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A recursive operations strategy model for managing sustainable chemical product development and production

K.L. Choy[a], G.T.S. Ho[a], C.K.H. Lee[b], H.Y. Lam[a], Stephen W.Y. Cheng[a], Paul K.Y. Siu[a], G.K.H. Pang[c], Valerie Tang[a], Jason C.H. Lee[a], Y.P. Tsang[a]

[a]Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong

[b]Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, Pokfulam, Hong Kong

[c]Department of Electrical and Electronic Engineering, The University of Hong Kong, Pokfulam, Hong Kong

Abstract

Sustainable consumption and production is a critical issue in the chemical industry due to increasing public concerns on environmental and safety issues. Organizations are urged to improve the quality of chemical products while minimizing the environmental impacts during production. In current practice, chemists and formulators have to determine both the ingredients to be used and the machine parameter settings during product development and production. Without appropriate operations strategies for managing sustainable consumption and production, a significant portion of the ingredients, toxic materials and pollutants are wasted or emitted during the trial-and-error processes when developing chemical products. In addition, inappropriate machine parameter settings, such as blending speed and blending temperature, result in inefficient energy use. Motivated by these issues, this paper describes a recursive operations strategy (ROS) model for achieving sustainable consumption and production in the chemical industry. The ROS model first identifies the business strategy, and then defines operations strategies by assessing the competitive priorities and policies with the use of artificial intelligence, including case-based reasoning and fuzzy logic, so as to manage the operations functions. The effectiveness of the model is verified by means of a case study. The results indicate that the model can provide direct guidelines for the users to develop products based on previously developed products. By so doing, the number of trials for testing various ingredient formulae can be reduced, minimizing the ingredient waste. The proposed model is also capable of achieving continuous improvement and determining the optimal production process conditions for avoiding unnecessary energy consumption.

Keywords: *sustainable consumption, sustainable production, product development, operations strategy, case-based reasoning, fuzzy logic*

1. Introduction

In view of improved standards of living, consumers now have higher expectations on products during purchasing. Together with a number of constraints stemming from public concerns, such as environmental, legislative and safety issues (Govindan et al., 2014), there has been a rapid growth in consumer demand for targeted end-use properties (Charpentier, 2009). In particular, chemical-based consumer products, such as soap, shampoo, detergents and cosmetics, have to be more multifunctional, micro-structured, and better engineered than that in the past, so as to meet the consumer requirements. This has posed new challenges to the chemical industry in remaining profitable and in achieving sustainable growth.

Because of the demands of the current industrial environment, a growing awareness of sustainable consumption and production has also been cultivated in the chemical industry. Traditionally, a significant portion of the chemical ingredients is wasted during chemical product development, and the determination of machine parameter settings used in production, such as temperature and speed, relies on human experience. Thus the efficiency of energy use is not monitored or controlled systematically.

In this paper, a recursive operations strategy (ROS) model is proposed to support sustainable consumption and production in the chemical industry. The goal of the model is to improve the sustainability level of the industry with respect to the reduction of waste and energy. Firstly, the overall business strategy of the company is defined. Then, operations strategies are designed to manage the operations functions based on specific competitive priorities. Subsequently, policies are designed with the use of artificial intelligence so as to manage the operations functions. The novelty of the proposed ROS model includes the integration of Case-based reasoning (CBR) and fuzzy logic that is applicable for managing sustainability in the chemical industry. CBR has been widely adopted as a knowledge support tool for solving problems in such experience-rich domains as chemical product development. For instance, Craw et al. (1998) presented a CBR approach for tablet formulation in pharmaceutical product development. Avramenko and Kraslawski (2006) used CBR to formulate fat and oil products. However, previous work mainly focused on improving the effectiveness of the chemical product formulation. The trade-off between effectiveness and sustainability was not fully considered. Furthermore, while the parameters used in chemical product development are usually expressed in linguistic terms, the practical adoption of parameters have to be determined quantitatively. Solely using CBR cannot dynamically suggest the appropriate parameters quantitatively. In line with these, the proposed ROS model is considered novel as it is one of the pioneering models focusing on the improvement of sustainability in chemical product development by integrating CBR and the fuzzy set theories. CBR is applied to provide knowledge support for developing new products such that the number of trials, together with the associated chemical disposal, can be reduced. Fuzzy logic is used to determine the appropriate parameter settings to be used in such a way that the energy consumption can be optimized. Continuous improvement can be made because of the learning abilities of CBR and fuzzy logic in policy design.

