Linking Human and Machine – Towards Consumer-Driven Automated Manufacturing

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***Abstract*— In this paper we establish a link between linguistic descriptors describing food preferences and product manufacturing processes. We show how this is achieved using a model-based methodology that translates consumer preferences into product and process specifications. The ultimate goal is the large scale personalization of formulated food product manufacture where consumers are also the co-creators of the food products they wish to buy. Firstly, we investigate how those sensory attributes for such products can map onto product and process specifications. Fuzzy set modelling is used to capture the preferences and perception for these attributes by different groups of people. Specifically, type-1 fuzzy sets are generated from interval-valued survey data for the linguistic descriptors (i.e., *thin, thick, smooth, pulpy*) and the sensory indicators (i.e., *smoothness, roughness and orange flavor*) that describe how consumers perceive and select orange based beverages. Then, the models are employed to establish the links between such product attributes and the actual formulation parameters to make the product. We demonstrate the manufacture of the desired orange beverage that emerged from the modelling approach by deploying the process parameters, which map onto those descriptors, on the controller of a continuous food formulation system which was selected due to its flexibility and its computer controller that provides the ability to redeploy new formulation specifications rapidly. With this overall methodology we demonstrate for the first time the digital, on-demand manufacture of soft beverages with targeted attributes, selected directly by a consumer group.**

Keywords*— *Fuzzy set; intervals; sensory attributes; product attributes; make-to-order manufacturing; oscillatory baffled reactor

I. Introduction

There is great deal of uncertainty and risk surrounding the level of success of new product development due to limited access to customers that current market research techniques afford. However, once such market segments are identified, then there is the question on how to re-configure manufacturing lines to quickly respond to such emerging markets. These are two of the key challenges that face the food manufacturing industry [1].

Customer-driven food product design is a recent trend in food industry, - with increasing consumer demands for more individualised products addressing a variety of needs ranging nutritional to flavour preferences. Such personalized food design requires strong communication between food manufacturer and consumers regarding the desired sensory properties of the food. Therefore, design and identification of the sensory descriptors are essential to develop optimal food and beverage products for individuals.

Here, sensory evaluation is used to identify factors that lead to the development of new products such as taste, touch, smell and appearance about the product and as well as consumer characteristics. The selection and meaningful comprehension of the sensory descriptors is critical of importance to ensure that all panellists refer to same sensory concept. A number of sensory evaluation methods have been investigated in order to effective sensory evaluation design [2],[3].

A number of methods have been developed to minimise uncertainty in sensory evaluation. Fuzzy sets have been shown to be a successful and useful method for modelling the opinions and perceptions of groups of people [4], [5] and a number of techniques have been proposed for deriving datasets from data [4], [6], [7], [8].

In this work, we focus on establishing a link between sensory and product attributes in order to eventually drive the control process underpinning a novel continuous flow reactor for personalised food and drink manufacturing – focussing here on the manufacture of orange-based beverage . Specifically, we define a set of sensory descriptors by setting the appropriate terms for a clear description of a beverage product and deploy interval-valued questionnaires to capture the perceptions (and associated uncertainty) of the terms by groups of participants. We subsequently model the survey responses through the Interval Agreement Approach (IAA) with fuzzy sets (FSs), which in turn enables the comparison between sensory attribute perception and measured physical properties of the orange-based beverage. As a result of this comparison, the final stage focuses on the production of the specified product with the demanded sensory attributes using continuous formulation system.

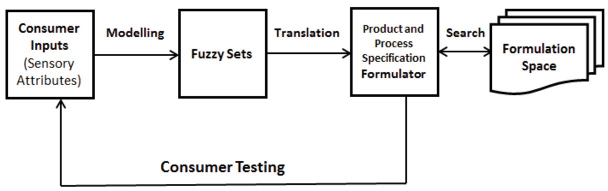


Fig. 1. Structure of the IAA data-driven food product manufacturing

In our previous work [9] a make-to-order manufacturing platform for formulated beverage products was demonstrated. In this work, we focus on the development of a methodology that integrates a model-based approach with a physical manufacturing platform for the rapid personalised manufacture of formulated products.

We demonstrate how to model FSs and IAA method for sensory evaluation of orange-based beverage . Fig.1 shows the structure of the fuzzy set data-driven food product manufacturing model. The first is performed by consumers who are required to define their perceptions and opinions of beverage product by interval based questionnaire. Once the definition of the linguistic descriptor is identified by the fuzzy set model then the formulator is used to translate those into technical specifications. The formulator has a wide range of recipes and ingredient pairing space which is generated by previously conducted experiments. Similarity measures on fuzzy sets such as the *Jaccard similarity* [10] are used to develop retrieval mechanism to retrieve the most similar ingredients and manufacturing sets that aim to achieve to deliver required sensory attributes and product functions.

