaborate on the conditions that favored, or even enabled, implementation of a new technology into the production process.

9.1. Mittersill Tungsten Mine, Austria

After more than 40 years of operation, the mine encountered challenges with ever decreasing head grades from their mine. While first an open pit, and subsequently the underground mine, delivered a head grade of about 0.9% WO_3, it decreased to below 0.3% WO_3 in the early 2000s. To counter the development of decreasing head grade and to turn marginal resources into reserves, a sensor-based ore sorting project was started.

A decade ago, tungsten ore from Mittersill Mine was tested with UV-fluorescence-based sorting, which highlighted the disadvantages of a surface detection method. This method violates the Fundamental Sampling Principle that all components of a lot must have the same probability of being detected. Scheelite ($CaWO_4$) inclusions embedded within a particle have zero probability of being detected. The consequence experienced was a grade of the rejected waste too high to be discarded.

As a second method, XRT-based sorting was tested and proved to be successful. A pilot with one XRT-based sorter demonstrated the positive effects and enabled the engineers and operator crew to study the behavior. With this knowledge, they designed a fully integrated plant that sorts the coarse portion of the run-of-mine ore, which is in total 0.5 million tons per annum. Today, the Mittersill Tungsten Mine is one of the most famous and well described sensor-based ore sorting plants. Detailed production data, economic feasibility and impacts on sustainability studies have been published. [44,89].

The sorters are introduced after the secondary crusher and treat the two size fractions, 1630 mm and 30–60 mm, in parallel. 50% of the mass is -16mm material, which passes the sorters. 50% of the mass fed to the sorters is separated as coarse waste with a grade of 0.03% WO_3. This means that the 25% of the run-of-mine stream are separated, increasing the mill feed grade by about 25%.

The coarse waste eliminated from the process relieves the constrained fine tailings facility and is sold to the local construction market as aggregate.

9.2. Karowe Diamond Mine, Botswana

A decade ago, the first trials with XRT-based sorters had been conducted at lab scale, but the main development was driven towards high capacity COLOR-based sorters [90].

Today, the Karowe diamond mine has become famous around the world for repeatedly producing exceptionally large stones with XRT-based sorting technology—one of them being the Lesedi La Rona, the third biggest diamond ever recovered and the second biggest of gem quality [91]. It was followed recently by the recovery of one of the largest diamonds in recorded history, the largest in Botswana, and the largest diamond to be mined at Karowe to date. The unbroken, 1758 carat stone was recovered through Lucara's state of the art XRT circuit, commissioned in April 2015. Weighing close to 352 g and measuring 83 × 62 × 46 mm, the diamond has been characterized as near gem of variable quality, including domains of high-quality white gem [92].

The main challenge for the process at Karowe was the relatively high amount of high-density material in the run-of-mine stream, resulting in high yields in the dense–medium–cyclone stage, which overstrained the traditional diamond recovery stages with XRL sorters. XRT-based sorting was identified as a possible technical solution and gradually implemented.

The successful implementation of X-ray transmission-based sorting has had a significant impact on the Diamond industry. This type of equipment accommodates the high-feed tonnages necessary to treat run-of-mine material. The detection and ejection efficiency enable production of a hand-sortable concentrate in one step.

Today, four size ranges are fed in parallel between 4 and 125 mm to XRT-based sorters with intermediate crushing and SGA mill liberation. The total mass flow to the XRT-based sorters adds up to about 1000 tph. The sorters have replaced the dense–medium recovery stages in those size ranges.

The main and most significant advantage of XRT-based sorting is the single stage recovery of Diamonds from run-of-mine ore to hand-sortable concentrate, at recovery rates of about 96% to 98%. This results in significant capital and operating costs savings. On the revenue side, three effects are noticeable. First is the large top size of the feed to the XRT sorters, which enables recovery of exceptional stones non-recoverable with traditional flow-sheets. Secondly, less diamond breakage is observed with a simplified flow-sheet, also resulting in a higher average price per carat. Thirdly, an increase in overall recovery of 6% in the +4 mm size is reported, as well as 4% increase in recovery in the –4 mm fraction, to which the dense–medium–cyclone has been optimized [84].

The technology has been truly disruptive to the industry and current state-of-the-art diamond processing flow-sheets fully rely on TOMRA XRT-based sorting technology for the particle sizes +4 mm.