The contributions of this paper include a novel recursive operations strategy model specifically designed for the chemical industry, an integrated approach to improving the sustainability of chemical product development and production, and a more sophisticated formulation of operation policies supported by the integration of artificial intelligence techniques. In addition, though CBR has been a promising tool in providing knowledge support in experience-rich domains, it does not take the vagueness of human thought and expression into account when determining the quantitative parameters used in product development and production. This research solves this problem by integrating CBR and fuzzy set theories in order to determine the appropriate parameter settings for maintaining sustainability.

The remainder of the paper is organized as follows: Section 2 reviews the literature related to this study. Section 3 introduces the proposed decision support model. Section 4 presents a case study for demonstrating the feasibility of the model. Section 5 gives the results and discussion. Finally, Section 6 gives conclusions of this study.

2. Literature Review

Considering the continued deterioration of the global environment due to global warming and scarcity of resources (Dadhich et al., 2015), the unsustainable pattern of consumption and production in the industrialized countries is viewed as the main culprit. According to Barber (2007), sustainable consumption and production is generally constructed as two parts: sustainable consumption and sustainable production. Sustainable consumption pays attention to the awareness of changing customer behavior, values and their motivation. On the other hand, sustainable production considers not only the quantity of goods or services, but also its production process, the extraction of raw material and the waste and pollution generated from the production cycle (Pusavec, 2010). With the increasing environmental concerns, a consensus is growing that a certain level of commitment to sustainability practices should be adopted (Hassini et al., 2012), and attention has been paid to minimizing the environmental impacts of process design and development (Nikolopouulou & Ierapetritou, 2012). For a successful enterprise, sustainable consumption and production helps to build a good image for the firm by producing customer-driven products with high quality. Prominent research areas include minimization of waste generated (Hilaly & Sikdar, 1995; Chang

& Hwang, 1996; Dantus & High, 1996; Kheawhom & Hirao, 2004) and reduction of energy consumption (Gadalla et al., 2006; Karuppiah et al., 2008; Sun et al., 2015).

In general, the focus on minimization of waste should not only on the manufacturing processes, but also on the product life cycle, from product development to final disposition (Freeman et al., 1992; Nazzal et al., 2013). Nuner, Bennett & Shaw (2016) investigated the strategic environmental decisions of a luxury car manufacturer to reduce the overall emission during the production process. In chemical product development, most products are developed through experimental trial-and-error approaches (Wibowo & Ng, 2004; Cheng et al., 2009; Hill, 2009; Conte, Gani & Ng, 2011). As a consequence, an appreciable amount of chemical substances are disposed of after experimentation before a product with the desired properties can be formulated successfully.

In order to minimize harmful chemical waste during the manufacturing stage, an enterprise should start from reviewing their business strategy and operation strategy so as to develop a long term sustainable business goal (Gunasekaran & Spalanzani, 2012). Business strategy clearly defines the business goal and mission of a company on how to achieve competitive advantage, while operation strategy is aligned with the organization's overall business strategy considering the competitive priorities, objectives and activities of operation for effective resources allocation (Adamides, 2015; Slack & Lewis, 2011; Teece, 2010). To achieve the business goal in sustainable production, environmental consideration is defined as a core direction to link strategies to operations (Simpson & Samson, 2010). Shoenherr (2012) studied the relationship between sustainable business strategy development on manufacturing plant operations considering environmental concerns. Leonidou et al. (2015) suggested that the implementation of environmental friendly business strategies facilitated the achievement of competitive advantage on product differentiation. By defining appropriate business strategies related to sustainable production, companies can hence formulate operations strategies to minimize waste during the production process. Shavarini et al. (2013) suggested that the business and operations strategies should be aligned to improve the business performance. Kim & Arnold (1996) proposed an operation strategy model to link business strategy with production strategy by considering the tradeoffs between competitive priorities, and setting the performance targets and action plans. Brown & Blackmon (2005) discussed the importance of aligning manufacturing and competitive strategies during operations. Kristal et al. (2010) studied the influence of operations strategy on competitive capabilities in terms of cost, time, quality and flexibility, on business performance. Oltra & Flor (2010) suggested that cost and quality had positive impacts on the business strategies in the relationship between operation strategies and business results while negative impacts were found on time and flexibility through an empirical study. In addition to the above four competitive capabilities, Nand, Singh & Power (2013) proposed an integrated operations strategy model by also considering the asset and operating frontiers. Longoni & Cagliano (2015) examined the environmental and social sustainability concerns when designing the operations strategy. To summarize, it is found that most of past studies mainly focused on investigating the influence of competitive capabilities, operations strategies and business performance through empirical study. By defining research hypotheses in the conceptual framework, determinant factors which would affect decision making on operations strategies are identified. In general, these factors include both internal and external considerations, environmental and social responsibility, competitive advantages and performance outcomes. However, due to the lack of knowledge support and applicable operation strategy model, practitioners can only plan the policy by considering the managerial implications and directions provided based on their past experience. After reviewing the past literature, it was found that the existing generic operations strategy models are unable to fill the gap to provide appropriate guidance in product development and production based on the changes in customer needs. The lack of a systematic approach in policy design and the lack of learning ability in the existing operations strategy models cannot satisfy the upcoming needs for continuously managing the sustainable consumption and production activities in the chemical industry.

