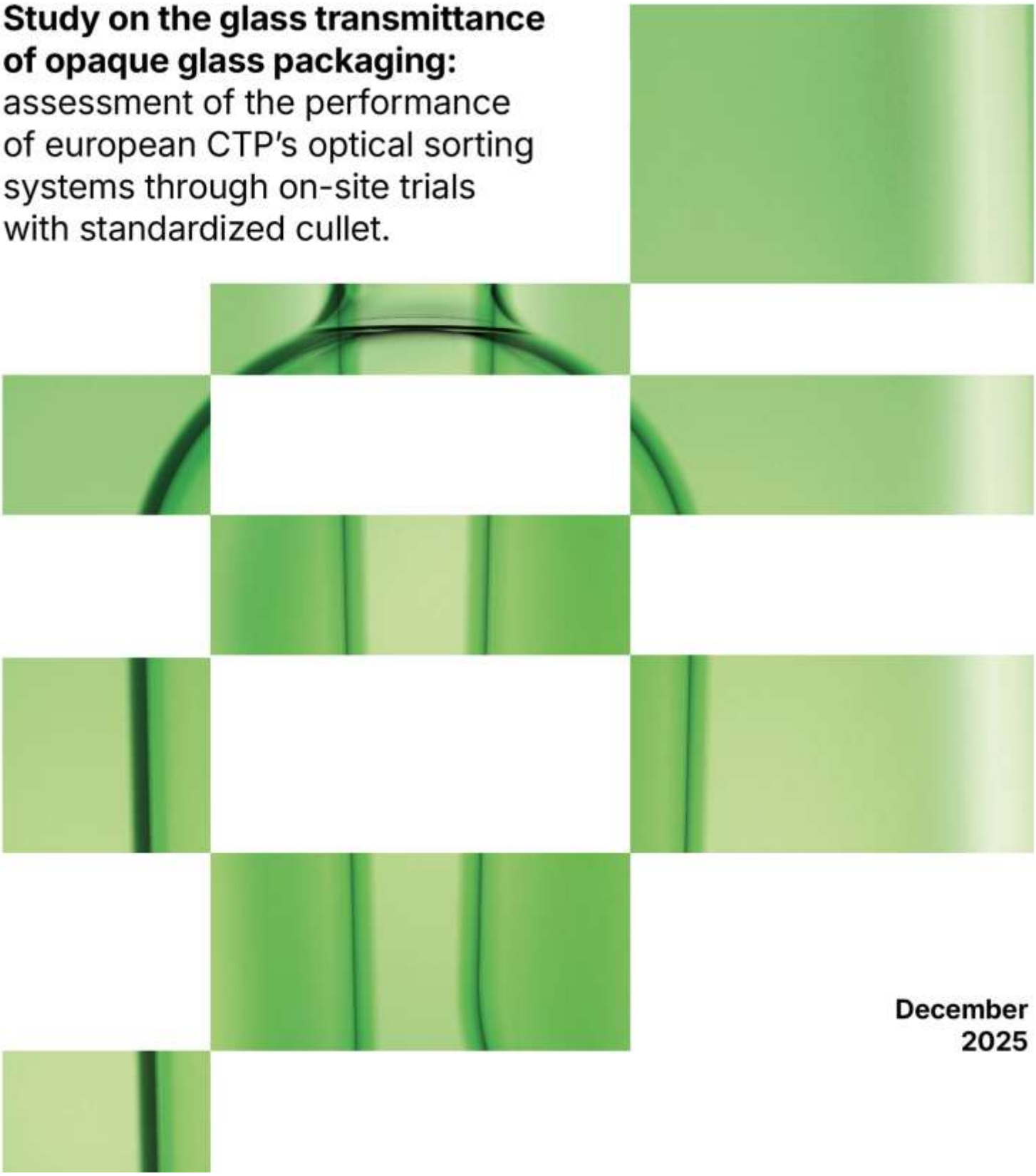
Study on the glass transmittance of opaque glass packaging: assessment of the performance of european CTP's optical sorting systems through on-site trials with standardized cullet.



December 2025

STUDY COMMISSIONED BY FEVE – THE EUROPEAN CONTAINER GLASS FEDERATION - AND CONDUCTED WITH THE OPERATIONAL SUPPORT OF FERVER MEMBERS

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1. Foreword and context introduction

Glass is a permanent material that can be recycled infinite times in a closed loop, without any relevant loss of quality in the process; thanks to both this underlying physical-chemical property and to a well developed material stewardship framework, soda-lime glass containers nowadays can generally be seen as one of the most advanced examples of packaging that is designed for material recycling, and is already actually recycled at scale throughout the European Union.

In fact, thanks to many years of awareness campaigns in the media, and of dedicated educational initiatives starting form as early as primary schools or kindergartens, today most European consumers know very well how to correctly dispose of end-of-service-life glass packaging; and thanks to important investment campaigns by Member States and their regional and local competent authorities, capillary infrastructures for the separate collection of glass waste have been developed and implemented in most countries of the Union. Therefore, once a glass packaging item (a bottle, a jar, etc) becomes a waste in the EU area, it is extremely likely that it will reach a Cullet Treatment Plant (henceforth CTP), becoming part of the site's raw input stream.

On the other hand, furnace ready cullet, which is the main output produced by CTPs by removing all foreign (i.e. non-glass) materials and contaminant components from the incoming raw cullet via a multi-step process, is a secondary raw material with product status[1] that is predominantly closed loop recycled (i.e. remelt by furnaces) to produce new glass containers with almost no limitations in terms of quality and quantity: bottles with up to 90 – 95% recycled glass in the batch mixture not only are technically feasible, but for certain market segments and geographical regions, they are also a well established and widespread production reality.

Therefore for a glass packaging item to be considered correctly Designed for Recycling, it is important that, in general, all design choices (type of components, materials of components, etc) are made in order to make the glass fraction of the packaging as easy

1 95% of the Furnace Ready Cullet processed by European Cullet Treatment Plants satisfy the Glass End-of-Waste Regulation 1179/2012, ensuring a closed loop recycling of glass packaging.

Sede operativa: Via Briati, 10 - 30141 Murano (VE)
T.+39 041.2737011
Sede secondaria: c/o VEGA Edificio Pegaso
Via delle industrie, 13 – 30175 Venezia Marghera
T.+39 041.5383108 • T.+39 041.5383112
P.I. IT04176390278 - spevetro@spevetro.it – **www.spevetro.it**

to separate from other materials/components as possible, and as easily recognizable as glass as possible by CTPs, that is rendering extremely unlikely that glass fragments are victims of false positive detection, that is of being erroneously recognized as non-glass (e.g. as ceramic pieces) by the machines installed in the treatment plants for the removal of contaminants.

Translating this general principle into explicit criteria and guidelines of design for recycling for all components of packaging mainly made of glass (e.g. bottles and jars for food and beverages' primary packaging) means identifying the specific provisions that minimize the negative impact of caps, labels, decorations, accessories, colours, etc on furnace ready cullet's final quality and treatment yield, based on the State of the Art of technologies installed in CTPs throughout Europe.

During the last couple of years this has been the main focus of two international technical committees of experts: the CETIE (*International Technical Center for Bottling and Packaging*) working group on Design for Recycling of Glass Packaging, and the CEN technical committee TC261/SC4/WG3 "Material Recovery", and in particular of its subgroup SG5: "Glass", that have worked on these topics with the final goal of drafting official European standards in support of the new Packaging and Packaging Waste Regulation (PPWR, Regulation 2025/40).

When the colour of soda lime glass packaging was taken into consideration under the Design for Recycling point of view by CETIE and, later, by CEN, the exchanges between technical experts of the glass recycling chain (e.g. representatives of producers of glass, of recyclers, of bottle fillers, of research centres, of sorting technology suppliers, etc) clearly highlighted that what is most important is not much the colour "tone" (green, amber, dead-leaf, etc), but the level of "opacity" of the colour.