The paper is structured as follows: Section II provides an overview of the sensory descriptor selection, the modelling approach of interval-valued survey data with fuzzy sets; and the continuous formulation system for beverage production. Formulated products are wide ranging and include fast moving consumer goods such as foods beverages, personal healthcare and pharmaceuticals, fuels, coating and many others. It is therefore, a significant global industrial sector facing similar challenges in new product development and introduction. We explain the experiment design and how to use interval agreement approach in section III. Section IV presents the results obtained from interval agreement approach and relation between sensory attributes and product attributes followed by the limitations and future work in section V. Finally, we presented the conclusions in section VI.

II. Materials and Methods

A. *Sensory Descriptor Selection for Orange-Based Flavour Beverage*

Sensory evaluation and manufacturing of orange-based beverages was performed as a case study to evaluate the performance of the proposed model. Orange-based beverage was selected because it is one of the most consumed soft drink in the world. The most important three product attributes (texture, mouthfeel and aroma) of the orange-based beverage were investigated. The sensory descriptors come from lists generated by spectrum terminology for descriptive analysis [11]. The terms thickness, roughness and orange flavour were used to describe mouthfeel, texture and aroma respectively as shown in Table 1.

B. *Fuzzy Sets from Interval-Valued Data*

In this paper, we employ the Interval Agreement Approach (IAA) [5], [6] to capture the opinions of a group of individuals in relation to specific concept such as sensory attributes of orange-based beverage. Specifically, the given method enables the modelling of inter- and intra-user (between individuals and within a single individual respectively) variation, using type-1 (T1) and type-2 (T2) fuzzy sets. We employ questionnaires where participants indicate their response using ellipses which enable participants to express their uncertainty about a given response. Subsequently, intervals are extracted from the left and right endpoints of the ellipses where the width of the interval indicates the participant`s certainty in their answer, a narrow interval is used when they are sure of their response, and a wider one when they are less certain. Examples of more or less uncertain responses are shown in Fig. 2.

The resulting intervals are modelled as FSs by the IAA which generates a membership function for each term based on the level of overlap of the intervals provided by the participants thus providing a comprehensive model of the group perception of the term in question, without data processing or further assumptions such as outlier removal [4].

C. *A Continuous Food Formulation System for the On-Demand Manufacture of Beverages*

The requirements of modern food formulation have undergone a considerable shift with changing consumption patterns and growing demand for-more customized products. In response to these challenges, current and future food manufacturing systems should be adaptable as to communicate with open innovation tools, to enable quick response to changing production requirements, to integrate multi input-output process control devices for in-line product quality monitoring and finally to include machine learning algorithms for optimum product and process performance. Moreover, recent advances in continuous manufacturing technology which include oscillatory baffled reactors (OBRs) and automated computer control allow companies greater opportunities to streamline formulation of new products and better product and process control.

Table 1. Sensory descriptors and Product/Process Attributes

Product Attribute	Sensory Descriptor	Manufacturing Set
Texture	Roughness	Particle/Droplet Size
Mouthfeel	Thickness	Viscosity
Aroma	Orange Flavor	Contained Vitamin C

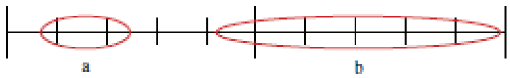


Fig. 2. Interval responses, where `a` is more certain response and `b` is less certain response [4]

Therefore, a novel beverage manufacturing platform was developed to allow the computer control of the physical properties of the product during its manufacture, which ultimately link to its sensory attributes. The platform comprises ingredient section, a computer-controlled ingredient dispensing system, the flow system itself (see Figure.3a), in-line quality and product physical property measurement sensors (e.g. for color measurement) and mixing mechanism as shown in Fig.3b.

This design enables superior mixing performance of ingredients in continuous conditions, for uninterrupted production but in a small footprint and the ability to redeploy formulation parameters and processes rapidly. Mixing is achieved by a series of baffles along the flow passage of the mixture with the assistance of an agitation mechanism that induces longitudinal oscillation of the mixture but with an overall forward net flow [12]. This arrangement allows for three key parameters that are directly controlled to determine the overall formulation process: oscillation frequency, amplitude and net flow.

III. Data Collection and Modelling

A. *Physical Product Property Measurement*

In this part, we demonstrate the application of the IAA based modelling in the context of commercially available orange-based beverages. The main reason not to use orange-based beverage samples from our continuous formulation platform is to prevent health and safety issues at this stage. The platform requires some documented work to organize a proper tasting session. However, physical properties of the commercial samples (e.g. viscosity, particles size, orange concertation) are within the formulation space of the formulator which means the formulator is able to produce similar and wide ranging orange-based beverage products. Four different orange-based beverages were purchased in order to generate sensory evaluation data of individuals. An interval-valued survey was designed to generate linguistic descriptors of orange-based beverage (*e.g., thickness, roughness and orange flavour)*.