In view of this, researchers have attempted to develop knowledge-based systems to help the chemical industry select the appropriate chemical ingredients during product development (Jacobs and Jansweijer, 2000, Lee, Choy & Chan, 2014). In fact, case-based reasoning (CBR) is a good candidate for solving the experience-driven tasks involved in chemical product development. The mechanism of CBR is used to solve new problems by using the experience previously gained from solving similar problems (Haque et al., 2000). The similarity between a new problem case and that of past cases is evaluated. Only the most similar case is retrieved and reused for problem solving. Users are allowed to revise the proposed solution so as to be suitable for the new case. With the knowledge discovered by CBR, industrial practitioners are able to make reference to similar past cases during chemical product development, reducing the number of trials and the chemicals wasted (Lee, Choy & Chan, 2014). Though integrating knowledge management and environmental issues is crucial to sustainable development (Tsang 2010), solely using CBR to provide knowledge support for chemical product development is not sufficient. Extra effort is still required to determine quantitative information, such as the exact parameter settings to be used in production. Lacking this information will hinder the industry from achieving sustainable consumption and production, in particular, the reduction of energy consumption.

In the context of the reduction of energy consumption, the optimal usage of energy is a critical issue. However, the usage of energy, in terms of the amount of resources required, temperature, machine speed and operation time, cannot be described with a single linguistic term such as “low” and “very low”. As a result, the quantitative values used in industrial processes are vague and there are no clear-out boundaries for industrial practitioners to associate the values to one linguistic term. Fuzzy theory is a very appropriate method for obtaining quantitative values based on fuzzy linguistic terms (Ma et al., 2006; Muñoz et al., 2008; Ordoobadi, 2008). It is very useful in dealing with the vagueness of human thought and expression (Tseng, 2013) and its capability in the determination of industrial process parameters has been well proven. For instance, Lao et al. (2011) applied fuzzy logic to determine the optimal temperature for food storage in warehouses. Lee et al. (2014) used fuzzy logic to determine the essential level of resources required for garment production. Nevertheless, it is observed that interest in such an application in the chemical industry is relatively low, in comparison to other industries. To narrow the research gap, there is a need to investigate how fuzzy logic can be used to improve the sustainability of chemical production.

After reviewing the past literature, it is found that the existing business strategy models mainly focus on investigating determinant factors in business development. A systematic approach for policy planning in existing models is neglected. In addition, due to a significant impact on both the waste minimization and the reduction of energy consumption in the chemical industry, this paper provides an extension by designing a novel recursive operations strategy model on the way to formulating operation strategies based on identified competitive policies. The proposed model integrates an operations strategy model with artificial intelligence, including CBR and fuzzy logic, to support sustainable consumption and production from product development to production processes of chemical products.

