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Towards online Near-Infrared spectroscopy to optimise food product mixing

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1 **Towards Online Near-Infrared Spectroscopy to Optimise Food**

2 **Product Mixing**

3

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7 **Abstract**

8 This paper advances the use of in-situ Near-Infrared (NIR) spectroscopy as the basis for an in-line
9 control system to optimise mixing time of food powder blends. A non-contact NIR fibre-optic probe
10 installed in a conical screw mixer was used to scan three powder mixtures characterised by different
11 particle size distribution and component distribution. The current state of the art is extended by
12 comparing Conformity Index and Standard deviation of the Moving Block Standard Deviation
13 (MBSD), establishing the optimal pre-treatment combination and investigating the effects of the
14 mixture properties on the results. Products with a broad particle size distribution were more accurately
15 represented using derivatives rather than SNV and Detrending, while products with a broad
16 component distribution showed good results with all pre-treatments.

17 This study evaluated the effect of data pre-treatments on mixing time for different physical properties
18 of powder blends and provided a general guidance on the most appropriate pre-treatment.

19

20 **Keywords**

21 Powder mixing, Near-infrared, food, quality control, spectroscopy

22

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24 **1 Introduction**

25 Food manufacture is subject to many safety and quality regulations in order to reassure the
26 consumer that the product is free from any unwanted substance and provide customers with a
27 consistent quality. Quality inspection protocols need to be in place to ensure confidence that products
28 leaving the plant fall within safety regulations and customer specification. Effective quality control is
29 thus a preeminent consideration in the food industry in that it ensures customer satisfaction and safety
30 are achieved as far as possible.

31 The attention of this study will be directed towards powder blending processes which are very
32 common in the food industries (Cullen, 2009). Mixing time has to date been typically based on
33 experimental experience and generally extended far beyond the time when full homogeneity was
34 indicated to accommodate natural variability and perceived risk. Off-line testing by taking samples
35 from a vessel and then performing a destructive analysis have been the most common option to assess
36 the product quality, however this method is time-consuming and often error-prone. Samples are not
37 necessarily representative of the entire batch and the insertion of the thief probe disturbs the powder
38 bed, so compromising the sampling and resulting in an inaccurate measurement. Segregation issues in
39 the sample compartment may arise if the particle size distribution of the components is wide (El-
40 Hagrasy et al., 2001). In addition, results are typically obtained after the production is ended, so not
41 providing a prompt feedback in the case of deviation. A detailed literature review of powder mixing
42 and standard sampling procedures can be found in the work of Muzzio, Goodridge et al. (2003).

43 Recent studies focussed on the in-line monitoring of food powder blending processes and in
44 particular on the evaluation of blend uniformity. Process Analytical Technology (PAT) comprises a
45 series of tools for designing and controlling manufacturing processes online and has been employed
46 by several types of industries aiming at ensuring the final product quality and increasing the
47 efficiency. The recent developments and main challenges to adopting PAT in the food industry have
48 been discussed (Cullen et al., 2014).

49 Near-Infrared spectroscopy (NIR) is the most popular PAT system adopted as an inline method to
50 monitor the powder blending process. Radiation in the NIR frequency range hits the sample and

51 provides spectra containing information on molecular absorption of overtones and combination bands
52 (Burns and Ciurczak, 2008). These spectra used to be difficult to interpret since a single band may
53 result from several combinations of fundamental and overtone vibrations, but progress in
54 chemometric tools now makes it easier to decode spectra, relate them to sample properties and
55 recognise scatter effects (Reich, 2005). The first industrial applications of NIR spectroscopy were in
56 the 1960s with the work of Norris and Hart (1963) who measured the moisture of agricultural
57 products. From then on, NIR spectroscopy gained importance in industry especially because it allows
58 monitoring and controlling the process in real time, without being invasive.

59 Mixing time has been assessed for different blending processes: for instance, NIR probes were
60 applied to a modified V- blender (Sekulic et al., 1996), a Nauta mixer (Berntsson et al., 2002) and a
61 lab-scale blender (Blanco et al., 2002). Further applications can be found in the work of Blanco,
62 Cueva-Mestanza et al. (2012) which provided a good review of blending time assessment and a
63 detailed comparison of the different methods and pre-treatments. Given the great success of NIR in
64 estimating the end time of powder blending, this technique was also employed to monitor and
65 determine the end time of other processes. For instance, NIR was applied to a fluid bed granulation
66 (Alcalà et al., 2010), a red peony root extraction (Wu et al., 2012) and a pan tablet coating process
67 (Möltgen et al., 2012). All these studies proved the feasibility of NIR as an inline instrument to
68 monitor the production and optimise the mixing time. Other studies focussed their attention on the
69 optimisation of the parameters to obtain more accurate results. It was demonstrated that multiple
70 sampling points provide for accurate and precise estimation of mixing end points (El-Hagrasy et al.,
71 2001, Scheibelhofer et al., 2013). Critical factors affecting powder blending, such as humidity,
72 component concentration, blender speed, particle size and powder density were identified (El-Hagrasy
73 et al., 2005). The effects of temperature and moisture content on the dehydration behaviour of
74 different materials were studied (Räsänen et al., 2003).

75 With this study the aim is to advance the field by establishing the optimal pre-treatment
76 combination and investigating the effects of the mixture physical properties on the results.
77 Specifically, the main purpose is to evaluate the influence of the distributions of the components and
78 the particle size on the results and on the choice of the pre-treatment. The study subsequently also

79 aims to optimise the mixing time of food powder blends. Analyses were repeated using two different
80 methods in order to verify the assumption that the effects of the physical properties and of the pre-
81 treatments were not depending on the algorithm employed. Homogeneity analyses in this way will be
82 tailored depending on the specific product and its properties. This will increase the accuracy of the
83 analyses and provide a more reliable result. This paper thus describes how with deep process
84 understanding, sophisticated measurement and appropriate data pre-treatment, the approach to
85 assessing powder homogeneity in food mixing using NIR can be further improved.

86 **2 Materials and methods**

87 **2.1 Materials**

88 The formulation of the materials used in this study cannot be revealed due to industrial confidentiality
89 reasons, but all the information required to place the research advances outlined in context and to
90 underpin the justifications are described.

91 Bread and confectionery powder mixtures aimed at the bakery market were analysed in this study; the
92 main components were flour, sugar, gluten and salt. Three different products were taken into
93 consideration:

- 94 • Product A: a blend with a narrow particle size distribution and more than one main
95 component;
- 96 • Product B: a blend with a narrow particle size distribution and one main component that
97 counts for more than 90% of the mass;
- 98 • Product C: a blend with a broad particle size distribution and more than one main component.

99 Figure 1 shows histograms with particle sizes of Product A and Product C and provides the mass
100 percentage for each component. Product A component dimensions range from 0.1 mm to 0.5 mm and
101 thus the size distribution is narrow. However, Product C has a broad particle size distribution; from a
102 minimum value of 0.09 mm to a maximum of 10 mm. Dimensions thus vary by more than two
103 magnitudes. Mass percentages of Product B components are 93.22% , 5.08% and 1.71%.