9.3. Umm Wu'al Phosphate Mine, Saudi Arabia

In 2009, there was one production-scale XRT-based sorter separating flint from carbonates, and the first lab-scale tests were conducted with apatite ore. Today, the biggest sensor-based ore sorting plant in terms of nameplate capacity is the 1800 tons per hour XRT-based sorting plant at the Umm Wu'al phosphate mine in Saudi Arabia.

This sorting application is a greenfield project located in Saudi Arabia close to the Jordanian border. The deposit contains silica in the form of silex, which imposed a challenge for milling and flotation. After extensive test work, Ma'aden came to the conclusion that XRT-based sorters would be the most beneficial solution for its new $560 million processing plant at Umm Wu'al. The plant is capable of processing 13.5 million tons of raw material per year.

The sensor-based ore sorters at Umm Wu'al sort more than 70% of the run-of-mine material by removing flint stones from the phosphate to reduce the silicon content. By this removal of waste material, the downstream process can be significantly downsized. The advantages gained include a smaller sorting plant footprint and considerably improved mill performance through the reduced consumption of energy, water, and chemicals per ton of final product. The applied XRT sorters have an operation width of 2.4 m, which allows processing of the feed of 13.5 million tons annually with nine units [93].

Figure 6 shows on of two parallel banks of sorters. The run-of-mine phosphate ore is screened and buffered in bunkers, before discharged and fed onto the XRT sorters. The parallel arrangement of machines to use the same two belts for discharging the drop and reject fractions is typical. The general arrangement with spacing between all machines, allows for the necessary maintenance access.

Figure 6. XRT-based sorters at Umm Wu'al phosphate mine, Saudi Arabia.

9.4. San Rafael Tin Mine, Peru

Despite the success of XRT-based sorting of tungsten ores and the often associated tin deposits, tin ore sorting was only tested in 2014, when it proved to be highly efficient for waste rejection at high tin recovery rates. This is enabled by the large crystallization of cassiterite (SnO_2), its high atomic density, and the favorable principle of XRT-based detection. The XRT sensor records the image of the planar projection of X-ray attenuation of the transmitted radiation. It has; therefore, a high advantage over the traditional density-based separation mechanisms, which rely on the differences of the specific density of whole particles to each other. These differences may be so marginal or non-existing, that Cassiterite concentration with densiometric processes is impossible unless the ore is further liberated. Contrary to this, the XRT image displays the two-dimensional atomic density distribution, and small Cassiterite inclusions become visible. This effect is also crucial for the success of XRT-based sorting in other applications, such as the tungsten ore or sulfide-associated gold ore in the previous chapters [67].

The San Rafael Mine is the largest underground tin mining operation in the world. The main methods of processing the ore are gravity separation and flotation. In 2016, a plant including XRT-based ore sorting was commissioned for waste rejection from a marginal development waste dump, now also treating low grade run of mine material from underground. Four COM Tertiary XRT machines process the feed in four parallel size fractions from 6 to 70 mm. Feed grade of approximately 0.6% tin is concentrated to 2.8% tin in the product, at recovery of 90% in about 19% mass yield to product. This enriched product fraction of the sensor-based ore sorting plan feeds to the wet section of the plant.

The plant, which is designed for 3000 tons per day (tpd), went into operation in 2016. Through incremental improvements and the addition of a secondary crusher to reduce circulation load on the primary crusher, the capacity has been further increased to up to 3700 tpd. San Rafael is not one of the largest installations, but it treats fine particle size fractions down to 6 mm, which reduces capacity per unit. Taking this into consideration, the units are delivering very good metallurgical performance at 200% of conventional feed capacity. Due to optimizations conducted on site, this is 50% above design capacity. The project is described here to highlight the second aspect of plant productivity—availability. Through continuous training and cooperation, operating, care, and maintenance procedures, both the metallurgical performance and the daily production rates were significantly increased.

In summary, the positive impacts are:

- Added value from previously sub-economic waste that can be mined with low cost;

- Increase of productivity of the main wet sections of the plant through lower p80 and increased plant recovery;
- Reduction of cut-off grade and increase in reserves;
- Reduction of environmental impact through reworking a potentially acid-forming waste dump.

The project was awarded the national prize for innovation in mining in 2017.