3. Methodology

In this section, the theoretical construct of the ROS model for improving the sustainability level of the chemical industry is presented, as shown in Fig. 1. In the first tier, a business strategy is formulated so as to define the scope of the ROS model. The business strategy has to align with the mission and core competencies of the organization. More importantly, social responsibilities of the organization have to be taken into account and environmental issues have also to be considered when defining the business strategy. In the context of chemical development and production, major environment issues include the minimization of waste and energy use. In the second tier, operation strategies have to be designed to allocate resources for supporting the overall business strategy. Competitive priorities in terms of cost, quality, time and flexibility are taken into consideration when designing the operation functions. Based on the operation strategies, appropriate policies are formulated in the third tier. The policies are supported by two modules, namely (i) Case-based Ingredient Formulation Module (CIFM), and (ii) Fuzzy-based Parameter Determination Module (FPDM), developed to improve the sustainability at the operation level. The function of the CIFM is to assist in the formulation of chemical products based on previous successful cases. By so doing, the number of trials for testing various ingredient formulae can be reduced, minimizing the ingredient waste. FPDM determines the optimal machine parameters such that the energy involved in production can be used in a more effective way. Based on the output from the two modules, action plans are formulated and users are provided with direct guidelines to address the environmental issues concerned. When the ROS model is implemented recursively over time, more similar cases will be stored in the CIFM whilst more decision rules will be obtained in the FPDM. Because of such a learning ability in the two modules, more informed decisions can be made with the use of the ROS model, and continuous improvement can be provided for future product development and production operations. Details of the ROS model are discussed in the following sections.

3.1 Business Strategy

The aim of a business strategy is to provide a long-term plan for a company. Before the company defines its business strategy, it has to take into considerations various factors, including the mission, market analysis and core competencies. The mission refers to the purpose of a company, which is usually presented in a form of statement to define the nature of the business, target group of clients and future business development. For market analysis, the company has to analyze and monitor the external business environment for market trends, threats, and opportunities in order to understand the needs of the market. Core competencies are critical to compete with other competitors. It involves the identification of the company strengths in the area of facilities, knowledge, technologies and logistics functions which outperform its competitors, and thereby provide valuable benefits for its customers.