104 2.2 Instrumentation

105 The experiments were performed using two conical screw mixers, each one equipped with a diffuse
106 reflectance fibre-optic probe. The fibre optic probe was installed on a side of the vessels at about 1.5
107 m from the bottom, which resulted to be the best physical location. The probe position is a
108 compromise between being sufficiently low in the vessel so as to scan blends at the starting of the
109 material loading phase, but not too low to prohibit installation welding requirements which need to be
110 undertaken from the inside of the vessel. Both blenders have a nominal capacity of 4000 l, are 3.52 m
111 high and probes are installed on a side of the vessel at about 1.5 m from the bottom. The screw orbit
112 arm rotates with a speed of 1.2 rpm, while the screw itself rotates at 70 rpm and at a distance of 5 mm
113 from the vessel side, so guaranteeing the glass probe cleanliness and avoiding powder remaining stuck
114 on it. Figure 2 shows the configuration of the conical screw mixer and how the NIR probe is
115 connected to the blender.

116 The fibre optic NIR heads contain two tungsten light sources which illuminate the sample. Scattered
117 light is collected by a thermo-electrically cooled InGaAs detector and guided via a 60 m long fibre
118 optic cable to the Bruker Matrix-F FT-NIR spectrometer. The probe outer diameter is 12.5 cm while
119 the nominal sampling diameter is 10 mm, which corresponds to a measurement area of 0.78 cm².
120 Spectral data were collected using OPUS software version 7.0 and analysed with Matlab version
121 R2014a. The spectral resolution was 16 cm⁻¹ and frequency region ranged from 10000 cm⁻¹ to 4600
122 cm⁻¹ (1000 nm – 2174 nm), resulting in 700 data points per sample. The sampling frequency was set
123 to 20 scans per spectrum and the total time between each spectrum was approximately 31 seconds.

124 2.3 Methods

125 Spectra were collected continuously during the whole production time from the point of loading the
126 first ingredient until the process was stopped. The fundamental assumption of the approach is that,
127 when the spectra are consistent and multiple spectral samples overlap each other, homogeneity has
128 been achieved. To support this assumption, off-line NIR probe tests were undertaken considering
129 known well-mixed ingredients, where the formulation was changed to test sensitivity, confirming that

130 concentration changes were apparent in the NIR signal. In addition, samples of the batches monitored
131 were also test baked and they all performed as expected, proving that their homogeneity levels were
132 sufficient to meet the product specifications. However, given that spectra are subject to noise, data
133 first need to be pre-treated before the analysis. Two methods were investigated to establish spectra
134 overlap: “Conformity Index” and “Standard deviation of the Moving Block Standard Deviation
135 (MBSD)”.

136 **2.3.1 Spectral pre-processing**

137 When dealing with solid samples, the data collected is largely influenced by light scattering: the Near-
138 Infrared light beam when hitting the powder sample is partially deflected by the solid particles
139 causing differences in the effective path length that in turn lead to significant variations in spectra.
140 Scattering effects are more likely witnessed in case of uncontrollable physical variations such as non-
141 homogeneous distribution of the particles, changes in refractive index, particle size distribution,
142 sample packing/density variability and sample morphology (Huang et al., 2010). Several pre-
143 treatments algorithms are available to remove scattering and in this study the most frequently applied
144 were considered. Since homogeneity analyses involve spectra belonging to different production
145 phases, and thus to different composition, only pre-treatments employing independent references and
146 isolating each spectrum from the dataset were considered.

147 *Derivatives*

148 Derivatives of spectra are calculated using the Savitzky-Golay algorithm. 1st and 2nd order derivatives
149 are most common: 1st order removes baseline change from spectra, while 2nd order also eliminates
150 linear trends across the spectra (Rinnan et al., 2009). Derivatives are very good at enhancing
151 differences between spectra and differentiate the overlapping signature, but they also increase noise.

152 *Detrending*

153 Detrending subtracts a polynomial fit from the original spectra in order to correct the baseline (Golic
154 and Walsh, 2006). The resulting spectrum is given by:

$$155 \quad X_{Dt} = X_{orig} - (a_0 + a_1\lambda)$$

156 where X_{DT} is the spectrum corrected with detrending, X_{orig} is the original spectrum, a_0 and a_1 are
 157 polynomial coefficients and λ is the wavelength.

158 *Normalisation*

159 The same weight is given to all the absorbances: each spectrum is in fact normalised to a length of 1
 160 by dividing it by the Euclidian norm (Rinnan et al., 2009).

$$161 \quad X_{norm} = \frac{X_{orig}}{\sqrt{\sum(X_{orig}^2)}}$$

162 where X_{norm} is the spectrum normalised and X_{orig} is the original spectrum.

163 *Standard Normal Variate (SNV)*

164 SNV normalises each spectrum to zero mean and unit variance by subtracting the mean of each
 165 spectrum and dividing by its standard deviation σ (Rinnan et al., 2009).

$$166 \quad X_{SNV} = \frac{X_{orig} - X_{mean}}{\sigma}$$

167 where X_{SNV} is the spectrum corrected with SNV, X_{orig} is the original spectrum, X_{mean} is the average
 168 value of the spectrum to be corrected and σ is the standard deviation of the sample spectrum.

169 **2.3.2 Conformity Index**

170 The Conformity Index (CI) was calculated as the difference between every single spectrum acquired
 171 and the target spectrum referred to the homogeneous blend; then this difference was weighted by the
 172 corresponding standard deviation σ on the respective wavelength.

$$CI_i = \frac{\text{spectra matrix}_{i,j} - \text{target spectrum}}{\sigma_i}$$

173 The Conformity Index has been used in previous studies to test the identity of the product and check
 174 potential unconformities (Bodson et al., 2006, Pestieau et al., 2014). The result is a second matrix
 175 where every column represents the difference between a single spectrum and the target one; for every

176 column the maximum values were calculated in order to create the vector describing the homogeneity
177 trend.

178 Target spectrum has to be representative of the finished product, hence spectra were collected at the
179 production end of multiple batches of the same powder blend and then averaged. All batches were
180 manufactured following the same production instructions: the mixing screw was activated at the
181 process start and raw materials are manually loaded into the vessel by operators while the screw is
182 rotating. Then when the loading phase is over, the screw is left rotating for a time which is specific for
183 every product and based on experience and is considerably in excess of what is required to attain
184 complete mixing. The number of the spectra included varied depending on the production frequency
185 and thus on the data availability. 50 spectra were used for Product A, 40 spectra for Product B and
186 100 spectra for Product C.

187 **2.3.3 Standard deviation of Moving Block Standard Deviation (MBSD)**

188 The standard deviation was calculated in both the wavelength and time domains. Initially the standard
189 deviation was calculated for every group of three consecutive spectra in the wavelength domain, so
190 forming the Moving Block Standard Deviation (MBSD) matrix. The standard deviation was then
191 calculated for each individual wavelength and the final vector obtained showed how spectra changed
192 over time (Sekulic et al., 1996).

193 The main advantage of MBSD is that it is calibration-free and thus it does not require a reference
194 spectrum. Hence analyses can be performed with no need of previous studies (Momose et al., 2011).

195 A block of three spectra in MBSD was found to be the optimal size after investigating how the block
196 dimension could impact on the results.

