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International Journal of
Food Microbiology 24 (1994) 1–9

International Journal
of Food Microbiology

Review Paper

Computer aided microbial safety design of food processes

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Abstract

To reduce the time required for product development, to avoid expensive experimental tests, and to quantify safety risks for fresh products and the consequence of processing there is a growing interest in computer aided food process design. This paper discusses the application of hybrid object-oriented and rule-based expert system technology to represent the data and knowledge of microbial experts and food engineers. Finite element models for heat transfer calculation routines, microbial growth and inactivation models and texture kinetics are combined with food composition data, thermophysical properties, process steps and expert knowledge on type and quantity of microbial contamination. A prototype system has been developed to evaluate changes in food composition, process steps and process parameters on microbiological safety and textural quality of foods.

Keywords: Modelling; Safety; Computer aided design

"Quality cannot be inspected into a product, but must be built in." This statement is certainly true for microbiological quality. Methods for microbiological analyses are slow and many perishable products are consumed, or at least shipped, before the results of tests are available. More and more attention is being paid to the prevention of microbiological problems. HACCP is a qualitative description of the processing and risks, but a more quantitative insight in the food process design alternatives is needed (Schellekens and Martens, 1992). In this respect, the object-oriented and rule-based expert system that is under development in the

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SSDI 0168-1605(94)00107-3

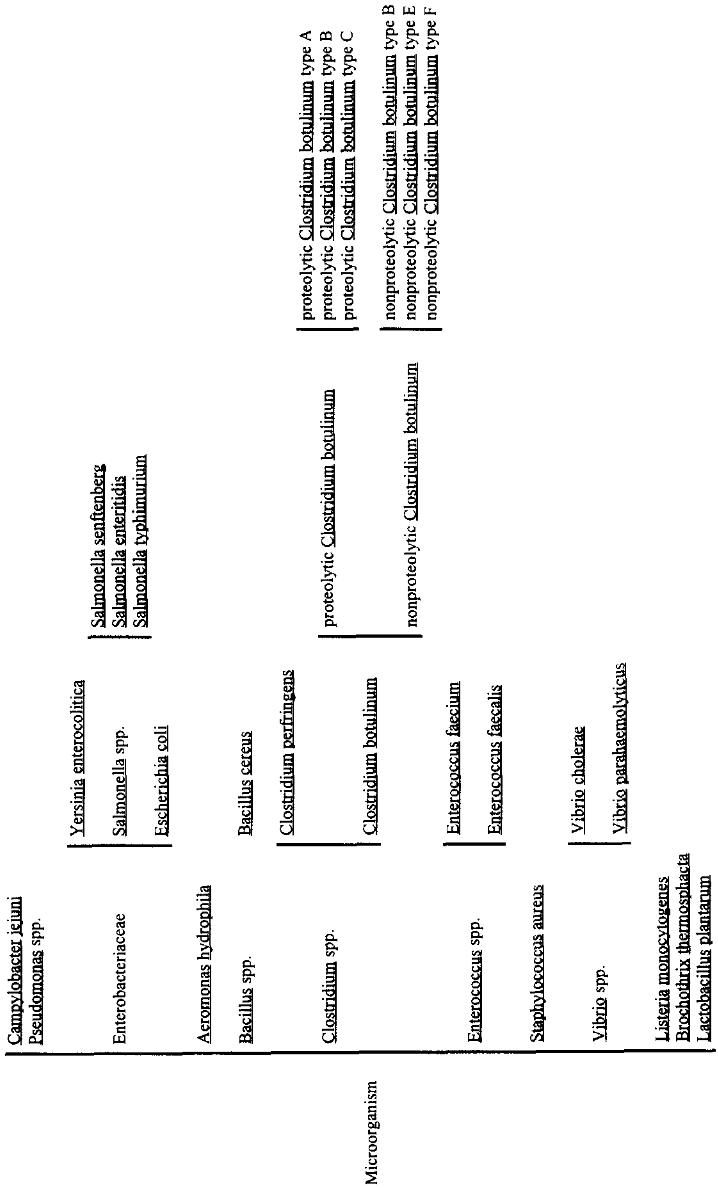

Fig. 1. Hierarchic structure of the object class 'microorganism' in the prototype system.