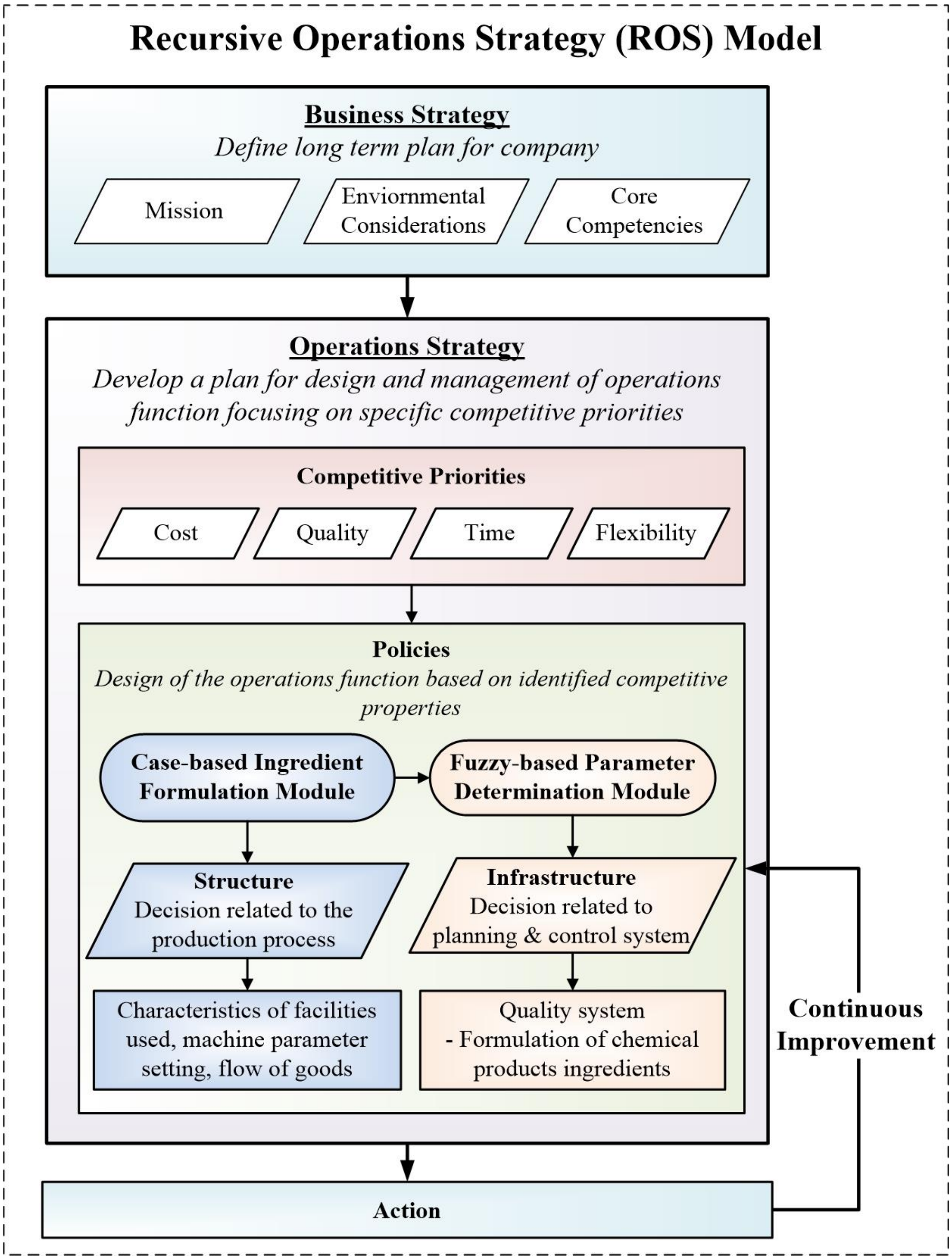


Fig. 1. A recursive operations strategy model for managing sustainable production of chemical products

3.2 Operations Strategy

After the business strategy is developed, the next step is to develop the operations strategy to enable sustainable consumption and production as well as a better use of resources. In general, the operations strategy is a plan for the design and management of the operations functions which focuses on specific competitive priorities. After reviewing the competitive priorities, policies can be designed to provide guidelines on the operations.

3.2.1 Competitive Priorities

Competitive priorities usually refer to four dimensions, which are (i) cost, (ii) quality, (iii) time and (iv) flexibility. To enable sustainable consumption and production in the chemical industry, one of the critical issues is to deal with the increasing public concerns on environmental and safety issues.

In general, the dimension of cost refers to offering products at a low price. To be sustainable in consumption and production, the production process of a product has to be fine-tuned so as to streamline the product flow. The cost may become higher and thus company has to control the cost carefully in order to be competitive in the market.

For the dimension of quality, it mainly considers high performance design, and product and service consistency. In the area of sustainable consumption and production, products not only need to have high quality and performance, but also to be designed in an environmentally friendly way with minimum toxic materials. During the production processes, the production flow and steps should be standardized so as to ensure the product quality and to minimize the emission of waste and pollutants.

The dimension of time considers the amount of time or speed to push the product into the market. Since product development is the starting stage in a product life cycle, the company could become the market leader if a new product can be produced and sold in the market earlier.

For the dimension of flexibility, the company is expected to fulfill the change in product customization and production volume based on customer needs. During the product development and production operations, the company has to revise the ingredients formulation and adjust the parameter settings of the machine tools, which would increase the level of waste and pollutant emission.

To summarize, a company has to pay attention on the abovementioned four dimensions of competitive priorities so as to compete favorably with its competitors and with concern on sustainable consumption and production.

3.2.2 Policies

In this stage, policies are designed based on the operations functions in terms of the identified competitive priorities. Since the concept of sustainability concerns minimizing or eliminating the environmental impacts of the operations functions, two modules, as shown in Fig. 2, are proposed to control and monitor the sustainability level in the production operations. With the knowledge extracted by the CIFM, the generation and screening of a number of chemical ingredients for product development becomes more efficient and effective. In this sense, the ingredient waste or chemical disposal incurred in the development process can be reduced. The output of the CIFM, such as the suggested ingredient formulae and operation procedures, forms part of the input of the FPDM. In the FPDM, a set of fuzzy rules is stored in a knowledge repository. Based on the rules and the inputted parameters, the FPDM determines the optimal machine parameters, such as temperature, speed and time, for production. As a result, the optimal process condition can be determined and the energy use can be more efficient.