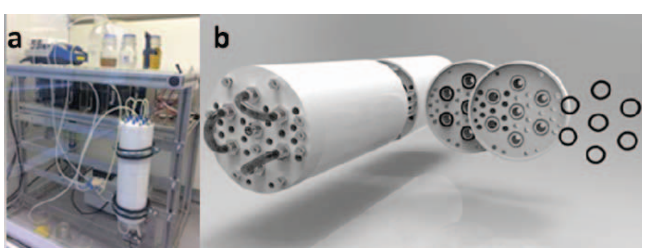


Fig. 3. Continuous formulation platform (a), the mixing mechanism (b).

Table 2. Sensory descriptors and adjectives

Sensory Descriptors	**Adjectives**	
Thickness	Thin	Thick
Roughness	Smooth	Pulpy
Orange flavor	None	Strong

Table 3. Viscosity, particle size and contained vitamin C results of the orange-based beverages used in sensory evaluation study

Samples	**Viscosity (Pas*s)**	**Particle Size (µm)**	**Contained vitamin C in 100 ml (mg)**
Orange-based beverage sample1	0.00233	1.55	20.0
Orange-based beverage sample2	0.00254	6.14	25.0
Orange-based beverage sample3	0.00269	103	32.0
Orange-based beverage sample4	0.00115	88.26	33.0

While the questionnaire was designed to gather participant perceptions of different perceivable properties of orange-based beverage on the other hand we measured the physical properties of the samples in order to establish link between sensory descriptors and product specifications. Laser light scattering was used to determine the mean particle size and distribution of orange beverage emulsion using (the HORIBA LA-920) laser scattering particle size distribution analyser. The instrument is available at the materials processing laboratory at Brunel University London. After the sample preparation, the droplet size could be measured by diluting the emulsion with deionized water (DI) before starting analysis. The unit of measurement of the particle size is (µm). Viscosity is considered a rheological property and a measure of fluid resistance to deformation by shear stress. The Advanced Rheometric Expansion System (ARES) instrument was used to measure viscosity of orange beverage emulsion. This device is available at the materials processing laboratory at Brunel University London. After the sample preparation, the viscosity could be measured according to steady strain rate test. All instrumental measurements were performed at ambient temperature. The product recipes are not provided due to confidentiality policies at play. We don't know the exact orange oil concentration of each product. However, the nutritional information is labelled. Orange is great source of vitamin C. The contained vitamin C was used to link between perceived orange flavour and orange concentration. The numerical models are then compared with the words model to build a link with sensory descriptors and product attributes.

A set of adjectives were modelled to describe each of sensory attributes such as thickness (thin-thick), roughness (smooth, pulpy) and orange flavour (none, strong) as shown in Tab. 2.

For the initial work presented in this paper, a workshop with 11 participants (6 female/5 male) was conducted for sensory evaluation analysis. Note that the set of participants is neither balanced nor large enough to draw conclusions from the data collected. This paper is solely a proof of concept of the proposed mechanism of linking consumer data to a manufacturing system which in the future will be exploited with larger balanced sets of participants. Participants were asked 3 questions (e.g.: `*What is the perceived thickness of the orange-based beverage*`) that required them to rate each corresponding sensory attributes using the ellipse method. One sample at each round was provided for tasting and participants were asked to take a sip of water to rinse their palette before tasting each sample.

B. *Processing Interval-Based Approach for Food Product Sensory Evaluation*

Various sensory response measuring methods have been used in order for food production and formulation. Classification, grading, ranking and scaling are the most traditional methods to measure responses. In classification, participants are asked to select an attribute or attributes that describe(s) the sensory feeling (e.g., sweet, sour and lemony for beverages). Each method has its own benefits and limitations. The degree of complexity is multidimensional in the food processing industry therefore, we employ the interval-valued data capture approach as introduced above together with the IAA based modelling for sensory evaluation due to both the simplicity and high usefulness (information content) of the resulting models.

The following steps were used to conduct the approach.

a. An interval-valued questionnaire was designed. The scale has four quarters and each quarter has ten intervals with 3mm space. In total the length of the scale is 120 mm which is a practically useful range for participants.