197 **3 Results and discussion**

198 In all the experiments the change of spectra over time was observed, eventually converging to the
199 steady state spectrum (see the example in Figure 3). The green spectra represent the beginning of the
200 production, when the blend was still under the level of the probe. The characteristic flat shape is due

201 to the fact that what is scanned in this phase is only the air present in the mixer. As air does not
202 contain any organic component, no relevant peaks can be observed in its spectra, therefore giving a
203 flat shape. As soon as the probe starts getting covered by the powder mixture, the spectra begin to
204 show a few peaks. This is represented by the blue spectra. The position of the peaks is related to the
205 different molecular groups, while the height of peaks depends on the concentration. Blue spectra are
206 shown to change over time indicating the composition is changing. In fact, during the process
207 different ingredients are added and blends are continuously mixed, leading to different powders being
208 scanned by the NIR probe. Spectra are seen to start to overlap after a certain time, as illustrated by the
209 red spectra. Since each sample of a given composition and concentration is uniquely identified by a
210 spectrum, the overlap demonstrates that samples of equal composition and concentration are being
211 scanned. As the powder is still being mixed by the screw, scans resulting in a near identical signal are
212 only possible if all the powder inside the mixer has the same concentration, thus indicating the blend
213 is homogeneous. Mixing time is therefore determined by the time it takes for the spectra to overlap
214 with each other and a steady state fully mixed spectrum is reached. Both methods, “Conformity
215 Index” and “Standard deviation of MBSD”, were applied to estimate this mixing time. Initially the
216 influence of pre-treatments on the calculation of mixing time was studied; subsequently it was
217 assessed whether the results of these homogeneity studies was affected by the physical properties of
218 the powder blend. The effect of component distribution was evaluated comparing results obtained for
219 Product A and B, while particle size distribution was studied by investigating the different effects on
220 Product A and C.

221 **3.1 Conformity Index**

222 The entire blend run was analysed employing different pre-processing techniques. Analyses were
223 repeated for 20 different batches to verify the reproducibility of the results. Blending profiles of
224 Conformity Index for Product A are shown in Figure 4.

225 Variations in profiles were observed when using pre-treatments, demonstrating the important role
226 of pre-processing algorithms in the estimation of mixing time. However, for all the experiments, an
227 overall qualitative behaviour was observed for four phases:

- 228 1) *1st stationary phase*: the profile is stable over time and its highest value is recorded. Powder is still
229 under the level of the probe and NIR is scanning only air which is very different from the final
230 powder blend due to both composition and state of matter. When loading the ingredients inside
231 the vessel, powder starts to disperse in the air phase, but not enough to determine any variation in
232 composition. The green spectra shown in Figure 3 represent this phase;
- 233 2) *Decreasing phase*: the CI suddenly decreases due to the powder approaching the probe level. NIR
234 starts scanning a powder mixture which is closer in composition and state of matter to the final
235 powder blend compared to the air phase. Referring to Figure 3, this phase illustrates the passage
236 from green to blue spectra;
- 237 3) *Oscillations*: the profile changes over time as a consequence of the variation in composition
238 during the production process. Spectra being scanned in this phase might present different peaks
239 due to new ingredients loaded into the vessel. The continuously rotating screw moves the powder
240 through the whole mixer, causing changes in composition even when loading of ingredients is
241 completed. Blue spectra shifting over time in Figure 3 describe the phenomenon of oscillations;
- 242 4) *2nd stationary phase*: the profile finally approaches the zero value and remains stable over time.
243 When spectral differences are no longer recorded, the scanned mixture has the same composition
244 and concentration of the ideal mixture. The stationary character of the results means the blend
245 composition is stable over time, hence it can be assumed that full homogeneity is reached. Red
246 spectra overlapping to each other in Figure 3 represent the 2nd stationary phase.

247 Mixing time is thus given by the starting point of the 2nd stationary phase, the sensitivity of detection
248 of which may change depending on the pre-treatment chosen. It is therefore of vital importance to
249 understand the effect of the different pre-treatments.

250 As can be seen in Figure 4, a plot of raw data (a) differs enormously from the ones obtained
251 following any pre-treatment: there is a peak in the 1st stationary phase and decreasing phase is soon
252 followed by 2nd stationary phase (starting at minute 4 in Figure 4(a)). Since it is unlikely that the blend
253 reaches the homogeneity soon after the powder mixture reaches the level of the probe, it is concluded
254 that raw data do not describe the process satisfactorily. Scattering effects in fact dominate when the

255 blend is under the level of the probe as a relatively small quantity of powder particles is dispersed in
256 the gas phase and NIR light deviates from the original path length. All pre-processing algorithms
257 studied (first and second derivatives, normalisation, SNV, and detrending) contribute to removing
258 scattering effects and to make the homogeneity starting point more distinct (Figure 4 b-f).

259 In order to investigate the effect of component distribution on choosing the right pre-treatment, the
260 same study was performed on Product B, which presents a very small variability given that more than
261 90% of the product is represented by the same component. The Conformity Index was evaluated for
262 18 different batches of Product B. Figure 5 presents the blending run profiles obtained for Product B.
263 None of the pre-treatment methods studied were able to reliably estimate mixing time due to the
264 oscillation phase not being accentuated sufficiently and thus being confused with the 2nd stationary
265 phase. Changes in composition are not easy to detect as a consequence of the reduced component
266 distribution of the product. The Conformity Index was shown not to be a suitable method for
267 measuring mixing time of blends with concentrations of a single component higher than 90% given
268 the lack of variability in the mixture.

269 In order to study the effect of particle size distribution on the pre-treatment choice, Conformity
270 Index analyses were performed on Product C. Calculations were repeated for 29 different batches of
271 Product C and an example of the results obtained is shown in Figure 6. The first notable difference
272 compared with profiles of Product A is the presence of high peaks during the oscillation phase at 11
273 minutes. Before this all the ingredients in the vessel had a similar nature and a similar particle size.
274 Soon after the introduction in the mixer of particulates almost 100 times larger than the other
275 components, the blend became more heterogeneous presenting parts of only fine powder and parts of
276 only particulate. Peaks at 11 minutes represent the variation when scanning the different parts of the
277 blend (fine powder and particulate). After these few peaks, the oscillation phase returns to that
278 exhibited prior to the addition due to the continuous movement of the screw acting to mix all the
279 ingredients (redistributed fine powder and particulate making the mixture homogeneous). Pre-
280 treatments such as SNV and Detrending show slight oscillations in the 2nd stationary phase, making
281 the homogeneity starting point less clear. Better results were achieved by derivatives, especially
282 second derivative, as the 2nd stationary phase was flatter and it was more evident when the oscillation

283 phase ends. Due to the greater variability introduced by the increase in particle size distribution, the
284 system was more heterogeneous and differences in spectra were enhanced. Pre-processing such as
285 SNV accentuated these differences even when the mixture was homogeneous: the stationary phase
286 was more oscillatory and it was more difficult to clearly assess mixing time. Derivatives on the other
287 hand were less sensitive to these variations and still clearly showed the start of the 2nd stationary
288 phase, so defining the mixing time. Since Product C is characterised by a broad particle distribution,
289 in order to assess its homogeneity, the distribution of particle sizes cannot be ignored. Techniques
290 such as SNV and Detrending were actually born to reduce particle size effects (Zeaiter et al., 2005)
291 hence they might be less suitable to analyse products with broad particle distribution. Derivatives, on
292 the other hand, retain the effects of particle size contained in a NIR spectrum. These results were
293 confirmed by a previous study determining the particle size distribution of a solid product: calibration
294 models built by pre-treating data with SNV achieved higher errors than by pre-treating data with
295 second derivative (Blanco and Peguero, 2008). Table 1 shows mixing time results for Product A and
296 Product C obtained using different pre-treatments.