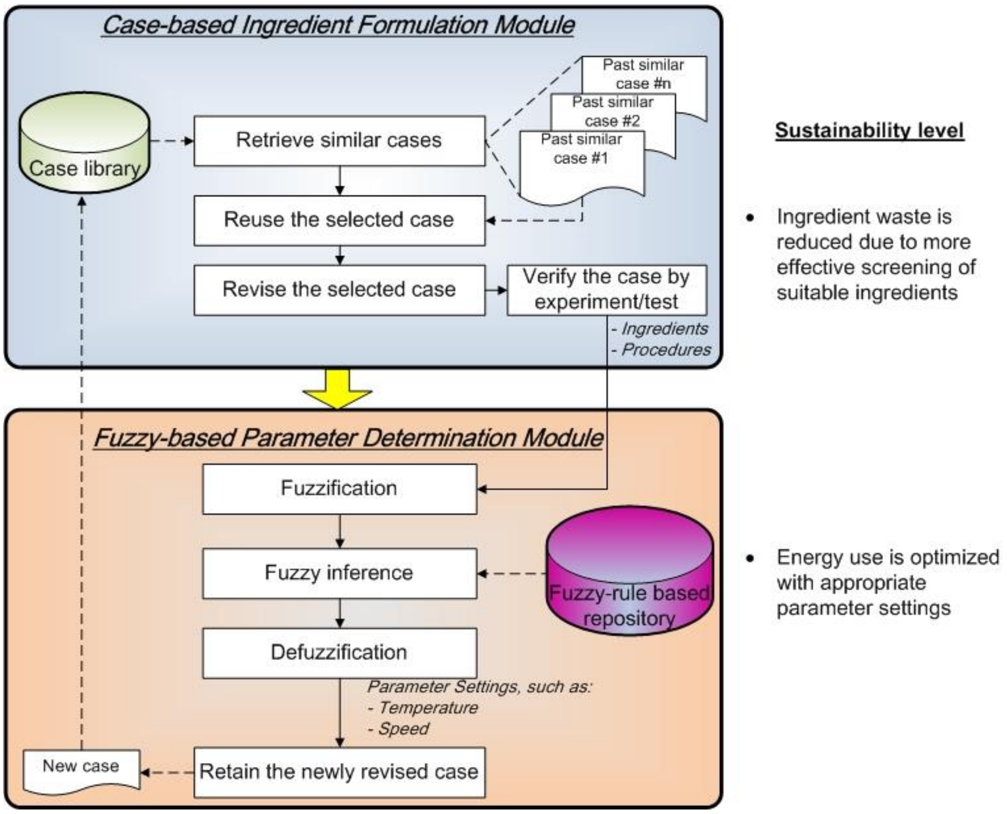


Fig. 2. Policies formulation for sustainable production of chemical products

3.2.2.1 Case-based Ingredient Formulation Module

In the CIFM, CBR is applied to provide decision support for chemical product development, based on previous cases. A case library is used to store historical cases, each of which records the details of the ingredient formulation of a particular product. Based on input enquiries, similar past cases are retrieved and serve as useful references for users, such as chemists and formulators, to develop their products in hand. To facilitate the case retrieval process, both inductive indexing and nearest neighbor approaches are adopted. Firstly, the inductive indexing approach is used to retrieve a batch of potentially useful historical cases. In the case library, historical cases are stored in the structure of an induction tree. There are several levels in the tree, each of which contains different clusters. Each level corresponds to one product characteristic, and cases are allocated to different clusters based on the product characteristics. For instance, if there are nine types of product categories, there will be nine clusters at the level corresponding to the "Product Category", and cases belonging to the same type of category will be stored in the same cluster. With reference to the product characteristics defined by users, a searching path will be formed along the induction tree for case retrieval, connects all the clusters containing the defined product characteristics. Along the path, cases stored in the cluster at the last level are retrieved as potentially useful cases. Using this inductive indexing approach can guarantee that the potentially useful cases retrieved must contain the desired product characteristics.

After a batch of potentially useful cases is retrieved, the nearest neighbor approach is applied to compare the similarities of the cases. It is expected that the case with the highest similarity value will be the most appropriate one for solving the ingredient formulation problem of the new case. Users are able to reuse the knowledge stated in the similar cases and revise it for the suitability of the new case.

The use of CBR helps identify a smaller number of previous cases containing similar chemical products, thereby greatly reducing the search space for ingredient screening and selection. Considering that knowledge and experience serve as a good starting point in chemical product development and production, the cases retrieved in the CIFM facilitates the retention of knowledge and experience gained from developing similar products in the past. On the other hand, new formulae have to be verified by means of experiments and tests in which parameters settings are crucial. In view of this, the FPDM is used to provide decision support on the determination of the parameter settings. After the new ingredient formula is verified, the new case is updated and retained in the case library for future use.