Table 1
Slots of the 'microorganism' object and values of the slots for some specific microorganisms

Microorganisms	Slots												
	a_0	α	b_2	β	c_2	D_{ref}	γ	p	q	T_{max}	T_{ref}	T_{trans}	z
Brochothrix thermosphacta	21.6	0.3	0.024	100	0.18	4.93	100	57.4	19.9	38.8	50	38.8	6.97
Lactobacillus plantarum	21.6	1	0.038	100	0.25	1	100	23.9	2.28	44.9	65.6	44.9	5.55

The different slots shown in this figure represent parameters that are needed for the calculations of microbial growth and inactivation with the model described by Van Impe et al. (1992). For more information, see the above mentioned article.
a_0 is the asymptotic level of the growth curve (ln cfu/g); α determines the transition velocity around T_{trans} from growth to inactivation; β and γ are parameters for fitting the growth-death transition zone; b_2 (°C^{-1} h$^{-0.5}$) and c_2 (°C^{-1}) are Ratkowsky parameters describing the maximum specific growth rate as a function of temperature; D_{ref} is the time (min) required to reduce the bacterial concentration by a factor of 10, at the reference temperature T_{ref} (°C); z is the increase in temperature (°C) necessary to reduce D_{ref} by a factor of 10; T_{max} is the theoretical maximum temperature (°C) for growth; T_{trans} is the transition temperature (°C) which determines the length of the transition zone ($T_{trans} - T_{max}$) between growth and inactivation; p is a measure for the decrease of the lag time when the temperature is increased; and q is the temperature (°C) at which the lag time is infinite (no growth).

FLAIR project AGRF-DT91-0047 could be very useful to obtain a quantitative insight in the design and processing of food products with a limited shelf life.

1. Object-oriented knowledge system

The expert system shell that is selected is PROKAPPA (Trademark of Intellicorp Inc.). In a very simplified way, an expert system shell may be regarded as an empty knowledge base and an inference engine. PROKAPPA is an object-oriented, rule-based shell. Rule-based means that if-then rules are used. Object-oriented means that items called objects are used that communicate with one another via messages. Object-oriented programming provides the following properties:
- Heuristics can be included (rules of thumb, intuitive rules).
- Object hierarchies are easily defined.
- Complex interdependencies between the objects can be represented.

In object-oriented programming, objects are very complex data structures. Fig. 1 and Table 1 illustrate how the object-oriented approach is implemented in the prototype system. The object class 'microorganism' has as real life objects particular microorganisms, like *Listeria monocytogenes*, *Lactobacillus plantarum*, *Brochothrix thermosphacta* or groups of microorganisms, like Enterobacteriaceae. These objects have slots for the parameters that determine their growth and inactivation, for instance the maximum temperature for growth and the decimal reduction time (*D*-value). These slots have values, e.g. the maximum temperature for growth for *Lactobacillus plantarum* is 44.9°C and its decimal reduction time is 2.44 min at 50°C. All the microorganisms have the same slots, but the values in the slots can be different. By classifying the objects in classes, all the procedures and variables are inherited from the more general classes, like the inheritance from parent to child. But if a specific value for the slot of a particular object is known, this value overwrites the value that was inherited from the object of the more general class. Thus, as can be seen in Fig. 1, *Salmonella enteritidis* inherits the values of the different slots of *Salmonella* spp. unless the specific values for the slots for *Salmonella enteritidis* are known.

Rules are used in the prototype system to determine the relevant microorganisms and the initial load of the microorganisms. It is impossible, and probably meaningless, to attempt to store the initial contamination levels of all product-microorganism combinations.

The inheritance mechanism combined with rules is a very powerful way to represent the relationships between ingredients, microorganisms, process steps and process parameters. For more detailed information on expert system technology the book by Meyer (1990) provides useful information.

2. General structure of the program

The basic data of the expert system are the product composition and the process steps from raw material purchase to consumption by a consumer. Information on the recipe (ingredients, process variables) is provided by the user, or can be obtained from existing recipes.

The thermophysical properties of the foods (thermal conductivity, density, heat capacity) are calculated based on the chemical (mass fractions of water, fat, carbohydrate, proteins, fibre, ash, bound water mass fraction) and physical (porosity, initial freezing temperature) properties of the ingredients (Nicolaï et al., 1994). Data on food ingredients and ingredient characteristics (protein-, carbohydrate-, fat-, fibre-, water-content, ...) are taken from the UK National Nutrient Databank [1].