297 Results obtained analysing blending run profiles using different pre-treatment techniques
298 demonstrated the importance of data pre-processing in the Conformity Index studies. In addition,
299 considering different product categories demonstrated how the choice of pre-treatment actually
300 depends on the properties of the powder blend. In order to set up a general method valid for every
301 product, the best option is to adopt a combination of pre-treatments, rather than relying on just one
302 technique, in order to obtain all the advantages provided by each algorithm. Normalisation was taken
303 into consideration as for all the experiments it proved to be best for the removal of initial scattering
304 effects which cause unwanted peaks after the 1st stationary phase. On the other hand it also flattens
305 oscillations making mixing time less evident, so other pre-treatments able to accentuate differences
306 need to be used together with Normalisation. Two combinations were studied: Normalisation + SNV
307 + Detrending and Normalisation + 2nd derivative. Results are presented in Figure 7. Product A mixing
308 time can be clearly estimated using both combinations (Figure 7 (a), (b)), but homogeneity of Product
309 B cannot be analysed properly by any of the combinations employed (Figure 7 (c), (d)). The blend
310 appears homogeneous as soon as the powder reaches the probe (minute 12), due to the extreme

311 component distribution. Product C mixing time can be estimated accurately using Normalisation +
312 derivative, but not by Normalisation + SNV + Detrending (Figure 7 (e), (f)). The large variation in the
313 particle size distribution of Product C is in fact responsible for the increase in variability, and SNV
314 and Detrending accentuate these differences excessively, causing oscillations also in the 2nd stationary
315 phase. Table 2 provides mixing time results for Product A, B and C obtained using pre-treatments
316 combinations of Normalisation+SNV+Detrending and Normalisation+1st derivative.

317 When analysing and test baking production samples, the time provided by
318 Normalisation+SNV+Detrending and Normalisation+1st derivative for Product A (33.25 minutes)
319 was estimated to be the mixing time of the batch analysed, which resulted in saving 26% of the total
320 time the product was mixed (45 minutes). While for Product C, time provided by Normalisation+1st
321 derivative (46.67 minutes) was estimated to be the mixing time of the batch analysed, so saving about
322 22% of the total time the product was mixed (60 minutes).

323 Normalisation + SNV + Detrending gives all the benefits provided by these three techniques:
324 initial scattering is removed, the oscillation phase is emphasised and the homogeneity starting point is
325 clearly detectable. This combination can be generally used for products with average or narrow
326 component distribution, but not for products with a single component concentration higher than 90%.
327 For this kind of material, represented here by Product B, the Conformity Index cannot be used reliably
328 to estimate the mixing time. Concerning particle size distribution, the preference is to employ
329 Normalisation + derivative as differences would be accentuated too much by SNV-Detrending due to
330 the high variability involved in these products.

331 **3.2 Standard deviation of Moving Block Standard Deviation (MBSD)**

332 Following analysis using the CI, the entire blend run was re-analysed with MBSD and different
333 pre-processing techniques in order to evaluate their effects. The same batches used to test the validity
334 of Conformity Index were further analysed using MBSD. Again the plots can be generally divided in
335 four parts, looking very similar to those seen for the Conformity Index. The only difference is given
336 by the high peak replacing the decreasing phase: standard deviation comes through a big rise due to
337 the significant change in composition recorded when powder approaches the probe level. Mixing

338 time, as with “Conformity Index” analysis, corresponds to the starting point of the 2nd stationary
339 phase.

340 Products A, B and C were analysed and compared in order to investigate the effect of component
341 distribution and particle size distribution when pre-treatment approaches are applied with the Standard
342 deviation of MBSD. Blending profiles of Standard deviation of MBSD for Products A, B and C using
343 the pre-treatment combinations Normalisation + SNV + Detrending and Normalisation + 1st derivative
344 are compared in Figure 8.

345 The same pre-treatment effects as found for the CI were found with MBSD, despite the two methods
346 focusing on different aspects. Product A was well described by both Normalisation + SNV +
347 Detrending and Normalisation+1st derivative as can be seen by comparing the plots in Figure 8 (a) and
348 (b): same mixing time was estimated. Product B could not be analysed employing any of the pre-
349 treatments or their combinations (Figure 8 (c) and (d)), and Product C could only be analysed using
350 Normalisation + derivative (Figure 8 (e) and (f)).

351 **3.3 Control program**

352 A program was developed to automate the homogeneity assessment into the factory control
353 systems in order to provide on-line indications of the mixing extent for the production process and
354 ultimately move to in-line control. A model for Conformity Index was built using the specific
355 application in OPUS software; for every product the target spectra were loaded and the best pre-
356 treatment combination and frequency range were specified. A lower limit of maximum Conformity
357 Index combined with a time under the limit criterion was used to indicate homogeneity. A script was
358 written using a text-based programming language in OPUS: the program includes one main program
359 and a sub-program that is called by the main program to calculate the time spent below the lower limit
360 of CI. The control program starts when the loading phase is over: the main script is initially run and
361 spectra are continuously collected during the mixing phase. For every scan, CI is calculated using the
362 model previously built and a check is made to ascertain whether the value is below the lower limit
363 previously set. One possible practical issue arises due to the oscillatory nature of the signal as a
364 consequence of mixing before homogeneity is achieved. As homogeneity approaches, the signal may

365 fall and rise repeatedly around the threshold. To avoid this issue, the program continues running until
366 consecutive values of CI under the lower limit are obtained for a specified time window. If the CI falls
367 below the limit and subsequently rises above the limit before the time limit criterion is satisfied the
368 blend cannot be considered homogeneous and the time counter is reset. This time was set to a value of
369 5 minutes. This was determined through experience and behaviour of the historical batches. Once the
370 signal remains below the threshold for the specified time, in this case 5 minutes, the program is
371 stopped and a message is displayed on the screen indicating that the blend is homogeneous and the
372 process can be stopped.

373 A possible situation could arise if the signal is noisy in that it may repeatedly fail to reach the time
374 criterion due to signal noise. For practical operational reasons, a limit is set based on existing over
375 cautious settings and, if 15 minutes has passed, a message is displayed saying that homogeneity
376 cannot be established.

377 Applying this control method to the data of the batches previously produced, it was evaluated that
378 up to 15 minutes of unnecessary blending and up to a third of the total batch production time can be
379 saved. This can lead to an increase in the productivity of about 33% with consequent benefits on the
380 profits.

381 **4. Conclusions**

382 The Conformity Index and Standard deviation of Moving Block Standard Deviation (MBSD) both
383 demonstrated their capability to determine homogeneity and they indicated the same mixing time.
384 Blending run profiles are quite different, but both can be divided in four parts: the last part being a 2nd
385 stationary phase whose beginning indicates the homogeneity starting point.

386 Raw data were not able to accurately determine the mixing time due to scattering effects obscuring
387 important information. Blending profiles generally improved by pre-treating data, in particular
388 derivatives were preferred for products with broad particle size distribution, as oscillations were less
389 enhanced and starting of 2nd stationary phase was more evident. Derivatives indeed retain the effects
390 of particle size contained in the spectra which need to be considered to assess the homogeneity of
391 products with broad particle size distribution. Neither the Conformity Index nor the Standard

392 deviation of MBSD were able to provide satisfactory estimates of the mixing time for products
393 characterised by a very narrow component distribution. These products show a high concentration of
394 one of the components (>90%) and none of the pre-treatment methods used nor their combinations
395 appeared to improve the mixing time predictions. Other methods need to be found to assess
396 homogeneity in products with a very narrow component distribution.