   The questions used were the following:

   - *"What is the perceived **thickness** of the orange-based beverage sample?"*
   - *"What is the perceived **roughness** of the orange-based beverage sample?"*
   - *"What is the perceived **orange flavor** of the orange-based beverage sample?"*

b. Possible answers were normalized from 0 (thin) to 10 (thick) for the first question, 0 (smooth) to 10 (pulpy) for the second question and 0 (none) to 10 (strong) for the last question which is more clear in terms of graphical representation of aggregated results.

c. The Interval Agreement Approach (IAA) [5],[6] was used to aggregate all individual responses provided by participants. The modelling of interval-valued data from multiple responses consists of the combining individual intervals into a distribution a type-1 fuzzy set by considering overlap of the interval. The graphical representation of the FS models resulting from IAA can be non-convex or non-normal. The non-normality is a result of the agreement operation. Less high FSs represent lower levels of agreement (overlap) of constituting intervals and conversely, higher FSs represent strong overlap (high level of agreement). Thus, graphical resulting of the FSs indicates the agreement or disagreement around a specific context across participants. The width of the models reflects the overall level of uncertainty regarding the respective concept, as perceived by the group of raters.

d. In order to summarise the participants' opinions expressed in the models resulting from the IAA, the centroid of the FSs is used as a basic numeric summarisation of the participant group perception. For details on centroid refer to [6]. Tab. 4 shows the centroids for each sample and sensory attribute.

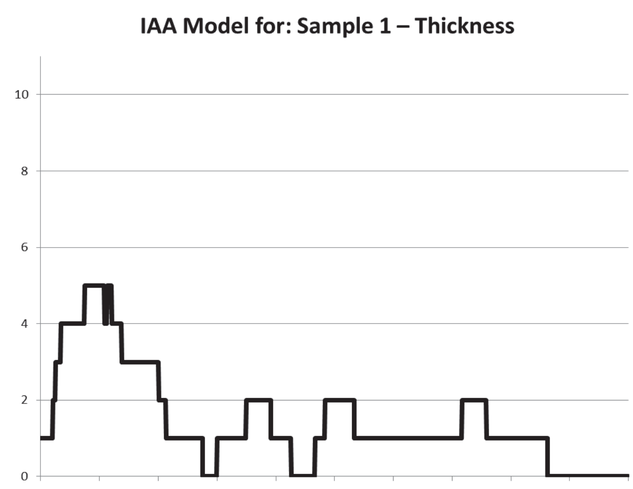
Table 4. Agreement model summaries based on the centroid.

	Sample1	**Sample2**	**Sample3**	**Sample4**
Centroid for perceived Thickness	3.277	3.711	4.416	4.123
Centroid for perceived Roughness	2.45	2.646	3.086	2.968
Centroid for perceived Orange Flavor	4.712	5.483	4.343	4.319

IV. Results

A. *Comparing Sensory Attributes Over participants` Perceptions*

We analyzed the perception of each sensory attributes using the IAA to describe the meaning of the sensory descriptors. Once the participant responses were collected, type-1 fuzzy sets were created to represent each sensory attributes as perceived by the group of tasters. The vertical axis on the following graphs represents the inter-user agreement. The number of intervals that overlap at a certain point determines the degree of memberships. In this case there are 11 participants, therefore, the primary membership domain is divided into eleven with membership degree level of 1/11. And horizontal axis represents the participants` perception in the meaning of a set of linguistic descriptor such as `thin` and `thick`. For more detail on the IAA, we refer the reader to [5].



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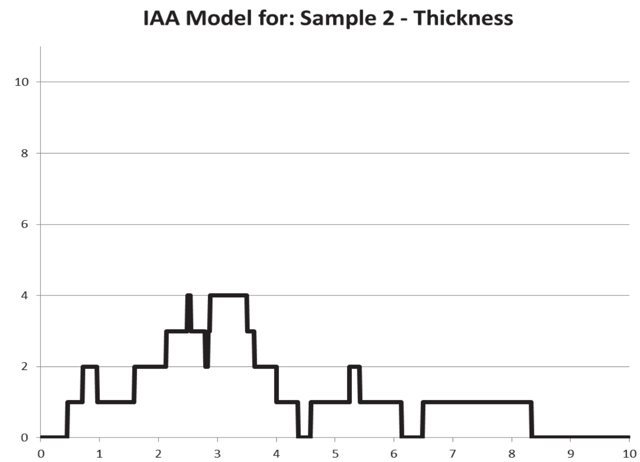