In fact, if a glass fragment is very opaque as a result of a high thickness and intense colouration (i.e. high concentration of chromophores)[2], the optical sorting machines that are installed in CTPs to remove CSP (ceramics, stones, porcelain) contaminants from the stream of good cullet could "mistake" it for a ceramic piece, since the recognition of glass VS CSP is made on the basis of the visible light transmittance of the fragment. In particular, once the light transmitted through the glass piece, as detected in three narrow wavelength bands centered in the red, green and blue regions of the visible light spectrum, falls below a certain level, the recognition algorithm of the sorting machine can identify the fragment as CSP, and instructs the system to reject it with a shoot of compressed air.

This false positive rejection of good "opaque" glass, however, does not necessarily mean that the erroneously rejected material is lost from the glass recycling loop, because in the

[2] But the same would remain true also if the cause of the "opacity" was different, like the presence of an opaque label still attached, or of an opaque surface decoration.

State of the Art cullet recycling chain the fraction rejected by CSP optical sorting machines can be reprocessed (e.g. ground, sieved, etc) together with the finer raw cullet fraction to produce Glass Sand, a secondary raw material that can still be closed loop recycled to produce new glass containers, though with additional quantity and quality limitations with respect to furnace ready cullet.

Given these limitations above, Glass Sand can be considered a "Plan B solution" for recyclability, with the best case scenario remaining always designing glass packaging in such a way that the glass fragments obtained from waste containers in the recycling process are easily and correctly recognized as "good glass" by CTP sorting machines, and thus end up in the furnace ready cullet material stream.
For the same reasons, all those design choices that may lead to the false positive rejection of glass as CSP contaminant in CTPs, including in particular the "level of opacity" of said glass as a result of its opacity and thickness, which is the subject of the present study, have been given by the CETIE and CEN expert committees a "Yellow" classification in the relevant traffic light tables of Design for Recycling guidelines at present under discussion, meaning "limited compatibility with State of the Art recycling process".

Therefore, the construction of a standardized indicator expressing the "level" of visible light transmittance through the glass of a certain container, the definition of a standard method for the calculation thereof, and the identification of the appropriate limit value embodying the boundary between Green (meaning "full compatibility with the State of the Art recycling process") VS Yellow Design for Recycling traffic light table classifications, are all of crucial importance.

A clear *a priori* identification of what is the visible light transmittance "threshold" that leads to the erroneous rejection of good "opaque" glass as a false positive piece of CSP by optical sorting machines installed in treatment plants could not be achieved by the experts of the CETIE and CEN working groups, especially because throughout Europe the existing CTPs exploit machines of many different generations and produced by different suppliers (in turn installing different light sources and detectors), oftentimes with detection/rejection criteria specifically tailored to the incoming raw cullet of that specific plant, and their intricate layouts and workflows (e.g. how many machines in series reject CSP pieces, how many try to recover good glass from rejected material streams, etc) are extremely varied, and strongly impact the final CSP rejection rates of each site.

For this reason, FEVE decided to request to Stazione Sperimentale del Vetro to devise a project for the determination of a set of robust scientific experimental data that could support the estimate of a minimum transmittance value representative of the State of the Art of the whole European glass packaging recycling industry, and especially of the actual capabilities of the varied technologies and layouts implemented at present in the CTPs of the EU bloc.

2. General introduction to SSV's experimental approach: Pillar 1 and Pillar 2

Stazione Sperimentale del Vetro is the Italian National Research Centre on Glass, and has been active in the domain of glass recycling, cullet quality, recovery of cullet treatment by-products, glass sand characterization, exploitation and optimization, etc for many decades; in particular, SSV has provided technical, analytical and research support to Co.Re.Ve., the Italian official body overseeing and promoting the collection and recycling of glass packaging waste, since the early 2000s, and has therefore built a vast expertise on topics such as CTP technologies, cullet quality, main contaminants of furnace ready cullet and their accurate quantification, even in trace amounts, etc.

Moreover, during the last two years SSV has been developing for Co.Re.Ve. a research project focused exactly on the topic of Design for Recycling of glass packaging, exploring the factors that foster and hinder the correct detection of glass fragments as glass, their potential implications and impacts on cullet quality and treatment efficiency, and also identifying and studying the main streams of loss of good glass.

Strong of this knowledge and experience, when tasked by FEVE of investigating experimentally the transmittance threshold for correct identification of thick opaque glass as glass by optical CSP sorting machines of State of the Art European CTPs, SSV built an approach based on two pillars:

- Pillar 1: a method for the in depth characterization of the transmittance distribution inside a bottle, starting from accurate measurements of transmittance spectrum and of thickness distribution;
- Pillar 2: a campaign of experimental industrial scale on site trials in several CTPs from all over Europe, performing only the treatment steps relevant for CSP contaminants removal on hundreds of kilograms of purposely manufactured standardized cullet, aimed at determining the final CSP rejection rates achieved by the CTP when treating said cullet (the lower, the better the "correct detection performance").

In particular, three purposely manufactured cullet batches were created by crushing and sieving to the appropriate size range homogeneous lots of three different models of 750 ml bottles, having three different dark colour tones, one green, one amber and one UVAG, purposely chosen because their weight (all around 700g or more) and design (two sparkling wine bottles and one "premium" bordelaise bottle) meant a relevant part of their body was quite thick, and thus had very low visible light transmittance, therefore representing a "challenging" material for optical CSP sorting machines.

Hundreds of kilograms of homogeneous purposely manufactured cullet for each colour were manufactured, and were fed (one colour at a time, where possible) into the industrial lines of nine different European CTPs, in order to determine for each plant and each colour

what was the final CSP rejection rate when treating only the standard cullet. This way, it was possible to obtain an overview of the levels of "opaque glass detection capability" across all the CTPs at the study that was representative and equitable, since the testing materials were exactly the same for all, thus representing a reproducible "challenge" for optical sorting machines.

Those data were then cross referenced with the in depth characterization of visible light transmittance distribution in the three models of bottles that were used for the manufacture of purposely manufactured standard cullet for on site trials in CTP, allowing to correlate the experimentally determined CSP rejection rate data (i.e. the weight percentages of the input samples that were rejected as CSP contaminant for each site and colour) with the transmittance threshold value below which the optical sorting machines of each plant started to reject the thickest, most opaque fragments of the bottles at the study.

In the following pages the two "pillars" of SSV's approach will be described in detail, also reporting for each the relevant experimental data gathered during the study, where sensitive in anonymous form, following the confidentiality clauses pre-emptively agreed upon; subsequently, the core principles and assumptions for the elaboration and cross referencing of data will be reported, together with the final results of the project[3].

3. Pillar 1: SSV's laboratory method for light transmittance distribution measurements on bottles

The laboratory characterization protocol that will be described in the next few pages was originally developed by SSV for the Co.Re.Ve. research project on Design for Recycling of glass packaging, and at its core it is a relatively simple test method devised to determine how much of the weight (in %) of a certain axial symmetric (i.e. applicable to round bottles and jars) container has visible light transmittance below a given reference value, for example a potential "limit".

[3] Some choices had to be made to ensure the scientific robustness of the study while guaranteeing its practical implementation:

- Only mass-tinted bottles were selected;
- The bottles were new and free of any elements normally found in commercial packaging at the end of its life;
- No mixtures of glass and CSP (ceramic, stone, porcelain) were tested, which are difficult to prepare and standardise and make the interpretation of results too complex;
- After crushing of the bottles, the glass fragments were sieved to test the 10–35 mm fraction, which is the optimal fraction for optical sorting machines.
- Some testing was done on the optical inspection machines, rather than on the whole main line, but always replicating the modus operandi of the CTP (e.g. number and sequence of passes).

The approach starts with the experimental determination of the visible light transmittance spectrum on a coplanar, optical quality (plane parallel polished faces, no scratches or bubbles, no cords, etc), standard sized test specimen approximately 2 mm thick, obtained from the bottle under study by cutting, grinding and polishing.