397 The study was performed using one type of mixer and three materials and it provides a general
398 guidance on the choice of pre-treatment based on particle size distribution and component distribution
399 of the material. Employing a different blender will surely affect the mixing time results, but should
400 not modify the target spectrum hence differences in mixing time evaluation process for the same
401 material should not be relevant and same pre-treatment should be applied. On the other hand, the use
402 of a different powder blend requires a prior investigation of the best pre-treatment before determining
403 the mixing time since particle size distribution and component distribution do not fully describe the
404 material. The amount of time and effort required to optimise pre-treatment mainly depends on the data
405 available, hence on the production frequency of the material under investigation. Mixing time
406 evaluation of products frequently manufactured will require a shorter time and a smaller level of
407 effort. The cost of operation will increase in an initial phase mainly due to more resources needed to
408 perform the analysis. However, after the model assessing mixing time has been built, this would only
409 require maintenance and operation costs will decrease. As the method is deployed in the factory,
410 experience will determine the breakeven point balancing increased initial resource against long term
411 mixing time savings. Such financial considerations are confidential to our collaborating company but
412 suffice to say role out of the technology is ongoing.

413 This study revealed the still unexplored effects of particle size distribution and component
414 distribution on the choice of the pre-treatment so representing a further step in the evaluation of
415 mixing time using Near-Infrared spectroscopy. Awareness of these properties and their effects allows
416 optimisation of blending time and helps reducing the risk of under/over-mixing.

417 Acknowledgements

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422

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Histograms with particle sizes of Product A (a) and Product C (b). Mass percentages of each components are reported at the bottom of the histogram. Product A components dimensions are similar to each other, while Product C presents a larger variability.

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Conical screw mixer configuration. (a) Configuration of the conical screw mixer. (b) Connection of the probe to the blender.

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Example of spectra collected during the production phase. Green spectra are recorded when the powder is still under the level of the probe. Blue spectra show powder reaching the level of the probe. Red spectra represent the homogeneous mixture.

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Profiles of Conformity Index calculated for Product A. Data were first pre-treated using different pre-processing techniques, and then Conformity Index was calculated. The vertical line represents homogeneity starting point according to the different pre-treatments.

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Blending profiles of Conformity Index calculated for Product B. Data were first pre-treated using different pre-processing techniques, and then Conformity Index was calculated.

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Blending profiles of Conformity Index calculated for Product C. Data were first pre-treated using different pre-processing techniques, and then CI was calculated. The vertical line represents homogeneity starting point.

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Comparison of pre-treatment combinations for Products A, B and C. Data were first pre-treated using Normalisation+SNV+Detrending and Normalisation+2nd derivative, and then Conformity Index was calculated. The vertical line represents the homogeneity starting point. Where the vertical line is missing it was not possible to determine the mixing time.

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Comparison of pre-treatment combination for Products A, B and C in Standard Deviation of MBSD analyses. Data were first pre-treated using Normalisation+SNV+Detrending and Normalisation+1st derivative, and then Standard deviation of MBSD was calculated. The vertical line represents homogeneity starting point. Where the vertical line is missing it is because it was not possible to determine mixing time.

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Mixing time results for Product A and Product C using different pre-treatments

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Mixing time results for Product A, B and C using pre-treatments combinations of Normalisation+SNV+Detrending and Normalisation+1st derivative

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	Raw data	1st derivative	2nd derivative	Detrending	Normalisation
Product A [min]	4.08	25.08	30.33	25.08	25.08
Product C [min]	20.42	47.25	41.42	47.83	-

Table 1: Mixing time results for Product A and Product C using different pre-treatments

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SNV
27.42
-

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	A	B	C
Normalisation+SNV+Detrending	33.83	-	-
Normalisation+1st derivative	33.83	-	46.67

Table 2: Mixing time results for Product A, B and C using pre-treatments combinations of Normalisation+SNV+Detrending and Normalisation+1st derivative

Figure 1 (a)

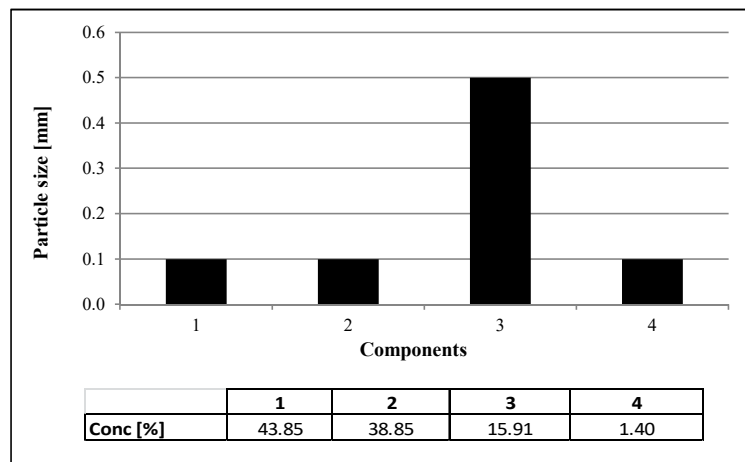


Figure 1(b)

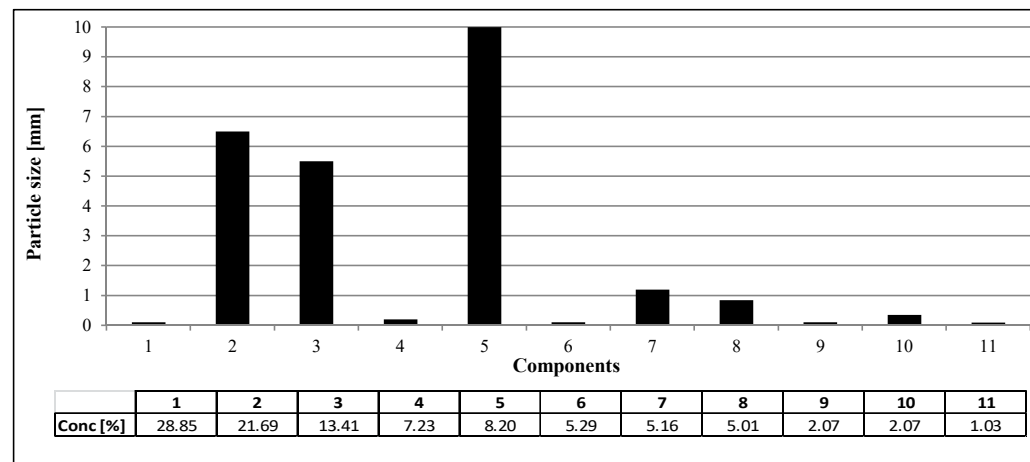


Figure 1: Histograms with particle sizes of Product A (a) and Product C (b). Mass percentages of each component are reported at the bottom of the histogram. Product A components dimensions are similar to each other, while Product C presents a larger variability.

Figure 2(a)

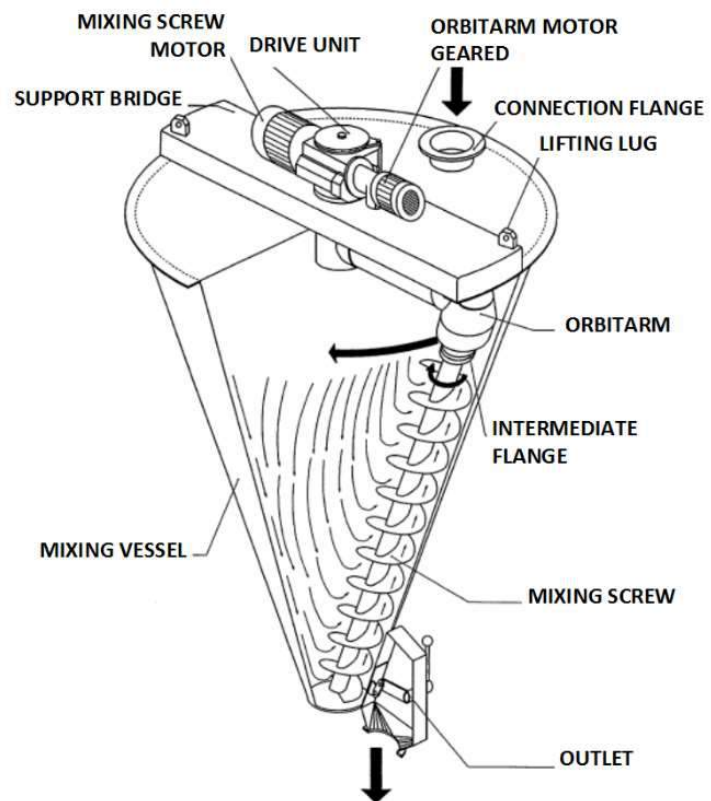


Figure 2(b)