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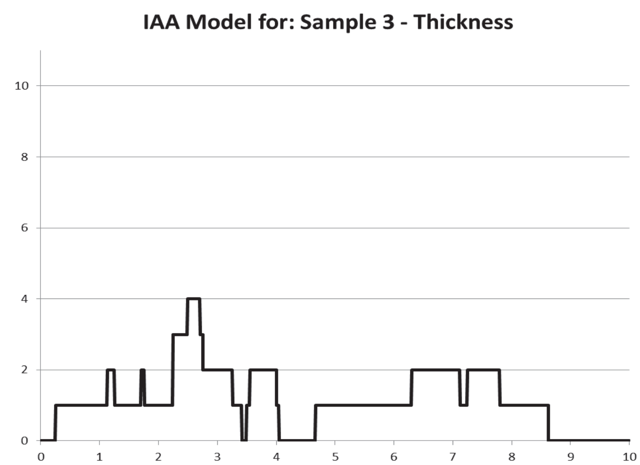

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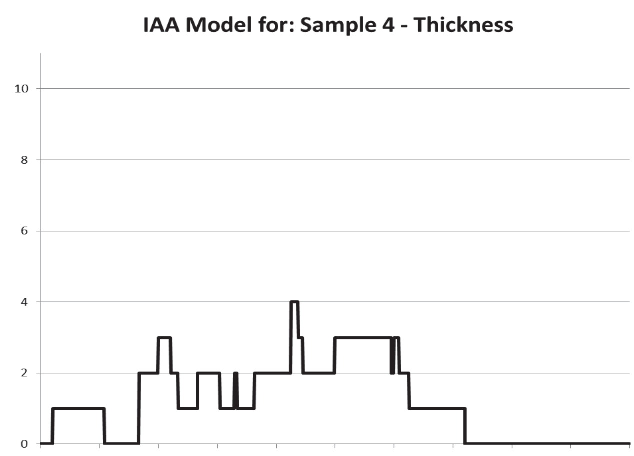


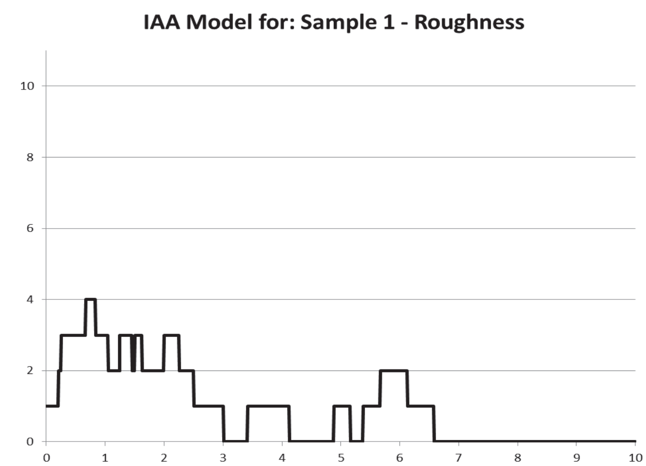
(d)

Fig. 4 T1 FSs obtained from IAA for the perceived thickness of the different supermarket-bought orange-based beverages (a) sample1, (b) sample2, (c) sample3 and (d) sample4.

The results from aggregated interval data are shown in Fig.4, Fig.5 and Fig.6. In these figures, higher scores on the y-axis indicate higher agreement amongst participant. The visual nature of the models makes it simple to discover trends (e.g., strong agreement or discord) between participants.

Fig. 4 shows the T1 FS model results for the perceived thickness of four different orange-based beverage samples purchased from different UK supermarkets. While some trends are apparent in the models, such as potential bi-modality for sample 3 (indicating that there are two different interpretations of the same sample for a given characteristic by different people), further experiments are required in order to investigate those different distributed results. As we mentioned above, sensory evaluation is a complex world, there are many factors that influence the perception such as participant age, cultural background and gender.

Fig. 5 represents the T1 FS model results for the perceived roughness of the orange-based beverage. Generally, there is higher agreement amongst participant for the roughness perception than for thickness which is interesting.



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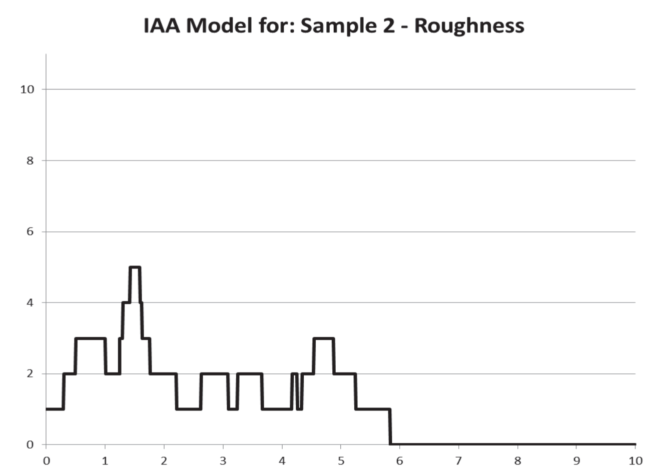