3.2.2.2 Fuzzy-based Parameter Determination Module

The FPDM is composed of an inference engine using fuzzy logic to determine the quantitative values of the machine parameter settings. Firstly, domain experts, such as chemists and formulators, are required to identify both input and output parameters for product development and production. The fuzzy characteristics of the parameters have to be defined in terms of the fuzzy set and membership function. A fuzzy set has the ability to classify elements into a continuous set using the concept of degree of membership. Domain experts are asked to determine the linguistic terms for describing each parameter and then describe each linguistic term by means of membership functions. Furthermore, a set of fuzzy rules has to be generated to indicate the "IF-THEN" relationship between the product properties and the machine settings. An example of a fuzzy rule is shown below.

> IF the pH value of the product is low and the viscosity of the product is low,
> THEN the blending temperature should be slightly increased and the blending

speed should be significantly increased.

Based on the rules, the FPDM starts with a fuzzification process in which the quantitative values of the input parameters are converted into fuzzy sets such as “low” and “high”. Each fuzzy set is associated with a membership function, allowing the parameters to carry a degree of membership in a fuzzy set within a range between 0 and 1. Given the input parameters, the input fuzzy sets are obtained and the inference engine retrieves any rules containing the input fuzzy sets in the knowledge repository. Based on the relationship of the parameters stated in the rules, the output fuzzy sets are generated and converted into quantitative values through the defuzzification process. The quantitative values of the output parameters, such as the optimal change of the blending temperature, are the suggested parameter settings for production.

These learnt parameters are recorded after adoption and stored in the new case for future use. As a consequence, the size of the case library is enlarged over time and the chance of obtaining cases with higher similarity values for problem solving is also increased. Furthermore, it is obvious that the fuzzy logic results determined by the FPDM can be enhanced by improving the quality of the fuzzy rules stored in the knowledge repository. In view of this, a regular evaluation of the fuzzy rules is needed so as to guarantee the decision making quality of the model. Proper refinement of the fuzzy rules will be done so as to make the model possess a learning capability when the fuzzy rules are recursively challenged and improved.

The ROS model is tested in fuzzy environments because, in an industrial environment, uncertainties or vagueness can arise from the characteristics of the chemical products, such as the viscosity of the products, as well as the process parameter settings used in production, such as the temperature and the speed of the machines. It is thus more convenient for the decision makers to describe these parameters in linguistics terms such as “low” and “high”. The ROS model adopts fuzzy logic to imitate human capability of making decisions. The knowledge acquired in terms of fuzzy rules has more physical meaning as conventional terms are used to describe the characteristics of the products.

4. Case Study

To validate the effectiveness of the proposed model, a case study is conducted in a Hong Kong-based personal care product manufacturing company. In current practice, there are no formal guidelines provided for the chemists and formulators when they are developing new chemical products. Considering that the development of chemical products consists of a series of specialized tasks, the quality of the products developed heavily relies on human experience. Without any decision support tools, it is difficult to guarantee the quality of the products, resulting in repetitive and time consuming product development. On the other hand, it is vital to retain the knowledge related to product development and production within the company, providing decision support for the less experienced staff.

To tackle the abovementioned problems, the ROS model is implemented in the company to achieve the goal of sustainable consumption and production.

4.1 Business Strategy Identification

The case company is listed on the Hong Kong Stock Exchange and is dedicated to supply a wide range of chemical products to hotels, airlines, and the hospitality and personal care industries. It manufactures products such as cosmetics, skin care and bath and body care products. It has a number of production facilities throughout the Asia Pacific region and advanced chemical and microbiological laboratories for product formulation and testing to ensure the quality of its products. The mission of the case company is to develop environmental friendly chemical products to hotels, airlines, and the hospitality industry and become the market leader in the personal care industry. Its competitive advantage is its ability to provide customized products on the request of its customers, since the company has a product development and production team which can directly respond to customers' needs.

4.2 Competitive Priorities for Defining Operations Strategy

Referring to the four dimensions of competitive priorities, i.e. cost, quality, time and flexibility, the case company considers that quality is the most important concern in fulfilling customer orders in regard to sustainable consumption and production. Currently, chemists and formulators have to determine both the ingredients to be used and the machine parameter settings during product development and production. During the product development and production operations, a significant portion of the ingredients are wasted, and toxic materials and pollutants are emitted during the trial-and-error processes when developing chemical products. It brings environmental concerns to the company, and therefore quality becomes a critical issue to be tackled in minimizing the emission of waste and pollutants.