The measurement is performed in air with an UV-VIS spectrophotometer, according to normal laboratory practice, and then the measured transmittance data as a function of wavelength are further elaborated to calculate an indicator of the "level" of opacity of the sample, following a procedure laid down in the CETIE voluntary standard DT41.20, also included in the draft of the future CEN official technical specification on test methods to determine the recyclability of packaging made of glass (informally called the "Glass DfR standard Part 2").

In particular, this indicator is calculated as the arithmetic average of the raw light transmittance values expressed in percentages and acquired in 5 nm steps, in the wavelength range between 430 nm and 650 nm, called the "Extended RGB range"; the definition of this indicator, sometimes referred to as "average light transmittance", and of this specific averaging interval (for example instead of the full visible light range), was decided within the CETIE working group on Design for Recycling of glass packaging, the rationale being this range encompasses closely the wavelength bands that industrial scale optical sorting machines' detectors exploit for the recognition of CSP VS glass.

Thanks to this spectrum acquired at a known standard thickness of 2 mm, by exploiting the empirical Beer-Lambert law it is possible to recalculate the transmittance vs lambda values at any different thickness X (and thus to "update" the average light transmittance indicator) following the formula:

$$Transmittance_{@\ X\ mm} = \ (Transmittance_{@\ 2\ mm})^{\frac{X}{2}}$$

This in turns allows to determine the distribution of values for the light transmittance indicator all over the body of a given container, provided a complete mapping of the bottle's glass thickness is available.

This latter could be acquired following many different approaches, e.g. from a tomography measurement, from a CAD 3D model featuring the nominal glass thickness distribution, from Hall Effect probe thickness measurements, etc, each one having its own characteristic degree of accuracy.

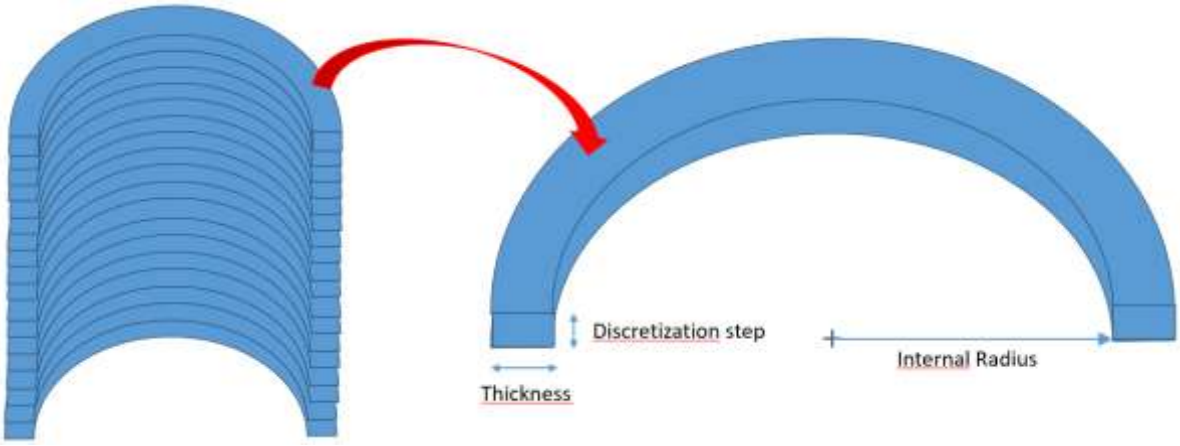
For this purpose, the method developed by SSV exploits image processing analysis on longitudinal sections of the containers at the study:

- the bottle is carefully cut longitudinally with a diamond impregnated saw, along a plane containing the vertical axis of rotational symmetry of the bottle;
- the glass “shell” (i.e. the cut surface) is painted white, while the central cavity of the bottle is masked with dark matte material, to enhance contrast;
- the picture is then elaborated by an image recognition algorithm, that maximizes contrast, draws the median line passing through the glass “shell”, divides it into a few thousands of small steps, then determines the thickness of the bottle for each point of the median line;
- additionally, the internal diameter is determined at regular intervals along the height of the bottle;
- to ensure better representativeness, this whole process is then repeated for several bottles of a given model, since their internal thickness and diameter distribution can vary to a certain extent.

With this wealth of data, it is possible not only to calculate the average light transmittance indicator value throughout the body of the bottle, but also to calculate the volume

percentage (and thus, also the weight percentage, since glass density is surely quite homogeneous) of glass that has thickness above any given value, and thus transmittance indicator below the corresponding value recalculated for that given thickness.

In fact, the image processing algorithm allows to "virtually" divide the bottle at the study into many vertically stacked "semi-ring" slices, having height = discretization step height, thickness = glass thickness for that step of the median line, and internal radius = internal radius of the bottle at that height, piled one on top of the other to "build" additively (like in a 3D printer) the body of the bottle[4].



Once a certain thickness value is selected, it is easy to determine how many "semi-ring" slices have thickness above that value, and by adding their individual volumes up, and dividing by the total volume of the bottle, it is possible to calculate the volume or weight percentage of bottle being thicker than that value.

4. Application of Pillar 1 to the bottles chosen for the study

The in depth characterization of the three models of bottles chosen for the study was the first step that was performed, since the accurate measurement of the thickness profile (repeated on several different individual specimens for each given bottle model) and of the reference transmittance spectra of the bottles were fundamental for the subsequent elaboration and interpretation of the data acquired from on site trials in CTPs performed with the cullet manufactured from those three lots of containers.

Below we report a series of pictures of the bottles chosen for the study, which were:

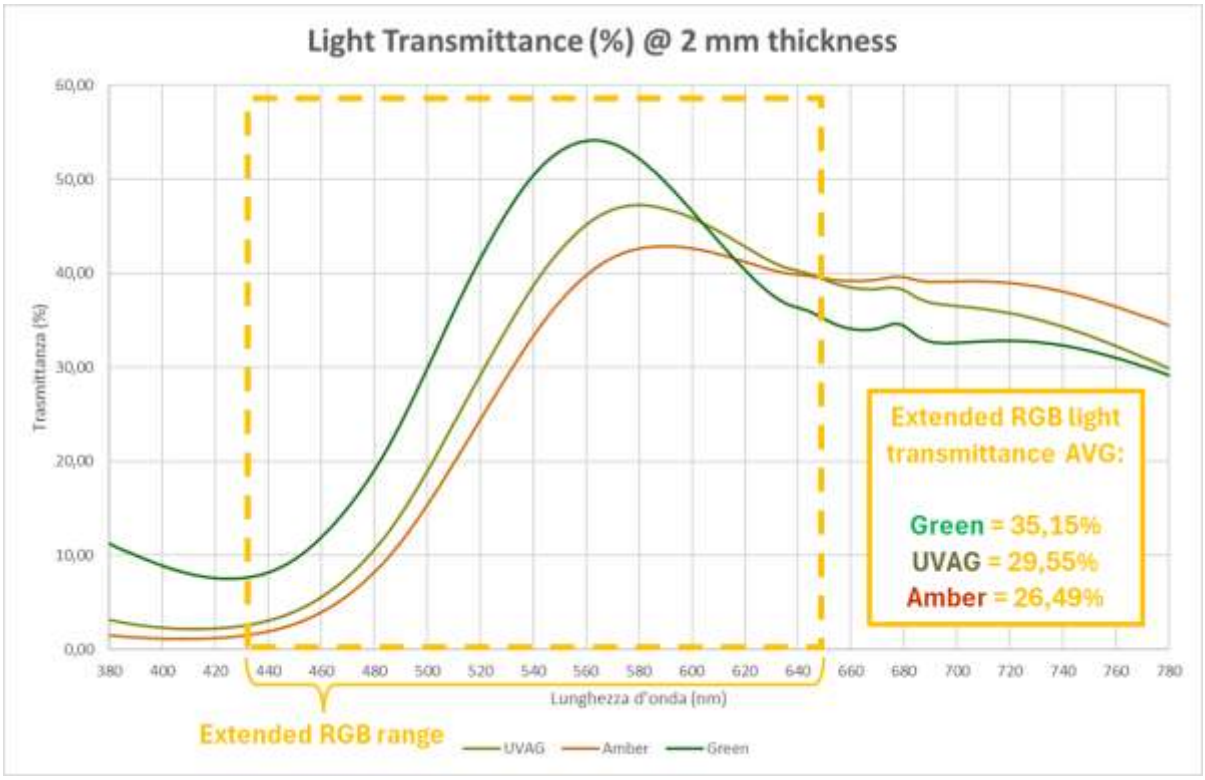
4 In even further detail, the half rings of the discretization steps from the start up to the center point of the median line (i.e. the center of the bottom of the bottle) "build" one half-shell of the bottle, and the half rings of the steps from the center to the end of the median line "build" the other half longitudinal section.