9.5. Renard Diamond Mine, Canada

A decade ago, near-infrared-spectroscopy (NIR)-based sorting was hugely successful in processing recycled plastic and paper streams with thousands of NIR-based sorters installed, but it had not yet been implemented in minerals processing. To assess the technical feasibility, a study was conducted which also explored the possibility to separate kimberlite from deleterious host rock [81].

Today, two reports have been published—one of them being a study for NIR-based kimberlite concentration at the Cullinan Mine in South Africa [78].

The flow-sheet was originally designed with large diamond recovery using an XRT-based sorter in the 16 to −45 mm size fraction, which is applied after the secondary crusher. The −16 mm feeds to the dense–medium separation. Concentrate from the large diamond recovery section and the dense–medium separation concentrate report to the final recovery stage.

The mine declared commercial production in January 2017. The team identified a process improvement via the installation of a NIR-based ore sorting circuit installed in front of the secondary (cone) crusher bin. In contrary to the Karowe Mine, which operates on XRT-based sorting technology only, the Renard Mine experienced significant non-kimberlite dilution in the plant feed. The capital was approved in August 2017, the project was designed and built, and it began operating in April 2018.

The objective of the ore sorting plant was four-fold: To minimize diamond breakage by removing hard rocks from the crushing plant feed; to upgrade the quality of the material to the process plant (i.e., increase the proportion of kimberlite to waste rock, such as felsic granite (Felsic/GR) and gneiss which are harder, barren rock types); to reduce the energy required for crushing (as the harder rocks have been removed); and to improve various circuit efficiencies throughout the plant.

The sorting technology uses a near-infrared sensor. The design focused on respecting a one-to-three size ratio (as in the feed fraction top size must not exceed three times the bottom size) reporting to the sorter, as well as ensuring the surfaces of the minerals were kept clean with wash screens and water sprays prior to the sorters. The ore sorting plant can be bypassed by switching the bypass chute (and operations are returned to the original design). This facilitated commissioning and start-up of the circuit, as well as providing operating flexibility.

Material reporting to the cone crusher bin is diverted to the sorter feed conveyor. The conveyed material feeds directly onto a double-deck screen, which sorts material into three streams: coarse (60–180 mm), medium (20–60 mm), and fine material (<20 mm).

The coarse fraction (60–180 mm) is directed to the primary ore sorting circuit. Material reports first to the primary ore sorter, which sorts it in two streams: accepts and waste. Waste material is fed (via primary scavenger feeder) to the primary scavenger sorter for a second sorting stage. The accepts are returned to the cone crusher bin via the accepts conveyor. The waste will be directed to the waste bin via the waste feeder.

The medium fraction (20–60 mm) receives material coming from the oversize material of the bottom deck and is sub-divided into two parallel and identical circuits. Each circuit is composed of a wash screen, which respectively feeds a secondary ore sorter. The screen undersize material reports to the dewatering screen. The sorters produce a "waste" stream and an "accepts" stream. Waste material proceeds to the secondary scavenger sorter for a second sorting stage. The accepts (from both stages) is returned to the cone crusher bin via the accepts conveyor. The waste proceeds directly to the waste bin.

The plant of the Renard Mine followed a McNulty Type 1 [94] start-up, which is characterized by reliance on mature technology, application of standard test-types of equipment, and meticulous pilot-scale testing on high-risk unit operations. It describes a fast ramp-up to design capacity, which was further exceeded by the installation of the NIR-based sorting plant [80].

9.6. Summary and Comparison of Lighthouse Installations

All lighthouse project installations resulted from a systematic testing and project development procedure and a positive risk assessment. But as for many innovative technology developments, there was always a burning platform, a specific challenge, that drove towards a favorable assessment and implementation, which finally got financially rewarded. Table 4 gives an overview on the lighthouse projects described in this manuscript. It can be seen, that in general, sensor-based ore sorting contributes to a higher productivity of mineral production systems across multiple segments and mineral applications. In addition, the reduction of operating costs and environmental impact.

Table 4. Summary of lighthouse installations.