Information on the heating, cooling and storing conditions (time, temperature, heating or cooling medium, heating or cooling medium velocity) is provided by the user or may be specific for a particular piece of equipment. Heat transfer calculations are based on the finite element method for solving partial differential equations. The calculated time–temperature profile inside the food product serves as an input for the calculation of texture changes as well as the calculation of microbial growth and/or inactivation. A dynamic model for growth and inactivation has been developed to cope with time varying temperature profiles (Van Impe et al., 1992). Additionally, the consequences of the impact of the statistical variation of process parameters and product properties is under development.

The choice of target microorganisms (for spoilage as well as for safety) depends on both the food products under consideration and the process. Important factors amongst the process parameters are the temperatures achieved during heating, cooling and storing and recontamination risks related to specific unit operations (e.g. cutting, assembling). For the target organisms of importance microbial growth and inactivation will be calculated. The final levels of microbial contamination will be compared with legal requirements the product should fulfil and with guidelines used for that category of product.

The time–temperature profile, together with the kinetic texture parameters will allow for the calculation of texture changes for specific conditions (Verlinden and De Baerdemaeker, 1993). The general layout of the program is shown in Fig. 2. Fig. 3 shows a typical display of the main screen of the expert system.

3. Determination of the target microorganisms

The microorganisms that can cause spoilage or are potentially hazardous in a product are selected from a knowledge of the ingredients and the process parameters. In the knowledge base, data are available on pathogenic and spoilage microorganisms that have posed problems in particular foods. This information is

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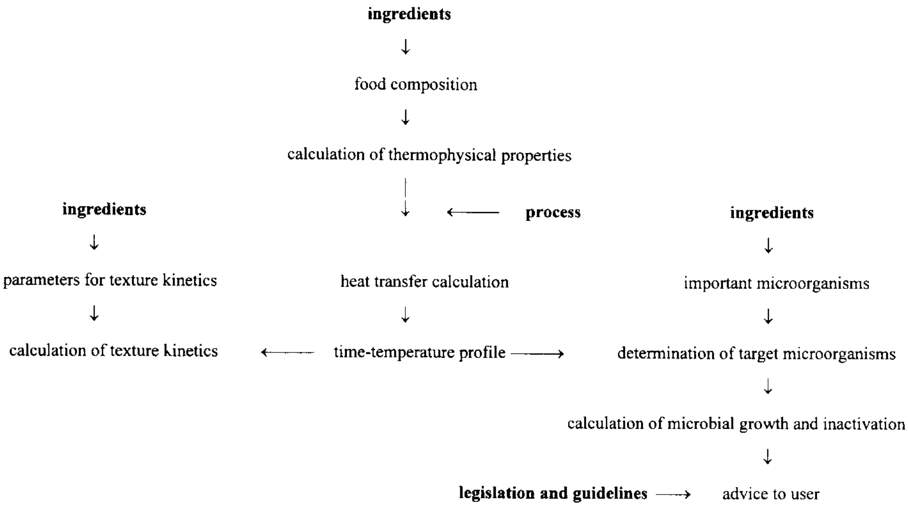

Fig. 2. General layout of the food design program.