1. For Green colour: a 750 mL sparkling wine bottle with average weight of approximately 740 g
2. For Amber colour: a 750 mL sparkling wine bottle with average weight of approximately 685 g
3. For UVAG colour: a 750 mL premium *bordelaise* wine bottle with avg. weight of approx. 990 g

The models were purposely chosen because their thickness distributions featured some areas of very thick glass, especially in the bottom regions, where average transmittance indicator values were accordingly very low, and thus fragments from those areas were expected to be challenging for correct recognition by CSP optical sorting machines in CTPs. The three different colours were chosen to represent the typical colour "tones" of the vast majority of the "dark" glass market (other colours, e.g. blue, being extremely niche).

In particular, the choice of performing the study with three different glass colours was aimed at verifying if the actual "shape" of the transmittance curve, and especially the lambda position of its maxima, had an impact on the ease of correct identification of opaque glass fragments as "good" cullet by industrial scale CSP optical sorters, which

could be expected at least to a certain extent, since the RGB detectors installed in the machines have varied sensitivities/efficiencies in different regions of the visible light spectrum.



In the graph above the transmittance spectra acquired on 2 mm thick standard optical samples obtained from the three bottles at the study are reported, together with the values of the average light transmittance indicators calculated in the extended RGB range (highlighted with a yellow rectangle in the figure) from those spectra.

Based on the evidences above, for equal thicknesses, the green bottles at the study were the “less opaque” (i.e. having highest value for their average transmittance indicator); amber bottles were the “more opaque” (i.e. having lowest value for their average transmittance indicator); UVAG bottles were in between.

Seen from another perspective, this means that certain arbitrary values of average extended RGB light transmittance (e.g. 10%, 5%, 3%) are reached with smaller glass thicknesses by the amber glass at the study, and by thicker glass for the green bottles at the study, as reported in the following table.

CRITICAL THICKNESSES [mm] FOR AVERAGE TRANSMITTANCE ("avg T", calculated in extended RGB interval 430 - 650 nm, following CETIE recommendations) TO BE EQUAL TO 10, 5 or 3% "REFERENCE VALUES".

Crit. Thick. [mm] to have -->	avg T = 10%	avg T = 5%	avg T = 3%
UVAG color	4,55	6,35	7,70
Amber color	4,05	5,70	6,90
Green color	5,35	7,40	9,00

These data depend only on the SPECIFC COLOR of the three bottles of the study;

If we look at these data the other way around, this means that, for a fixed thickness value, amber has the lowest "extended RGB average transmission" value, and green the highest

Subsequently, several specimens of all the three bottle models under study were cut longitudinally and analysed with the image processing algorithm for thickness distribution measurements described above, thus laying the foundation works for the elaborations that will be described in the section dedicated to the interpretation of this project's experimental datasets coming from on site trials in Cullet Treatment Plants.

To provide a quantitative idea of the different thickness distributions of the three bottle models at the study, and of the corresponding distributions of light transmittance indicator values, we report here below a table where for each bottle model we show the weight percentages of glass in the container having light transmittance indicator below the arbitrary values of 10%, 5% and 3%.

WEIGHT PERCENTAGE OF BOTTLE HAVING AVG TRANSMITTANCE (extended RGB) BELOW THE 10%, 5% and 3% REFERENCE LEVELS

(that is having thickness LARGER than the critical values of the table here above)

%wt of bottle for which -->	avg T < 10%	avg T < 5%	avg T < 3%
UVAG (990 g)	92,5%	28,8%	11,8%
Amber (685 g)	46,7%	23,1%	17,4%
Green (750g)	39,7%	12,1%	7,1%

These data depend on BOTH the COLOR AND THICKNESS DISTRIBUTION of the three bottles of the study;

Even if this UVAG is a bit "less dark" than this Amber, the studied UVAG bottle has on average higher thickness than the studied Amber bottle, with the result that a large part of UVAG fragments are darker than Amber fragments.

In particular, the results are practically obtained for each [bottle ; transmittance value] pair by calculating the cumulative volumes of the "semi-rings" having thickness larger than the critical thickness values reported in the table, and by dividing them for the total volume of the relevant bottle.

5. Pillar 2: SSV's approach to on-site industrial scale trials in CTPs with standardized purposely manufactured cullet

As mentioned earlier, in order to derive an estimate of the "opaque glass detection capability" of the State of the Art CTPs of the EU region, and to be able to do so in the most fair, reproducible and scientifically reliable way, SSV deemed it was necessary to develop an experimental approach that could satisfy at the same time a certain set of core requirements, namely:

1. Since the optical inspection of glass cullet by CSP sorting machines is a "statistical/probabilistic" process, with many difficult to control parameters (e.g.

orientation of fragments, superimposition of fragments, level of "dirtying" of fragments by glass dust or whatever, etc) that can influence the final outcome of the process in terms of quality of the output (connected to how frequently false negatives = contaminants are let through as good cullet) and efficiency of the rejection (connected to how frequently false positives = good glass fragments are rejected as CSP), the approach needs to involve a statistically relevant number of fragments.

2. Since there is the need to acquire an overview of the *State of the Art* of the European CTPs, it is necessary to perform the study in several different plants from a number of EU Member States, especially focusing on the leading countries in terms of glass container production and recycling (i.e. at least Italy, Germany and France), investigating a wide range of technology suppliers, new VS old machines and plants, simple VS complex treatment workflows, many VS few steps of CSP sorting, etc.

3. It is necessary to challenge in a quantitatively reproducible (and thus fair) way all the treatment plants willing to participate to the study, and the testing material to be used for the trials should be tailored in order to be very difficult to be correctly identified by CSP optical sorters, so that the actual amounts of false positive rejected material (i.e. testing material mistaken for CSP) would be high enough that potential losses of testing material into the plant lines or contaminations of foreign material from the plant lines (which should also be minimized by appropriate strategies in the testing protocol) would have very little impact on the final calculated false positive CSP rejection rates.

4. The study needs to verify if the colour tone of glass has an impact on the "difficulty" of recognition of cullet fragments by industrial scale CSP optical sorting machines, and in doing so must explore colour tones that are actually representative of majority of the present day market of "opaque" glass containers.

5. Since the final goal of the study is to evaluate the opaque glass detection capability by the CTPs, and not by single machines/technologies, the experimental approach for trials must take into account all of the industrial treatment steps that deal with CSP contaminant rejection, including also potential recovery lines that inspect the CSP rejects in order to try to recover the good glass erroneously removed by compressed air jets (be it false positives = fragments targeted by the jets, or oversorting = "innocent victims" caught in the jets aimed at other fragments).

6. Since the picture of the State of the Art to be obtained from the study must be true to the actual treatment capabilities of EU CTPs, the relevant operational parameters (e.g. material input flow rate to the machines) and all the settings of the machines have to be representative of the "typical" setup of the plant, e.g. the one that is used most business days; in case the CTP tailored in a relevant way the setup to the incoming raw

cullet, the choice of the correct "normal" setup for the trials should be made upon inspection of the testing material by the plant personnel.

7. Since the trials should be performed preferentially on the industrial scale treatment lines, to assess the actual "real service life" performances in recognition of low transmittance glass by the CTPs, the amount of material to be tested and the number of operations to be carried out on site would need to be compatible with one or maximum two work shifts time, to reduce at a minimum the disturbance to the daily commercial operation of the hosting treatment plants.