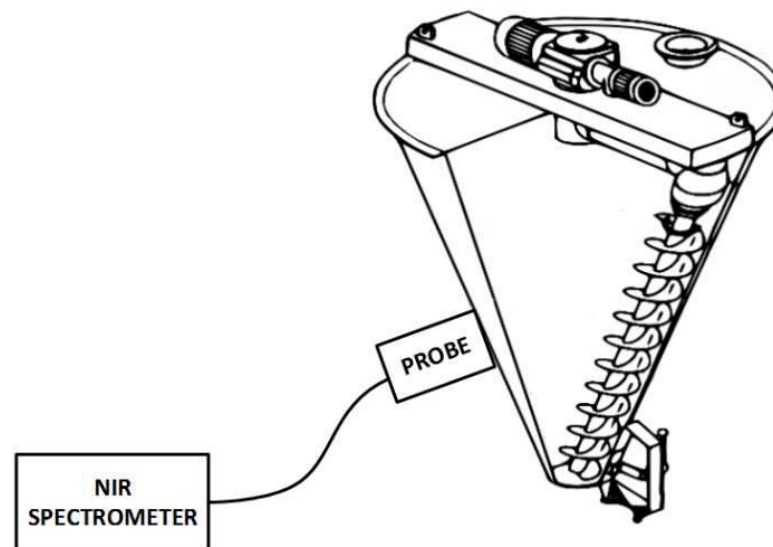


Figure 2: Conical screw mixer configuration. (a) Configuration of the conical screw mixer. (b) Connection of the probe to the blender.

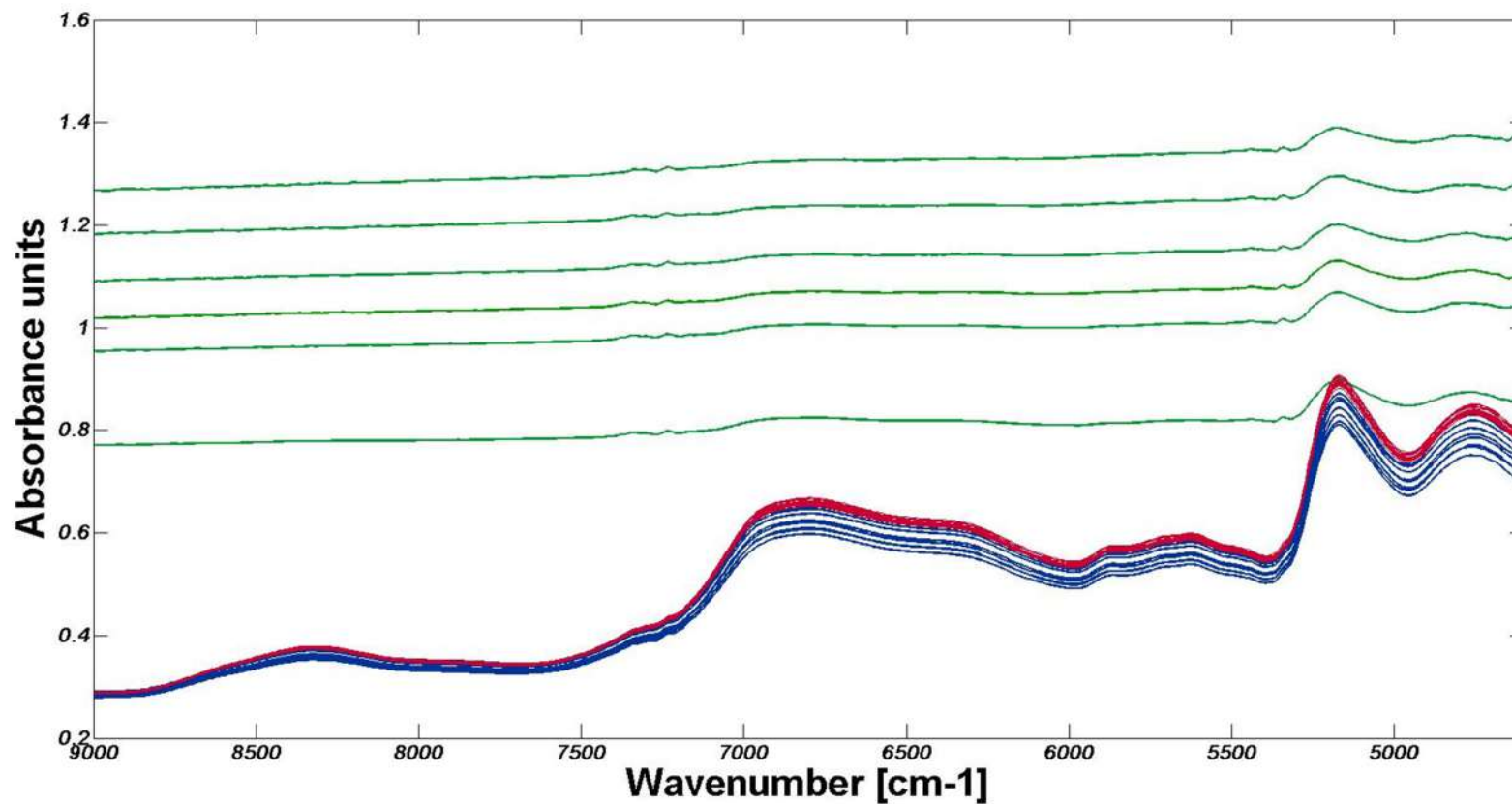


Figure 3: Example of spectra collected during the production phase. Green spectra are recorded when the powder is still under the level of the probe. Blue spectra show powder reaching the level of the probe. Red spectra represent the homogeneous mixture.