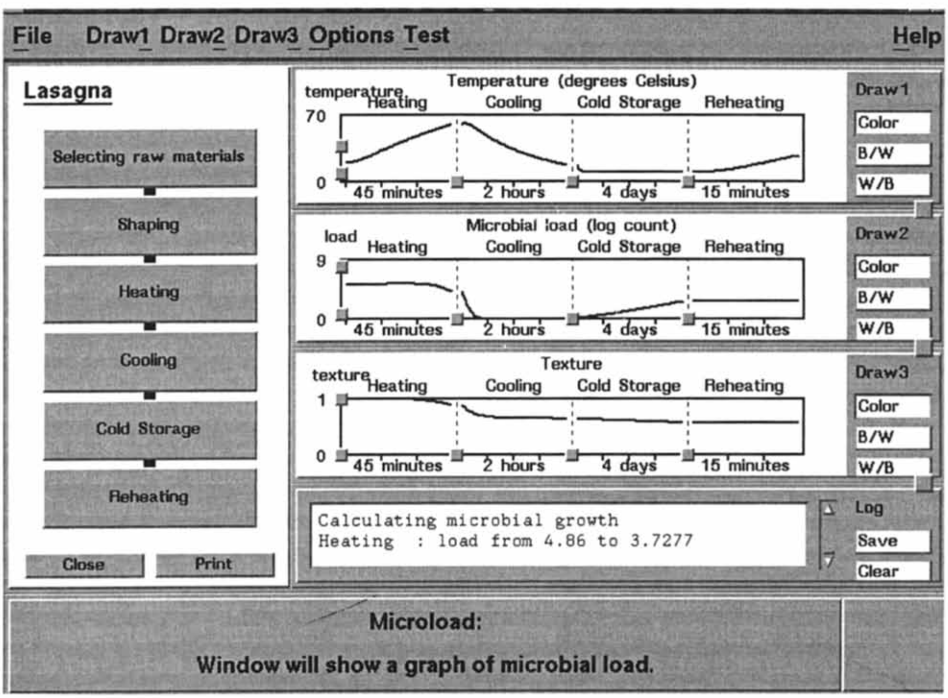

Fig. 3. Display of the main screen of the expert system showing on the left the flow chart of the process (here production of lasagna) and on the right graphs of temperature evolution (drawing area 1), microbial growth and inactivation (drawing area 2) and textural changes (drawing area 3) in the coldest point of the product. The temperature is given in °C, microbial growth and inactivation is given in log counts and the textural changes are shown as relative changes.

obtained from documented instances of food poisoning and spoilage cases. The object-oriented approach permits inheritance mechanisms, so microorganisms of for instance vegetables ('parent') are inherited by the subgroup carrots ('child'). But specific microorganisms can also be linked to particular foods: the 'child' can have characteristics that are different from the 'parent'. The initial contamination level of a specific microorganism in a particular food product is defined in a set of rules. The microbial load of a mixture of food ingredients is calculated as the weighted mean of the load of the individual ingredients.

Apart from the knowledge base relating microorganisms to specific food products, another dataset is necessary with the parameters for the calculation of microbial growth and safety. For each relevant microorganism the following are listed in this database: minimum and maximum temperature for growth, minimum and maximum pH for growth, minimum and maximum a_w for growth, *D*-value, *z*-value, growth rate, parameters needed to calculate the temperature dependence of the maximum specific growth rate and the lag phase, the asymptotic level of the growth rate and a parameter that determines the transition velocity from growth to inactivation (Van Impe et al., 1992). Currently, these parameters are not available for all relevant microorganisms. For *Lactobacillus plantarum* and *Brochothrix thermosphacta* fairly accurate parameters for the calculation of growth and inactivation under dynamic temperature conditions are available. For the other microorganisms literature data are gathered to have a fail safe prediction.

In addition to the properties of the food ingredients, the process parameters are important for the choice of target organisms. The complete sequence of unit operations is taken into account. Critical temperatures during heating are chosen based on inactivation data for important food pathogens in cook-chill products with a limited shelf life (Schellekens and Martens, 1992). 95°C is chosen because a heating of 10 min at 90°C is generally accepted to give a 6-*D* reduction of non-proteolytic *Clostridium botulinum*. 6-*D* Reduction of *C. botulinum* type B and E in homogenates of cod or carrot have been obtained after 7 min of heating at 90°C (Gaze and Brown, 1990). Taking into account the time to achieve a temperature of 90°C and the cooling phase, 95°C seems to be a reasonable critical temperature. Heating for 2 min at 70°C is widely accepted to achieve a 6-*D* reduction of *Listeria monocytogenes* (Gaze et al., 1989). Taking into account the inactivation effect during heating or cooling, the next critical temperature is chosen at 75°C. The processing time required for a 7-*D* kill of *Salmonella* in cooked beef and roast beef is 5 min at 62.2°C (Goodfellow and Brown, 1978). 65°C is therefore chosen as the next critical temperature. This way, heating processes are divided in four groups depending on the maximum temperature obtained in the coldest point. Critical temperatures are 95°C, 75°C, 65°C and 55°C. It was decided to work with a limited list of microorganisms in order not to retard the calculations in the prototype system. In products that have been heated in the coldest point of the product to temperatures of above 95°C only spores survive. Consequently, proteolytic *Clostridium botulinum*, *Clostridium perfringens* and *Bacillus cereus* are monitored in these products. At temperatures below 95°C, non-proteolytic *C. botulinum* spores can also survive the heating process. When

Table 2
Relation between maximum temperature in the coldest point and target microorganisms