The solution/approach proposed by SSV was to perform in 9 CTPs spread across Europe a series of industrial scale treatment trials, stopping the commercial operation of the plant for one shift, and feeding some hundreds of kilograms of standardized purposely manufactured cullet alone (approximately 100 kg for each of the three colours, working separately, i.e. sequentially colour by colour, everywhere possible), with fragment size mainly in the range 10 – 35 mm, into the "coarse cullet" main treatment line of the plant, and to simulate step by step on said material only the passages of the "normal"[5] treatment workflow that deal with CSP contaminants rejection or with recovery of good glass from CSP rejects, with the final goal of assessing the plant's CSP rejection rate when working on the purposely manufactured cullet of the three colours at the study.

This type of approach met positively all the theoretical requirements because:

1. Approximately 100 kg of this standard sized purposely manufactured cullet are made up of a few thousands of fragments, serving as a relatively robust statistical base for the inspection by the CSP optical sorting machines, even considering the case of recovery lines, that treat only the fragments rejected as CSP by the main line (all false positives in case of the trials with purposely manufactured cullet). In this case, in fact, even if "main line" CSP rejection rates of a few weight percentage points out of the total input material were experienced during the trials, still the recovery line machines would have to inspect at least a few kilograms of fragments (1 kg per every 1% of CSP rejection rate by the main line), and thus at least a few hundreds cullet pieces.

2. The sites where to perform the trials at the study were chosen and proposed by FEVE and FERVER to be as representative as possible of the present day European treatment plants, and were located in several member states of the EU, focusing especially on countries with strong glass container production and recycling industries, namely: Italy (3 plants), Germany (2 plants), France (1+1 plant in French-speaking Switzerland), Netherlands (1 plant), Czech Republic (1 plant).

[5] The workflow that "commercial" raw cullet undergoes therein, including multiple passes and recovery lines, when present.

Given their individual layouts, that will not be described or commented upon in detail in this report due to confidentiality and anonymity reasons, it is possible to state that the selected plants represent a nice sample of the present-day technological "landscape" of the cullet treatment industry, with some plants featuring very complex layouts and highly automated and integrated workflows, and others with very simple, few-passages-long treatment streams; some with brand new, highly advanced, latest generation inspection machines, others with simpler machines from older technology generations; some featuring only machines supplied by the leader of the market, others only machines supplied by the first runner-up, others a mix of the two, others machines from the third supplier in terms of market share; etc.

3. The choice of producing on purpose a triplet of controlled fragment size purposely manufactured cullet batches starting from homogeneous lots of three strategically chosen bottle models of three different colours (more information on the choice of bottles and on characteristics of the cullet is available in Section 4 and Section 6) allowed to provide a standardized, reproducible challenge to all 9 Cullet Treatment Plants.

   In addition, focusing on the fragment size range between 10 and 35 mm allowed to consider on one side the most "difficult" to inspect fragments (since larger fragments have higher probability of being thick, and thus to have low transmittance, compared to finer fragments), and on the other to still work on material that has dimensions fully within the nominal range of the material "normally" treated by the plant machines (in fact, larger pieces are typically intercepted and sent back to the crushing stage prior to reaching the optical sorters).

   Moreover, the combination of the 100 kg starting weight for each purposely manufactured cullet sample to be inspected, and of the abundance of low transmittance fragments in the standardized testing material, connected to both the high weight percentage of thick opaque glass in the bodies of the bottles crushed for the study and to the choice of a "coarser" fragment size range, made it possible to obtain sizeable quantities (a handful of kilograms at the very least) of CSP false positive rejects in almost all the hosting CTPs, so that the contaminations by "commercial" material already present in the lines or the losses of purposely manufactured cullet into the lines always had a very limited impact on the final results of the trials.

   In particular, to further avoid as much as possible losses and contaminations, the specific testing protocol applied in each CTP was purposely tailored by SSV technicians; the strategies employed changed site by site, and included, for example:

   - feeding the optical machines with the purposely manufactured cullet as close as possible to the machine itself, typically on the vibrating tables just upstream, by using

hand scoops, simulating as much as possible the normal "carpet density" of the input material (advice on optimal feeding rate was always requested to the plant personnel).

- recovering the pass-through and shoot-out material downstream the sorter as close as possible; most times this meant putting collection buckets, bins or sacks downstream the machine or its vibrating channels, but in one case it required to install collection bags directly INSIDE the machine body; sometimes the "good glass" fraction had to be intercepted before being discharged into the large heaps of commercial furnace ready cullet by putting the shovel of a mechanical shovel just below the outlet of conveyor belts or of chutes.

- avoiding as much as possible the passage of material inside step-chutes, in order not to lose standard cullet in their anti-abrasive-wear pockets; where impossible, sometimes step chutes were covered using plastic interlayers (the ones used to stack the various layers of bottles in a shipping pallet) as "slides" over the pockets; where even this was impossible, the pockets were cleared of "commercial" material at the beginning of the trial and then after each passage of standard cullet they were emptied again, to ensure that all the purposely manufactured testing material was inspected by the downstream machine.

- avoiding as much as possible bucket elevators, that are an important source of contaminations and losses, which often meant moving the material from one machine to the other using shovels, buckets and wheelbarrows, thus simulating "by hand and on foot" the normal workflow of the plant; for this reason, the standard cullet was always packaged into several 25 kg buckets, easier to handle than single big bags or crates. In one case avoiding the bucket elevator was not possible, therefore in that specific plant, to minimize the impact of losses and contaminations, the amount of purposely manufactured cullet used was doubled, and all 600 kg of glass fragments were fed together (i.e. NOT colour separated) to the plant lines; in that case, the information on individual colour false positive rejection rates was recovered after the test, by inspecting the "mixed-colour" CSP rejects obtained from the plant in SSV's laboratory, separating the three colours by hand on a light table.

4. The three bottle models' colours, as already mentioned in Section 4, were purposely chosen to investigate the different "response" of CSP optical sorting machines to the commercially relevant colours typically exploited for the manufacture of thick "opaque" bottles because of their filtering power against light radiation harmful for the product (e.g. UV and short wavelength visible light).

5. + 6. The specific approach to be followed to simulate during the trials the part of each CTP's workflow that was actually relevant for CSP rejection or for recovery of good

glass from CSP rejects was tailored on a site by site basis by means of in depth discussions on plant layout, machines, material streams, shooting logic (shoot on contaminants or on glass) and settings etc between SSV's technicians and hosting CTP's personnel. Such information is covered by confidentiality agreements and cannot be disclosed in this report.

7. The 100 kg per cullet colour sample size, for a total of 300 kg of standard material to be treated by the industrial lines of the plants, was chosen as best compromise between on one side the need for a large enough statistical basis for the trial and the need to keep potential contaminations and losses low enough to guarantee a satisfactory quality to experimental results, and on the other the opposite need to complete all the steps required for the test in maximum 8 to 10 hours. With a typical workflow consisting of 3 or 4 CSP focused treatment steps to be simulated and a typical team consisting of 4 or 5 people (1 or 2 of which usually from SSV), this timing was achievable.

In a couple of cases, either due to specific preference of the site managers, or to timing constraints, the test was performed only by the local plant personnel, without presence on site of SSV personnel; in these cases the testing protocol was nevertheless tailored together with SSV's experts, and the local personnel was thoroughly instructed in detail on how to best perform the study, what special cares to apply in the procedure, how to record the input and results of the test, etc.

6. Pillar 2: The three standardized purposely manufactured cullet batches prepared for the trials

The three large batches of purposely manufactured standardized cullet were produced by SSV by crushing and sieving to a defined grain size three homogeneous lots of new containers (never filled, capped or labelled) of three different models and colours of bottle; since 100 kg of "finished" cullet were required for each of the 9 CTPs hosting the trials, SSV acquired a couple of tonnes (3 standard sized pallets) of each of the three models of bottle chosen for the study (already presented in Section 4) and proceeded to crush and sieve the thus obtained fragments to an appropriate size range, chosen to embody as much as possible the material fraction that in treatment plants is treated by the "coarse cullet" line.