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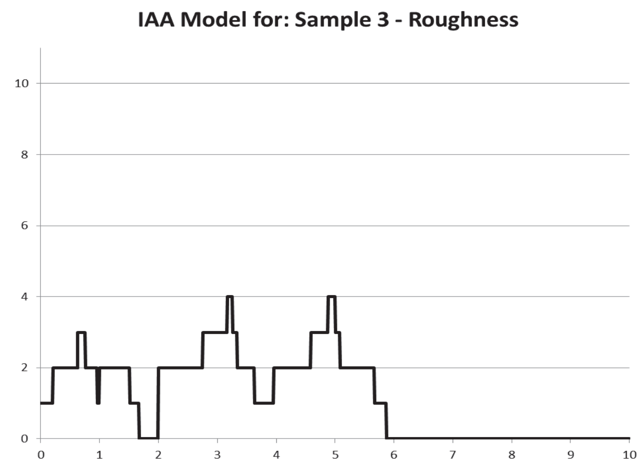

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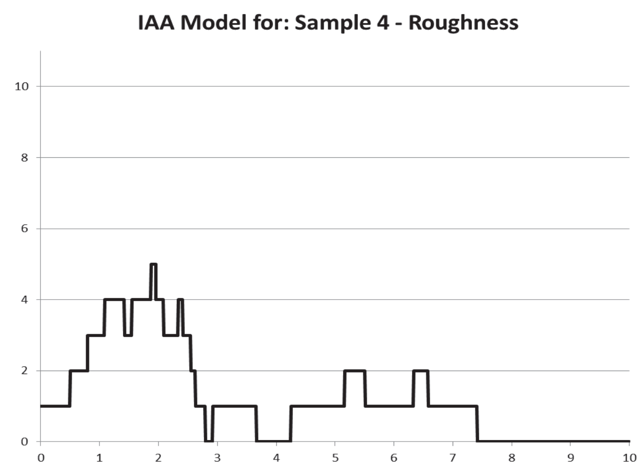
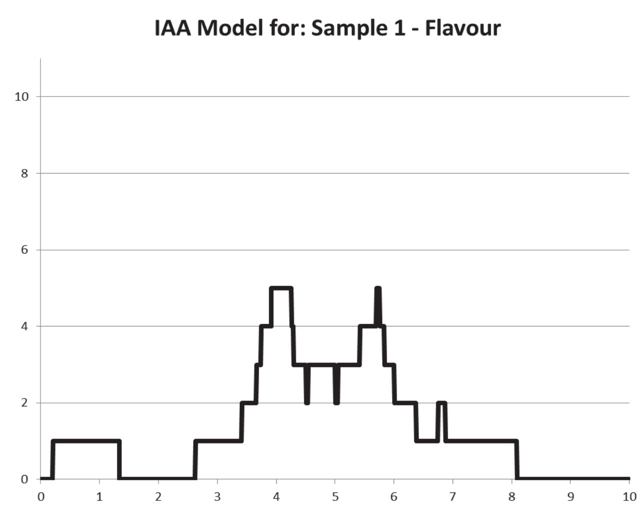


(d)

Figure 5 T1 FSs obtained from IAA for the perceived roughness of the different supermarket-bought orange-based beverages (a) sample1, (b) sample2, (c) sample3 and (d) sample4.



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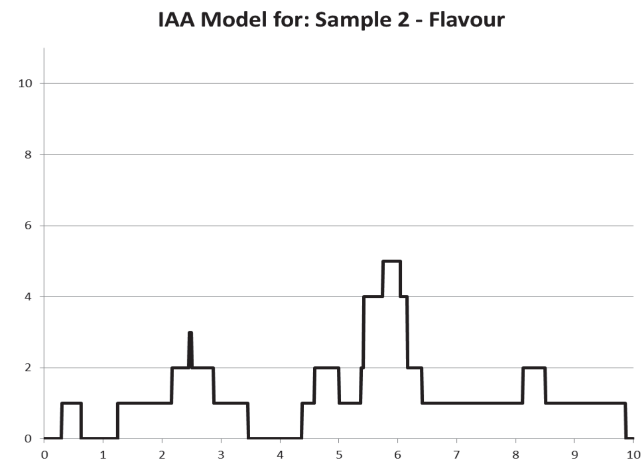