Figure 4 (a) Raw data

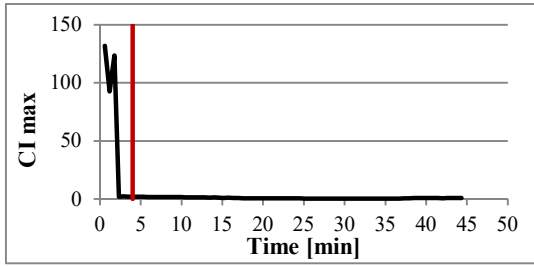


Figure 4 (b) First derivative

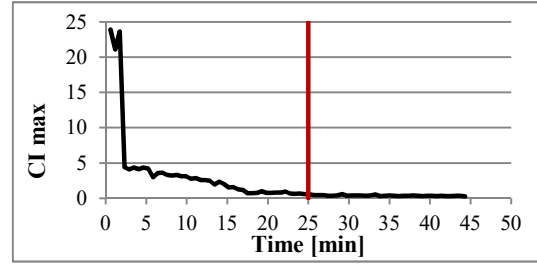


Figure 4 (c) Second derivative

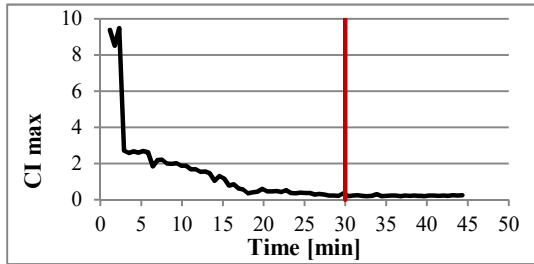


Figure 4 (d) Detrending

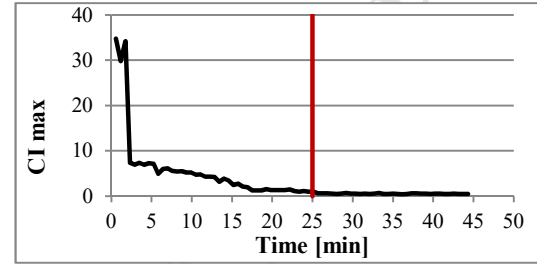


Figure 4 (e) Normalisation

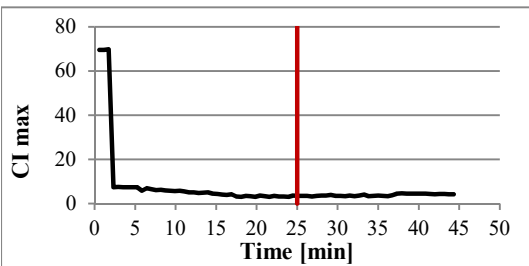


Figure 4 (f) SNV

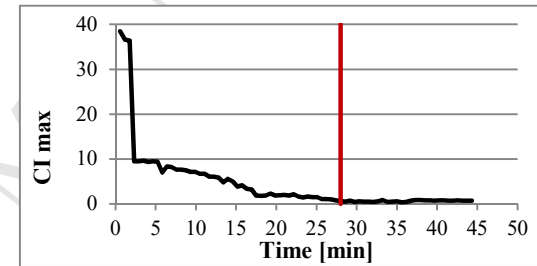


Figure 4: Profiles of Conformity Index calculated for Product A. Data were first pre-treated using different pre-processing techniques, and then Conformity Index was calculated. The vertical line represents homogeneity starting point according to the different pre-treatments.

Figure 5 (a) Raw

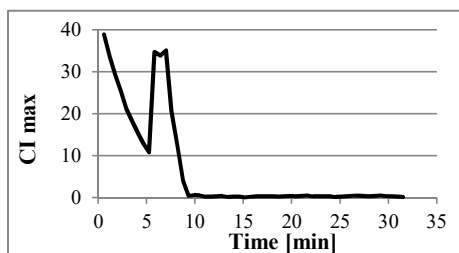


Figure 5 (b) First derivative

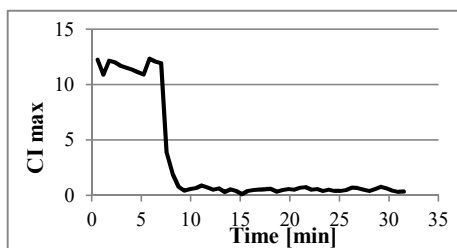


Figure 5 (c) Second derivative

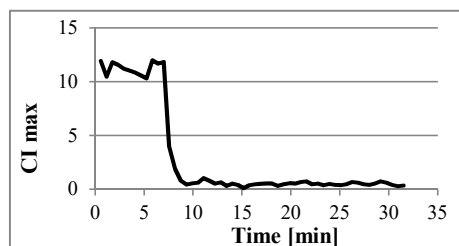


Figure 5 (d) Detrending

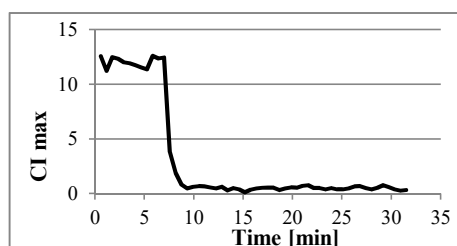


Figure 5 (e) Normalization

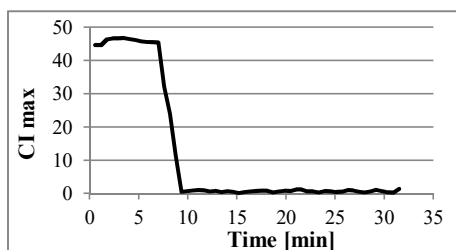


Figure 5 (f) SNV

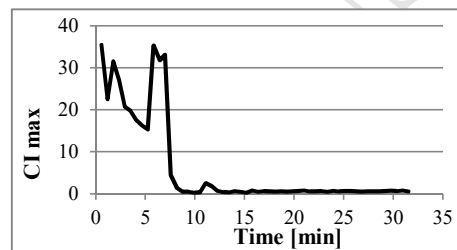


Figure 5: Blending profiles of Conformity Index calculated for Product B. Data were first pre-treated using different pre-processing techniques, and then Conformity Index was calculated.

Figure 6 (a) Raw data

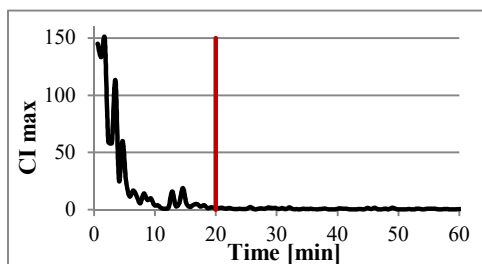


Figure 6 (b) First derivative

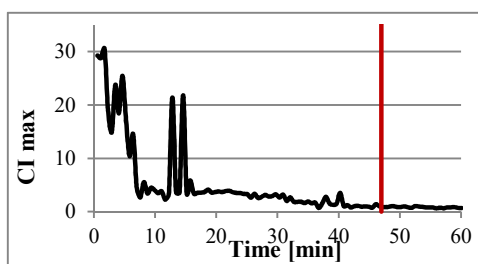


Figure 6 (c) Second derivative

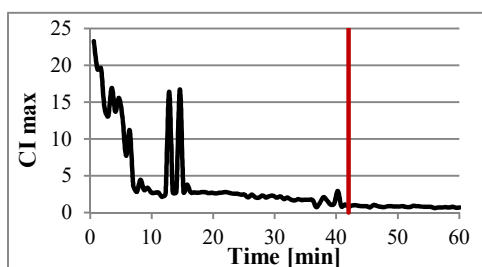


Figure 6 (d) Detrending

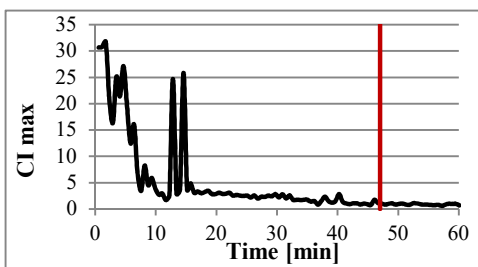


Figure 6 (e) Normalization

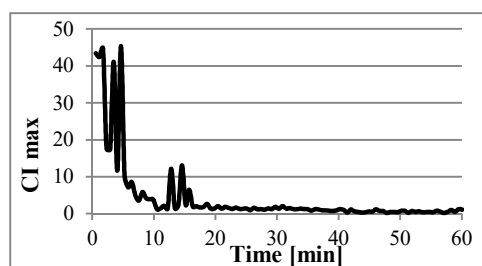


Figure 6 (f) SNV

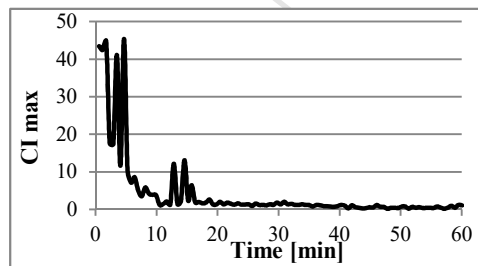


Figure 6: Blending profiles of Conformity Index calculated for Product C. Data were first pre-treated using different pre-processing techniques, and then CI was calculated. The vertical line represents homogeneity starting point.