The choice of containers for the manufacture of purposely manufactured cullet, as anticipated in Section 4, was made taking into account that they needed to have at the same time two crucial characteristics:

- They had to be as critical as possible in terms of recognizability by optical sorting machines, that is they needed to have intense colouration (i.e. high concentration of chromophores in composition) and relevant portions of their body having high thickness, thus resulting in a lot of crushed material having low visible light transmittance values.
- But to ground the study into the reality of the cullet treatment plants, they had at the same time to embody examples of glass containers that play a statistically relevant role in the present glass packaging (waste) market in terms of shape (no bizarre geometries), size (only 750 mL, no Magnums or larger, since these latter represent a small niche production) and colour (no blues or blacks, that are again niche).

The crushing was performed in a controlled and reproducible way between the three lots of bottles, and the controlled fragment size was achieved by sieving the crushed materials between a large square mesh steel grid with 20 x 20 mm holes (having approx. 28 mm diagonal), and a drilled steel plate with circular holes of 10 mm diameter. The coarser material remaining on top of the square mesh grid was sent back to crushing, while the finer fraction passing through the holes of the drilled plate was discarded.

This way, the vast majority of the good output fragments obtained from the procedure had average size between 10 and 30 mm, with a few oblong pieces passing through the square mesh large grid having length around 35 – 40 mm.

Left: A bucket containing approximately 20 kg of UVAG standard purposely manufactured cullet; Right: 600 kg of mixed colours standard purposely manufactured cullet inside one sector of the shovel of a large mechanical shovel

For ease of handling during trials, the purposely manufactured cullet was packaged in plastic buckets each containing approximately 25 kg of single-colour material; 4 buckets

= approximately 100 kg per each cullet colour, thus 12 buckets for a total weight of 300 kg of cullet were used for each trial in CTP (except for the one plant where 600 kg were treated); in plants whose location was close enough to Italy for SSV technicians to travel via van, the testing material was brought along the same day of the trial; in more distant plants, or plants were the involvement of SSV's technicians during the trials was not welcome or not possible for timing issues, the material was pre-emptively shipped using heavyweight delivery services.

Thanks to the specific strategies implemented jointly by SSV and CTP plant personnel to keep contaminations and losses of testing material to a minimum, in most plants the treatment of the purposely manufactured standardized cullet led to the subdivision of the input material into a large quantity of "clean" furnace ready standard cullet, and a small quantity of CSP rejects, almost exclusively constituted by false positives, i.e. the thickest and most opaque fragments of the input purposely manufactured cullet mistaken by the machines for CSP pieces, with some minor contaminations by the plant lines (sometimes actual CSP, sometimes organic, sometimes labelled glass); in most cases the sum of the weights of the "good glass" and "CSP rejects" fractions came very close to the initial weight of the input cullet, meaning that losses into the lines were minimized.

Left: Steel crate collecting the "good cullet" fraction from the one mixed-colour trial performed during the study (some contamination by "commercial material" from the bucket elevator and plant lines is visible);

Right: "Good green purposely manufactured cullet" fraction collected inside the shovel of a large mechanical shovel during a single-colour trial performed during the study

Left: Steel crate collecting the "CSP rejects" fraction from a single-colour (green cullet) trial performed during the study, with a handful of contaminant pieces visible (real CSP, one organic piece, few labelled glass fragments);

Right: four samples of purposely manufactured cullet rejected as false positives by CTPs

At the previous page we report some pictures of the typical aspect of the "good cullet" and "CSP rejects" fractions obtained from the treatment of SSV's standard purposely manufactured cullet during the project's trials in Cullet Treatment Plants.

7. Experimental results obtained on-site from CTP treatment trials on standardized purposely manufactured cullet

From the campaigns of trials performed in the 9 hosting CTPs on the standardized purposely manufactured cullet produced for the study, it was possible to collect the following 27 anonymized quantitative data on colour-specific final CSP rejection rates by the plants. As a rule of thumb, lower results indicate a better performance by the CTP in correctly recognizing thick opaque glass fragments as "good cullet", while higher percentages indicate a higher rate of "detection mistakes" by the plants.

CSP Rejection rate [%wt]	Plant A	Plant B	Plant C	Plant D	Plant E	Plant F	Plant G	Plant H	Plant I	AVG
UVAG bottle 990g	4,6%	18,0%	2,4%	3,0%	30,8%	0,8%	5,7%	6,9%	4,2%	**8,5%**
Amber bottle 685g	2,2%	14,8%	4,4%	2,1%	22,1%	0,2%	3,6%	11,6%	4,6%	**7,3%**
Green bottle 740g	0,1%	14,6%	1,0%	2,2%	3,7%	0,5%	1,7%	4,9%	3,1%	**3,5%**

Tab 1: colour-specific CSP false positive rejection rates obtained in the 9 CTPs hosting the study's trials

To be more precise, the data reported above in Table 1 represent conservative (i.e. in excess) estimates of the False Positive CSP rejection rates of the various CTPs for the three colours of standard cullet at the study; in fact, the reported weight percentages include not only thick opaque fragments specifically targeted by the compressed air rejection jets (i.e. the actual false positives), but also some inevitable/physiologic effects connected to the "statistic" way industrial technologies perform optical inspection (to put it in the terms used by a plant technician during a trial, "it's like looking through a back-lit waterfall of cullet and shooting at opaque spots with a shotgun"), namely:

- The reported percentages include relatively thinner, not-so-opaque fragments that were "seen" superimposed, i.e. one in front of the other, by the detectors of the inspection machine, resulting in a longer "effective thickness" (i.e. longer optical path inside glass of the detected light ray) and thus in a lower effective light transmittance, low enough to trigger the rejection response. While the probability of having superimposed fragments in the stream of material being inspected is independent from its "opacity" level, the probability that superimposed fragments are individually "opaque enough" to be rejected when detected together is inversely proportional to the level of average transmittance of the treated material (i.e. more opaque cullet implies more shooting at superimposed fragments).

- The reported percentages include not-so-opaque fragments that were "seen" sideways by the machine, i.e. for which the optical path of the detected light ray inside glass was significantly longer than the actual fragment thickness, resulting in a lower effective light transmittance, low enough to trigger the rejection response. Once again, the probability of having fragments positioned sideways is independent from their opacity, but the darker the individual fragments on average, the more probable their rejection due to the lengthened optical path produced by their physiological "skewed" orientation.

- The reported percentages include not-so-opaque fragments rejected because of mirror edge effects, i.e. fragments appearing opaque due to reflection/deflection of light by their edge fracture surfaces.

- The reported percentages include the so-called oversorting, i.e. the "innocent victim" fragments that were rejected by the optical inspection machines not because of their individual opacity, but because they were accidentally caught in the compressed air jets together with the actual targets of the rejection. Oversorting is a physiological consequence of the way optical inspection machines reject contaminants, and, though mitigated by recovery lines, it cannot be completely eliminated.

Some observations on the data acquired through the experimental trials are reported here below.

The data of Table 1 exhibit a substantial degree of variability between different plants for each given colour, and also from colour to colour in the same plant: rejection rates as high as over 30% and as low as practically 0% were registered. On average, UVAG glass had a rejection rate of 8,5% with respect to the input material, Amber was rejected at 7,3%, and Green cullet was rejected at a level of 3,5%.