Process temperature range in the coldest point	Pathogenic target microorganisms	Spoilage target microorganisms
> 95°C	Proteolytic *Clostridium botulinum* *Clostridium perfringens* *Bacillus cereus*	Psychrotrophic *Bacillus* spp.
75–95°C	Microorganisms from above + Non-proteolytic *C. botulinum*	
65–75°C	Microorganisms from above + *Listeria monocytogenes* *Streptococcus* spp.	
55–65°C	Microorganisms from above + *Salmonella* spp. *Staphylococcus aureus* *Aeromonas hydrophila* *Campylobacter jejuni* *Yersinia enterocolitica* *E. coli* *Vibrio* spp.	Enterobacteriaceae Lactic acid bacteria *Brochothrix thermosphacta* *Pseudomonas* spp.

processing temperatures are below 75°C, *Listeria monocytogenes* and *Enterococcus* spp. are non-sporeformers that can cause safety problems. In the lower-temperature region (below 65°C) the list of possible surviving microorganisms becomes large. A summary of the temperature range achieved during heating and target microorganisms chosen is shown in Table 2.

Some unit operations, like slicing, packaging after heating, assembling can recontaminate the food, so all the microorganisms that have caused spoilage or safety problems in the food type under consideration will be assumed to be reintroduced into the product. The level of recontamination depends on the cleanliness of the production room.

The above reasoning allows choice, based on the ingredients and the process, of the most important target microorganisms for a specific food preparation process. The limited number of target organisms saves calculation time and concentrates on the most important microorganisms causing spoilage or safety problems in cook-chill foods.

4. Applications

The expert system can be seen as a computerized HACCP-analysis. From the graphs of the temperature profile and the microbiological growth and inactivation the critical points for microbiological spoilage or safety problems can easily be determined. Corrective actions can be simulated in order to determine process changes with the lowest cost. The expert system offers a full documentation of the process and product: recipe, chemical composition, cost if needed, equipment and process parameters. This documentation is very useful to obtain a certification of the ISO 9000 series. Those involved in product formulation can immediately evaluate the effect of changing ingredients or adding products to lower the pH or a_w to obtain a longer shelf live. Process engineers can determine the effects of changing process parameters, how critical are deviations from set points and the consequences of replacement of a piece of equipment with other cooling or heating characteristics. Another important application of the software is training. By playing with the process parameters, students can have an immediate feedback of the consequences of a change. Fundamental knowledge on heat transfer in foodstuffs and the consequent microbiology can be well illustrated.

Acknowledgements

The authors wish to thank the European Communities for the financial support of the FLAIR (Food Linked Agro-Industrial Research) project AGRF-DT91-0047. Author Jan F. Van Impe is a senior research assistant with the NFWO (Belgian National Fund for Scientific Research). Nutrient Databank (c) Royal Society of Chemistry 1988–1992. The Databank includes Crown copyright material (c) Crown copyright 1978–1992.

References

Gaze, J.E., Brown, G.D., Gaskell, D.E. and Banks, J.G. (1989) Heat resistance of *Listeria monocytogenes* in homogenates of chicken, beef steak and carrot. Food Microbiol. 6, 251–259.

Gaze, J.E. and Brown, G.D. (1990) Determination of the heat resistance of a strain of non-proteolytic *Clostridium botulinum* type B and a strain of type E, heated in cod and carrot homogenate over the temperature range 70 to 92°C. Technical Memorandum 592, CFDRA.

Goodfellow, S.J. and Brown, W.L. (1978) Fate of *Salmonella* inoculated into beef for cooking. J. Food Prot. 41, 598–605.

Meyer, W. (1990) Expert systems in factory management. Knowledge-based CIM. Ellis Horwood, London, 339 pp.

Nicolaï, B.M., Verlinden, B.E., Obbels, W., Schellekens, M., Grobben, J., Martens, T. and De Baerdemaeker, J. (1994) Computational and modeling aspects of a computer-aided design package for the preparation of cook-chill foods. In: Proc. Food Processing Automation Conference, 9–12 February, Orlando, Florida, pp. 190–199.

Schellekens, W. and Martens, T. (1992) 'Sous vide' cooking. Technical Survey Report EUR 15018 EN, European Communities, ALMA, Leuven, Belgium.

Van Impe, J.F., Nicolaï, B.M., Martens, T., De Baerdemaeker, J. and Vandewalle, J. (1992) Dynamic mathematical model to predict microbial growth and degradation during food processing. Appl. Environ. Microbiol. 58, 2901–2909.

Verlinden, B.E. and De Baerdemaeker, J. (1993) Development and validation of prediction models for texture change under varying temperature conditions. Presented at the 6th Int. Congress Engineering and Food, Makuhari Messe, Chiba, Japan, 23–27 May.