	Main Challenge Leading to Implementation	Sensor Type	Size Range/Capacity per Sorter	Main Positive Impacts
Mittersill Tungsten Mine, Austria	Decreasing head-grade	XRT	16–30 mm/25 tph 30–60 mm/40 tph	Decreased cut-off grade and increase in reserves Increased flotation recovery Reduction of fine tailings Additional product: aggregates
Karowe Diamond Mine, Botswana	High density ore unsuitable for dense–medium separation (DMS) concentration	XRT	4–8 mm/30 tph 8–14 mm/60 tph 14–32 mm/120 tph 30–60 mm/175t ph 60–125 mm/ 250 tph	Large diamond recovery Replacement of DMS Reduction of diamond breakage Increased recovery Reduction of specific operating costs
Umm Wu'al Phosphate Mine, Saudi Arabia	High wear due to flint in phosphate	XRT	12–25 mm/50 tph 25–50 mm/100 tph 50–75 mm/150 tph	Reduction of wear in crushers and mill Reduction of the feed to the wet section of the plant Reduction of water and reagent consumption Reduction of fine tailings
San Rafael Tin Mine, Peru	Declining head-grade, environmental liability for waste dump	XRT	6–14 mm/20 tph 14–22 mm/40 tph 22–32 mm/60 tph 32–70 mm/100 tph	Reduction of cut-off-grade and increase in reserves Increased flotation recovery Reduction of fine tailings Elimination of an environmental liability
Renard Diamond Mine, Canada	High non-kimberlite dilution	XRT NIR	16–45 mm/280 tph 20–60 mm/60 tph 60–180 mm/ 150 tph	Large diamond recovery Increased recovery Decreased specific operating costs Increased plant capacity

10. Summary and Conclusions

The last decade has presented milestone achievements for the sensor-based ore sorting industry. It can be concluded that the market has identified and accepted the value that sensor-based ore sorting machines can add to operations in various mineral applications.

The increasing number of machines operating in the field and the developments described in this article have led to multiple steps being taken on the technology roadmap. Most notable is the development of the XRT-based sorting machines, which has seen a doubling of design-feed capacity as well as increased mean time between failures. However, the development of sensor-based ore sorting is not yet saturated on any front and we can expect more to come.

A repetition of machine installations, which mark the market entry barrier and technology readiness can been reported in the applications listed in Table 5.

Table 5. Possible applications of main sensors.

Sensors	Applications
X-ray luminescence (XRL)	Diamond recovery
Line scan cameras (COLOR)	Limestone concentration
	Magnesite concentration
	Quartz concentration
	Rock salt concentration
	Emerald concentration
X-ray transmission (XRT)	Diamond concentration
	Lithium ore waste rejection
	Cassiterite ore waste rejection
	Tungsten ore waste rejection
	Coal waste dump retreatment
	Apatite waste rejection
Near-infrared spectrometry (NIR)	Talc concentration
	Kimberlite waste rejection
	Fluorite waste rejection
Laser scattering (LASER)	Quartz ore processing

The industry is more than ever regarding sensor-based ore sorting as an option for the process route and takes it into consideration at the early planning stages of a project. The growing interest is expressed in ever increasing test work volumes at the test centers of the suppliers. The repetition of tests for similar ore types has led to standardization of test work procedures, which enables a common understanding in the industry as well as confidence in sampling statistics and repeatability.

It seems that the call expressed by Wotruba in 2006, in his presentation "Sensor Sorting Technology—is the minerals industry missing a chance?", to include sensor-based ore sorting as an option for all flow-sheet developments has been heard in the industry [30]. An increasing test volume on multi-ton scale confirms that the industry is developing serious and well-defined projects and is systematically and strategically pursuing business opportunities. These projects in development phase will eventually turn into operating installations.

For the next decade, no saturation in machine development or project development is expected. The next steps on the technology roadmap are an increasing number of high-capacity, multi-machine installations which will strengthen the trust in the technology. In parallel, the current development paths to decrease specific costs by increasing the capacity and availability of the equipment, as well as increasing the detection efficiency will continue.

As a next step, integrated sensor-based ore sorting and comminution circuits will evolve. Here, sorting steps with intermediate liberation will unfold the full theoretical potential that the technology can bring.

With trust and operational experience evolving, the vision of close-to-face waste rejection enabled by portable or semi-mobile sensor-based ore sorting will slowly become reality. Condition for this is that miners also adopt the technology and develop operational procedures to unfold its potential.

Sensor-based ore sorting is on its way to become a standard technology for physical separation, as the technology, its providers, and the operators mature. For some mineral applications, market development is completed and a repetition can be witnessed. In others, these lighthouse applications stand as an example that it is possible to profit from the technology, when professionally evaluated and eventually implemented.

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