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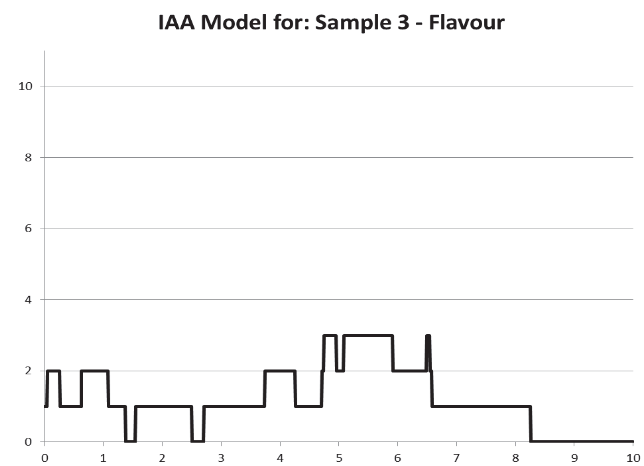

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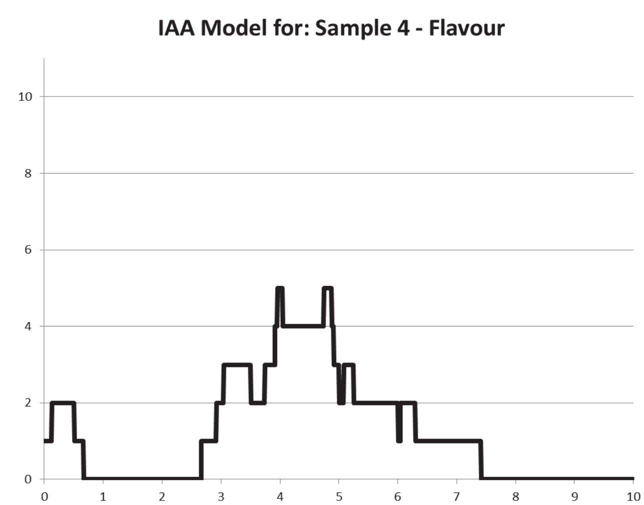

(d)

Figure 6 T1 FSs obtained from IAA for the perceived orange flavor of the different supermarket-bought orange-based beverages (a) sample1, (b) sample2, (c) sample3 and (d) sample4.

Fig. 6 shows the agreement for the perceived orange flavour for each sample. There is relatively high agreement on the flavour perception amongst participants for the first and third sample. Orange quality and growing region take important roles on the perception of orange flavour. Once again, this requires further study to understand flavour sensation conducting a sensory study workshop including orange samples from different regions of the world (e.g., North America, Latin America, Europe, and Asia).

B. From IAA Modelingl to Product/Process Design

Each characteristic parameter of the formulated orange-based beverage such as main ingredient concentrations (Arabic gum, xanthan gum and orange oil) and manufacturing parameters (residence time, oscillatory amplitude and frequency) were modelled using the *Central Composite Design* approach in our previous work [9]. The obtained experiment results indicate that there is strong influence between product composition and product properties. Once the composition of the main ingredients is changed we measured different rheological results. Fig. 7 represents the relationship between the physical properties of the orange-based beverage and the human perception-based fuzzy set models obtained from the interval valued survey and the IAA. The centroid number is used as a basic numeric summary of the participants` agreement.

Fig. 7 shows the viscosity measurements and FS model results. The viscosity is represented by the diamond/blue line and the square/red line represents the centroid number of the FSs models. The trend indicates that there is a correlation between the viscosity of the orange-based beverage and its perceived roughness. The same correlation is found between the particle size and roughness as shown in Fig 8. On the other hand strong correlation between perceived orange flavour and vitamin C concentration could not be established with the same accuracy as the other sensory product attribute relationships. It may be that by increasing sample size and by defining alternative linguistic descriptors the accuracy may be increased but this is a topic of further research.

The exciting finding from the results shown is that there is indeed a potential for directly relating consumer-perceived qualities such as thickness and roughness to physical manufacturing properties which can be controlled during the actual manufacturing process, thus putting consumer-driven "on-demand" manufacturing within the reach of commercial production facilities.

Once consumers requirement are defined for the corresponding sensory attributes by IAA method, then the continuous food formulator as described above lets anyone create and manufacture their customized beverage product. Consumers can use knobs to identify the interval of thickness, roughness and flavor intensity. We can use nowadays coffee machines as example, the user can indicate the level of sweetness by adjusting the amount of sugar. The continuous food formulator will enable to set more product attributes. Composition and concentration of the ingredients and mixing parameters are automatically calculated based on consumers inputs. In this stage, previous experimental results are considered to compare the similarities of physical product attributes of potentially successful recipes with that of new product requirements.