Figure 7 (a), Product A, Norm-SNV-Dt

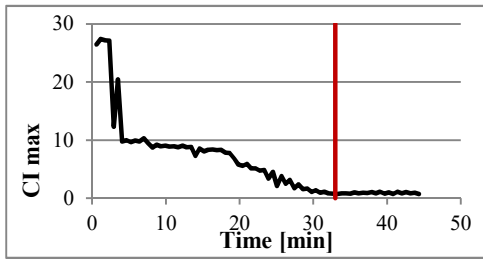


Figure 7 (b), Product A, Norm-First derivative

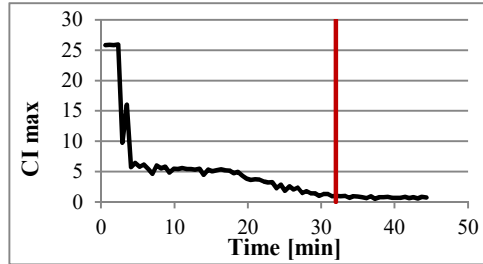


Figure 7 (c), Product B, Norm-SNV-Dt

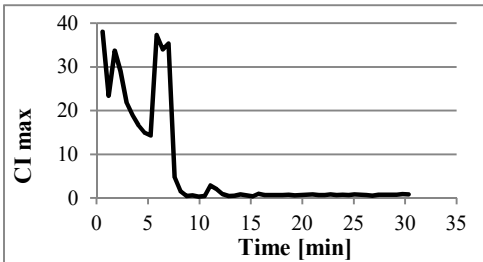


Figure 7 (d), Product B, Norm-First derivative

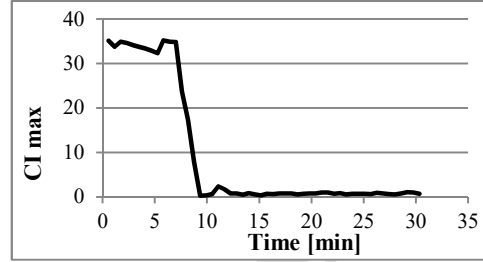


Figure 7 (e), Product C, Norm-SNV-Dt

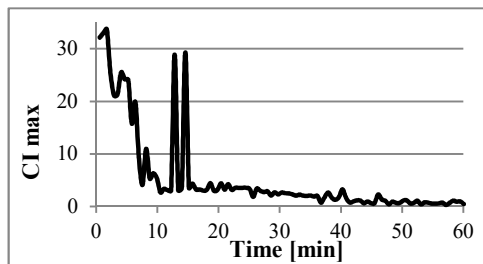


Figure 7 (f), Product C, Norm-First derivative

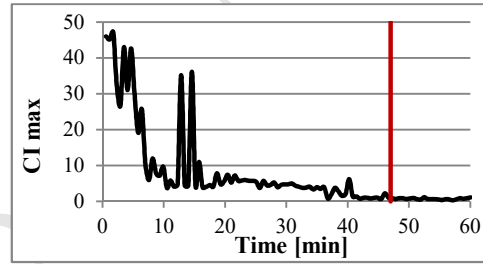


Figure 7: Comparison of pre-treatment combinations for Products A, B and C. Data were first pre-treated using Normalisation+SNV+Detrending and Normalisation+2nd derivative, and then Conformity Index was calculated. The vertical line represents the homogeneity starting point. Where the vertical line is missing, it was not possible to determine the mixing time.

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Figure 8 (a), Product A, Norm-SNV-Dt

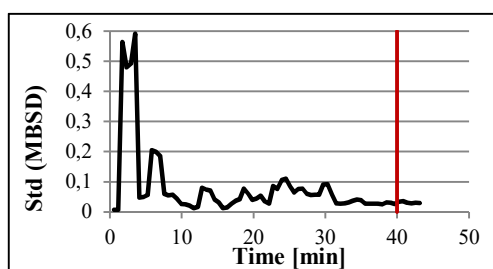


Figure 8 (b), Product A, Norm-First derivative

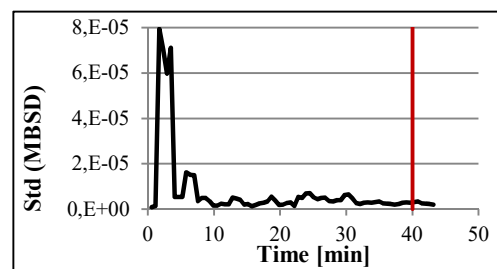


Figure 8 (c), Product B, Norm-SNV-Dt

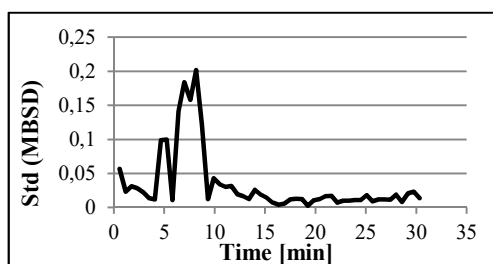


Figure 8 (d), Product B, Norm-First derivative

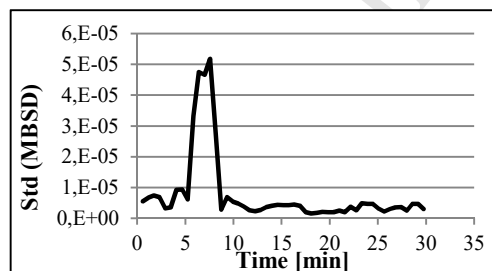


Figure 8 (e), Product C, Norm-SNV-Dt

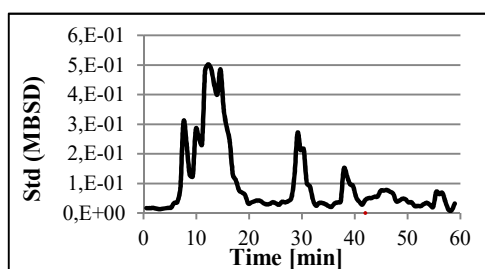


Figure 8 (f), Product C, Norm-First derivative

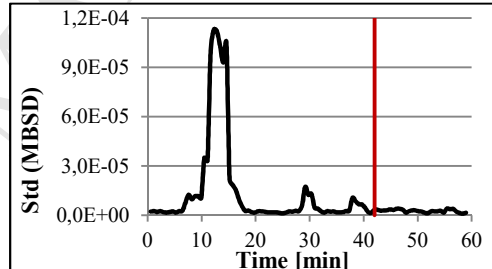


Figure 8: Comparison of pre-treatment combination for Products A, B and C in Standard Deviation analyses. Data were first pre-treated using Normalisation+SNV+Detrending and Normalisation+1st then Standard deviation of MBSD was calculated. The vertical line represents homogeneity starting the vertical line is missing it was not possible to determine mixing time.

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Highlights

- Novel approach using Near Infrared spectroscopy to optimise mixing time is proposed
- Particle size and component distribution influence the pre-treatment choice
- Derivatives preferred for products with broad particle size distribution

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There is no conflict of interest for any of the authors to be declared.

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