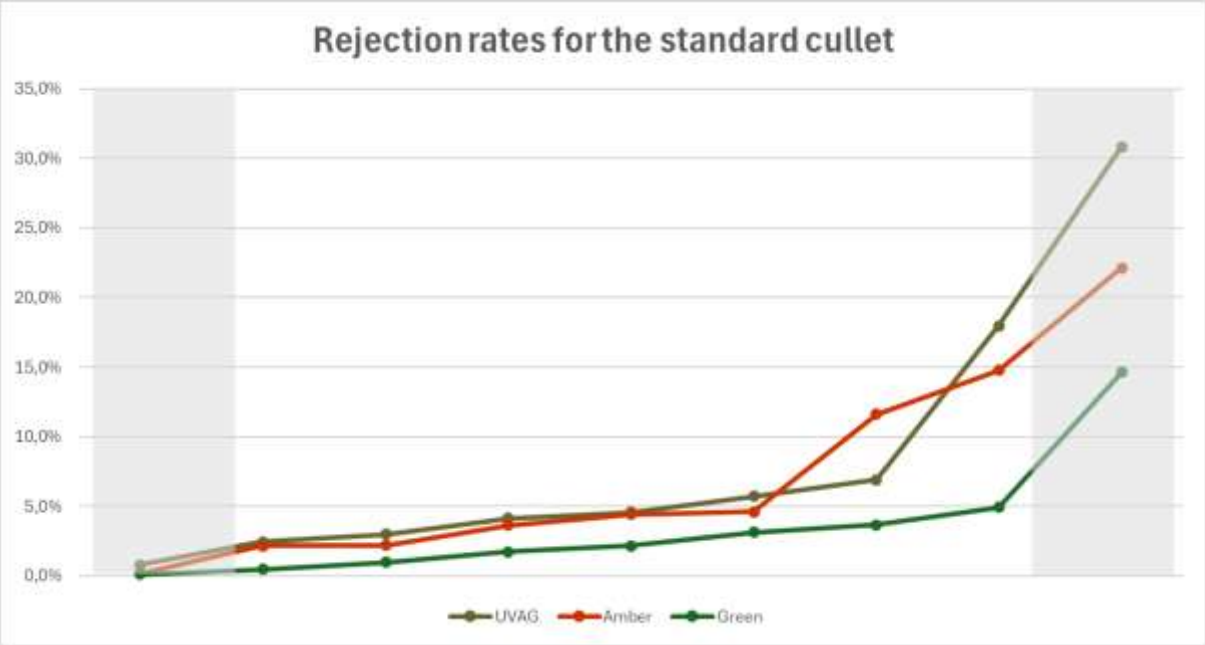
The individual CSP false positive rejection rates of green standardized cullet, be it because of the thickness distribution of the green bottle model, because of a relatively easier detection of green coloured glass compared to the other two colours at the study, or to both effects at the same time, were in general almost always found to be sizably lower than the values registered for amber or UVAG glass.

The highest rejection rates, and thus the worst performances in opaque glass "recognition", were measured in case of "older" CTPs like Plant A, characterized by simpler workflows, fewer treatment steps, older machines, less advanced detection technologies, etc, or in case of "modern" CTPs where the high quality levels imposed by the customers' technical specifications for the output cullet forced the plant to push the existing inspection equipment to very "strict" setups, like plant E.

In this latter case, in particular, it is evident that the installed optical sorting machines found it comparatively easier to recognize correctly dark green cullet (rejection rate around 4%), and more difficult to discriminate low transmittance amber or UVAG glass from high transmittance ceramics (e.g. thin/translucent porcelain), so to ensure extremely low CSP concentrations in furnace ready cullet (few ppm), they were forced to reject fragments starting from a relatively higher transmittance threshold, thus rejecting more material in the end. It is also interesting to note that in some plants on some standard testing materials (especially on green cullet) false positive rejection rates much below 1% were measured; in these cases, the few handfuls of fragments that were actually rejected are most probably more linked to statistic/randomic unfavorable detection events (superimposition, sideways, mirror edge, etc observation) on not-so-opaque fragments, rather than to the intrinsic absorption of light signal by thick opaque glass fragments: in fact, these false positive glass pieces were often qualitatively not much different in size, thickness and shape, from most fragments that were detected as good glass.

When the data of Table 1 are rearranged in ascending order colour by colour (thus losing the correlation with the plant where they were measured), building three so-called benchmarking curves, the final obtainable result are those reported in the Table below and in the graph at the following page.

	Tab. 2 Measured rejection rate data, ordered from smallest to largest, color by color								
UVAG	0,8%	2,4%	3,0%	4,2%	4,6%	5,7%	6,9%	18,0%	30,8%
Amber	0,2%	2,1%	2,2%	3,6%	4,4%	4,6%	11,6%	14,8%	22,1%
Green	0,1%	0,5%	1,0%	1,7%	2,2%	3,1%	3,7%	4,9%	14,6%



Graph 1: Benchmarking curves for the three sets of colour-specific experimental CSP rejection rates

From Graph 1 it is possible to observe that the bulk of the statistical distributions of experimental points is quite close-packed, with only one or two data points at the high-end extreme of the range being "far off"; moreover, given this specific far-from-Gaussian conformation of the data distributions, in most CTPs the opaque glass correct detection level was better than the average, so that the experimental CSP rejections rates were lower than the statistical average of the distribution in the 67% of CTPs for Amber and Green purposely manufactured cullet, and up to 78% of CTPs for UVAG glass (see coloured bars in Table 2).

8. Results interpretation principle: the link between CSP rejection rates and transmittance threshold

Having manufactured the three purposely manufactured cullet batches used for all the on site trials of the study starting from homogeneous lots of bottles of the same three models

allows to draw a direct correlation between the colour-specific CSP rejection rates measured in a given CTP and the corresponding transmittance threshold below which that CTP started rejecting good glass of that colour; in particular, the key to unlocking such correlation lies in the in depth knowledge of thickness and transmittance distribution values within the body of each bottle model, obtained through the application of the method of Pillar 1 described in Sections 3 and 4, and in a series of foundation assumptions, namely:

1. Since it is impossible to estimate precisely how many discarded fragments were rejected due to superimposition, orientation, mirror edges or oversorting phenomena, and how many were shot on purpose because they were actually individually "seen" by the machine as "too opaque" (the real false positives), we assume conservatively that all the rejected fragments were false positives.

2. Since the rejection by the machines is triggered by low transmittance values, we assume that the fragments of standard cullet rejected by the CTPs were actually the ones having the lowest transmittance levels in the models of bottle at the study.

3. we assume that the fragmentation of the bottles is perfectly random and all bottles are substantially identical, so that when we take into account the $X\%_{wt}$ of fragments that have the lowest transmittance inside the standard cullet, they can be considered to derive from the $X\%_{wt}$ "darkest" part of each bottle.

Given these assumptions all together, we can therefore infer that when in a CTP the false positive rejection rate measured experimentally from the trials when treating a certain colour of standardized cullet is $X\%_{wt}$, it can be extrapolated into a "conservative" scenario where this means it is the darkest, and thus thickest $X\%_{wt}$ of each single bottle of that colour/model that is being rejected.

And thanks to the detailed measurements of thickness distribution performed with the image processing method of Pillar 1 of the study, it is then possible to identify what is the critical thickness for which exactly the X% of the weight of the bottle of that model/colour has thickness higher than this critical value, and thus transmittance lower than the corresponding Lambert-Beer recalculated critical transmittance.

This latter critical transmittance value, that is the light transmittance indicator recalculated at the critical thickness, represents a conservative estimate of the minimum visible transmittance threshold for which the machines of the CTP started rejecting by mistake good glass, leading to a CSP false positive rejection rate of $X\%_{wt}$.

In particular, this transmittance threshold can be considered conservative because the colour-specific experimental CSP rejection rate by the CTP lines, that represents the starting point of the elaboration, was estimated slightly in excess, which in turn was

connected to two main reasons: first, because from the rejection rate (the $X\%_{wt}$) we did not deduct the oversorting and other statistic effects like superimposition of fragments, unfavorable orientation of fragments, etc, as already mentioned (see foundation assumption no.1); and second, because the experimental study with standardized purposely manufactured cullet was focused on the coarser fraction (10 – 35 mm) obtained from the crushed bottles, and not on the whole material obtained from crushing, which surely led to a slight overestimation of the rejection rates by CTPs, since the treated testing material was relatively "enriched" in difficult to recognize, dark-thick fragments.