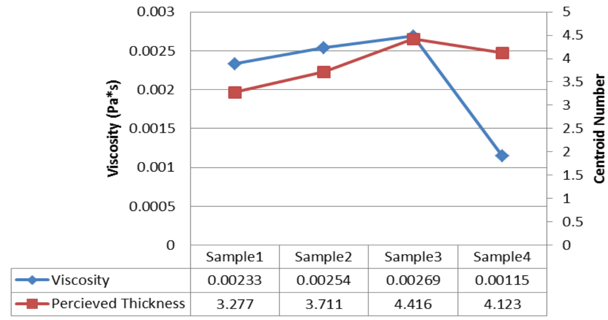

Figure 7 Relation between viscosity and perceived thickness of orange-based beverage samples

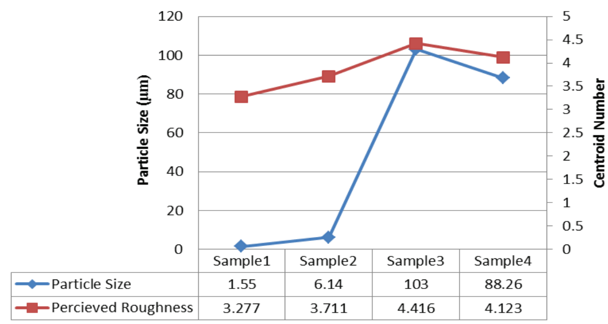

Figure 8 Relation between particle size and perceived roughness of orange-based beverage samples

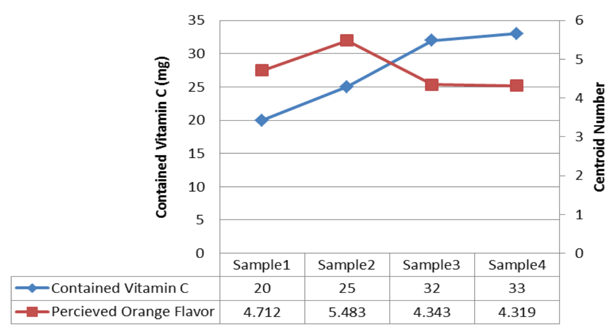

Figure 9 Relation between contained vitamin C and perceived orange flavor of orange-based beverage samples

V. LIMITATIONS AND FUTURE WORK

The traditional human-based recipe design and subsequent and manufacturing design processes are very time consuming and thus inflexible and unsuitable for on-demand personalised manufacturing approaches. In this, interval-valued consumer data capture in combination with IAA based FS modelling was used to gain insight and comprehension into the meaning of linguistic descriptors for make-to-order beverage product processing. Although the initial results show potential, the proposed approach still has several notable limitations.

On the modelling side, the control of factors influencing sensory perceptions is a complicated task, this is primarily due to the participants being human, and as such their perception of thickness, sweetness, or other attributes varying. Perception often transcends basic human physiology i.e. sample thickness on the tongue, taste bud reaction to acidity or a more evident swallowing reaction; and may be affected by ethnic background, upbringing, psychology and past experiences with food products. Therefor a wider and balance participant selection must be carried out whilst maintaining the same diversity for accurate and reliable results.

On the manufacturing side, there must be a carefully maintained balance between sensory attribute limits that translate into a parameter that does not inhibit the actual manufacturing. A prime example of such a parameter is viscosity. Highly viscous requirements may render manufacturing either impossible due to blockages or expensive since plant reconfiguration will be required. It is notable to point out that in the case of the modular OBR, changes to the geometrical parameters can be carried out by a scaling up, which has proven to be simple and inexpensive [12].

Despite the above noted limitations, the future plan is to develop a feedback control system that will enable the direct configuration of manufacturing settings based on desired human-perceived properties of beverages and other foods. Indeed, the approach detailed in this paper may be employed to enable a feedback controller where human rating of outputs can directly be fed into the production configuration to change it “on-the-fly” based on consumer preference. Our future research will continue by exploring more linguistic words and orange-based beverage samples in order to improve the robustness of the proposed model. Further approaches (such as based on similarity) are required to derive relationships between sensory and product variables.

VI. CONCLUSIONS

In this paper, we focus on the human-perceived meaning of linguistic descriptors of orange-based beverages in order to establish a potential link to controllable manufacturing process parameters, this facilitating personalized, on-demand manufacturing. Initial, small scale interval-valued survey data modelling using type-1 fuzzy sets was performed to generate models of consumer perceptions of several linguistic descriptors such as thickness and flavor. Centroids of some of these models were then shown to match standard manufacturing properties, indicating presence of a link. Initial results are encouraging and indicate the potential value of FS based modelling to enable a future generating of consumer-driven on-demand manufacturing as well as consumer-in-the-loop control and refinement of existing products. The IAA method is particularly useful for the generation of rich models without the need for post-processing. Finally, the results indicate that the proposed approach in combination with a recently patented oscillatory flow reactor has great flexibility for rapid product formulation and changeover.

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