9. Interpretation of experimental results from trials in CTP and laboratory measurements

To extrapolate from the available datasets a value for the minimum light transmittance threshold for the correct identification of thick opaque glass by CSP optical sorting machines that could be as representative as possible of the overview of the present average detection capabilities of State of the Art European CTPs, obtained from the 9 trials on site performed during the FEVE-SSV study, the first attempt at data interpretation/elaboration was made starting from the arithmetic averages of colour specific CSP rejection rates of Table 1.

Following the interpretation principle described in Section 8, the first step was therefore to determine from the Pillar 1 datasets regarding the thickness distributions inside the three models of containers at the study, which was the critical thickness T_{crit} inside each bottle model for which the weight percentage of glass being thicker than T_{crit} was exactly equal to the average experimental CSP rejection rate obtained for that colour of purposely manufactured standard cullet during the trials on site.

In fully explicit terms, by iterative calculation we looked for the critical values of thickness for which:

- The %wt of Green bottle glass being thicker than Tcrit was exactly 3,5% → $T_{crit\ green}$ = 9,8 mm;
- The %wt of Amber bottle glass being thicker than Tcrit was exactly 7,3% → $T_{crit\ amber}$ = 9,2 mm;
- The %wt of UVAG bottle glass being thicker than Tcrit was exactly 8,5% → $T_{crit\ UVAG}$ = 10,5 mm;

In particular, from the individual thickness distribution datasets obtained from each of the specimens of the same model of bottle that were cut longitudinally and image analyzed in the study for each colour, an individual $T_{crit_[colour]}$ was extrapolated; these values were then averaged colour by colour, yielding the above reported colour specific final results of critical thickness.

Subsequently, starting from the light transmittance data acquired on standard 2-mm thick optical quality specimens of the three colours of glass (see Section 4), by means of the Beer-Lambert law it was then possible to recalculate the transmittance spectra for the average $T_{crit_[colour]}$ thickness values, in turn allowing to calculate the corresponding extended-RGB-average light transmittance indicator critical values:

$T_{crit\ green}$ = 9,8 mm → critical transmittance @ $T_{crit\ green}$ = 2,3%

$T_{crit\ amber}$ = 9,2 mm → critical transmittance @ $T_{crit\ amber}$ = 1,2%

$T_{crit\ UVAG}$ = 10,5 mm → critical transmittance @ $T_{crit\ UVAG}$ = 1,0%.

Finally, with the aim of developing a colour-agnostic estimation of the Design for Recycling minimum transmittance threshold, the above reported colour specific values were averaged among themselves, leading to a final estimate for the minimum extended-RGB light transmittance indicator value for correct recognizability of opaque thick glass as glass in the average State of the Art European CTPs equal to:

Colour-averaged transmittance threshold for the correct recognition of opaque glass as glass in CTPs = 1,5%.

The above reported Design for Recycling transmittance threshold embodies the average capability of European present day CTPs in dealing with "opaque" glass, but since the experimentally acquired data highlighted a certain degree of statistical dispersion in the opaque glass recognition performances (i.e. in the CSP rejection rates measured on site) by the various CTPs that hosted the trials with standard cullet, an approach including also a sort of "confidence interval" was deemed interesting.

In this case, given the broad spread between the "core" of the statistical distributions of measured colour-specific CSP rejection rates and their maximum extreme values, as confidence interval it was decided to take into consideration the standard deviation of the datasets without the two extremes, i.e. calculated excluding the highest and lowest rejection percentages for each colour (hence the highlight in gray in Table 2 of Section 7).

The elaboration/interpretation of data was then repeated in a similar fashion to the one just described above, this time starting from CSP rejection rate values that were obtained by adding this additional "tolerance" to the colour-specific averages of Table 1, that is:

- For Green: 3,5% (AVG) + 1,6% (DEV.ST no extremes) → CSP rejection $rate_{w/\ tolerance}$ = 5,1%$_{wt}$;
- For Amber: 7,3% (AVG) + 5,0% (DEV.ST no extremes) → CSP rejection $rate_{w/\ tolerance}$ = 12,3%$_{wt}$;
- For UVAG: 8,5% (AVG) + 5,3% (DEV.ST no extremes) → CSP rejection $rate_{w/\ tolerance}$ = 13,8%$_{wt}$;

The corresponding critical thickness values for which the weight percentage of glass being thicker than T_{crit} was exactly equal to the above reported CSP rejection percentages (including the standard deviation "tolerance") was then calculated from image processing thickness distribution data; the results were:

- For Green, a CSP rejection rate$_{w/\ tolerance}$ = 5,1%$_{wt}$ corresponds to a $T_{crit\ green\ w/\ tolerance}$ = 9,3 mm;
- For Amber,a CSP rejection rate$_{w/\ tolerance}$ = 12,3%$_{wt}$ corresponds to a $T_{crit\ amber\ w/\ tolerance}$ = 8,2 mm;
- For UVAG, a CSP rejection rate$_{w/\ tolerance}$ = 13,8%$_{wt}$ corresponds to a $T_{crit\ UVAG\ w/\ tolerance}$ = 7,4 mm.

Subsequently, the transmittance spectra were recalculated for these critical thicknesses exploiting the Beer-Lamber empirical law, yielding the following new values for the extended RGB average light transmittance indicators for the three glass colours:

- For Green, from a $T_{crit\ green\ w/tolerance}$ = 9,3 mm → critical transmittance @ $T_{crit\ green\ w/\ tolerance}$ = 2,7%
- For Amber, from a $T_{crit\ amber\ w/tolerance}$ = 8,2 mm → critical transmittance @ $T_{crit\ amber\ w/\ tolerance}$ = 1,8%
- For UVAG, from a $T_{crit\ UVAG\ w/tolerance}$ = 7,4 mm → critical transmittance @ $T_{crit\ UVAG\ w/\ tolerance}$ = 3,3%

Finally, the above reported colour specific values of transmittance threshold (including a confidence interval) were averaged among themselves, leading to a final colour-agnostic estimate for the minimum extended-RGB light transmittance indicator value for correct recognizability of opaque thick glass as glass equal to:

Colour-averaged transmittance threshold for the correct recognition of opaque glass as glass in CTPs (including confidence interval) = 2,6%.

10. Conclusions

The experimental cullet treatment trials performed by SSV with hundreds of kilograms of purposely manufactured cullet of three colours in nine CTPs across Europe, coupled with the interpretation method connecting the CSP false positive rejection rates measured in those nine sites with the critical transmittance thresholds that triggered the rejection events, demonstrated that the examined cullet treatment plants have remarkable performances in discriminating between low transmittance glass and actual CSP pieces.

In particular, based on the experimental data gathered during the study performed on behalf of FEVE and with the support of plants from FERVER, SSV demonstrated that on average, CTPs are capable of correctly detecting thick, opaque glass as "good" glass up to extended-RGB average light transmittance indicator values as low as 1,5%, or 2,6%

when including in the evaluation also a confidence interval that takes into consideration the statistical spread of experimental data.

Given the specific elaboration method developed and exploited by SSV to extrapolate the above reported considerations, and especially by virtue of certain assumptions intrinsic to it (see Section 8), the values of average transmittance threshold obtainable from the experimental study represent conservative estimates of the actual present day detection/recognition capabilities by cullet treatment plants of the EU, and in particular in many State of the Art sites the correct identification of thick opaque glass as glass (and not as a false positive CSP contaminant piece) could be achieved by industrial scale CSP optical sorting machines for levels of average visible light transmittance even lower than 1,5%.

When the aim is to define a transmittance limit able to cover the vast majority of the tested plants, to be introduced in legislation on design for recycling, the experimentally determined values considered together with the applied confidence interval could support the proposal of a minimum transmittance threshold of approximately 2.5%.

MURANO
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R&D MANAGER
Ing. Simone Tiozzo

THE LABORATORIES DIRECTOR
Dr. Nicola Favaro