4.3 Policies Design with the CIFM

In order to develop the CIFM, a case library has to be constructed and the past product development records have to be stored as cases. Another critical issue in the development of an effective case-based model is the design of the case retrieval mechanism. In the CIFM, the inductive indexing approach is firstly applied to retrieve a group of matching cases, followed by the nearest neighbor approach to rank the cases according to the similarity values.

4.3.1 Construction of the case library

To construct the case library, data related to the product attributes are collected. The attributes collected can be classified as objective and subjective attributes. Objective attributes refer to the general description of a product, such as product category, color, function and weight, while subjective attributes refer to the sensorial properties of a product based on human perception, such as product softness, stickiness and greasiness. Past product records are stored as cases in the case library and the criteria for searching for cases are based on both the subjective and objective attributes. Domain experts are required to classify past cases into different clusters according to their objective product attributes, and have to input a score ranging from 1 to 10, for each subjective product attribute. Fig.3 shows some attributes used in the case library.

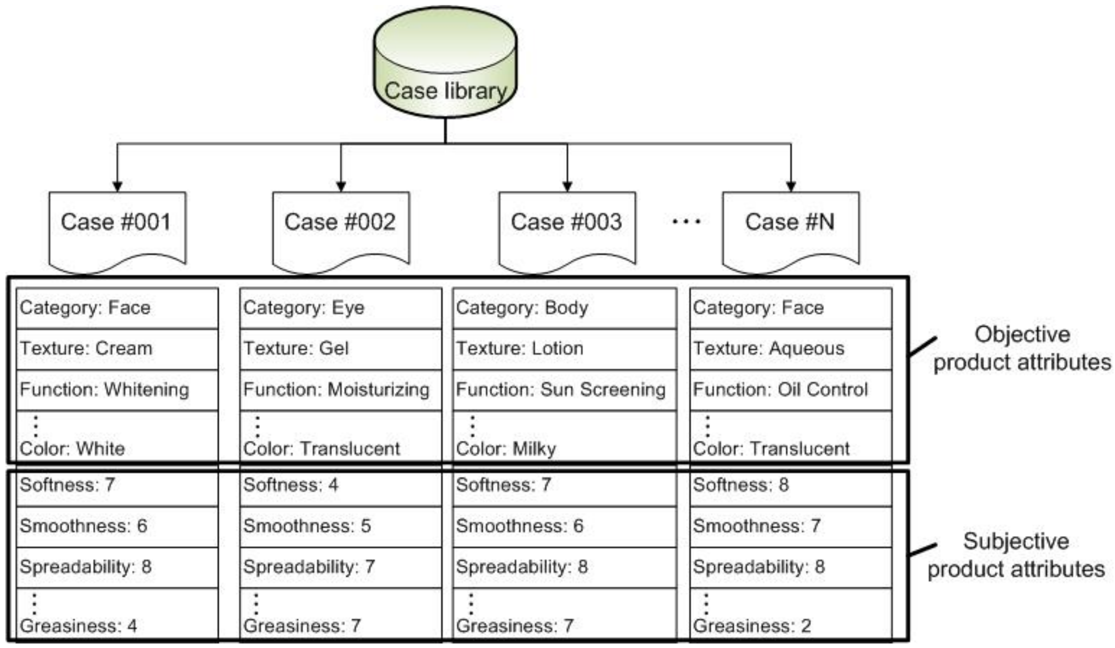


Fig. 3. Product attributes in the case library

In addition, the content of the cases has to be designed, including the ingredients, operational procedures, and parameter settings used during product development. For example, any chemicals involved in the product, such as active ingredients, solvents and additives, are listed in the content. Furthermore, the procedures and the process conditions used to mix the ingredients together for achieving the desired product specification are also recorded. In the CIFM, when a case is retrieved and selected by users, the content of the case will be displayed to users, allowing them to make use of the stored knowledge for developing the new products in hand.

4.3.2 Design of the case retrieval mechanism

To retrieve cases from the case library, the inductive indexing approach is firstly applied in order to temporarily retrieve a group of cases based on the objective product attributes. This involves the construction of an induction tree, with different levels corresponding to the objective product attributes. Cases are allocated to different clusters under each level of the tree, based on their product attributes. When users input the desired product attributes during product development, a search path is identified, as shown in Fig. 4, to browse the induction tree and retrieve cases from a particular cluster. Using this inductive indexing approach can ensure that the cases retrieved contain the objective product attributes identical to those defined by the users.

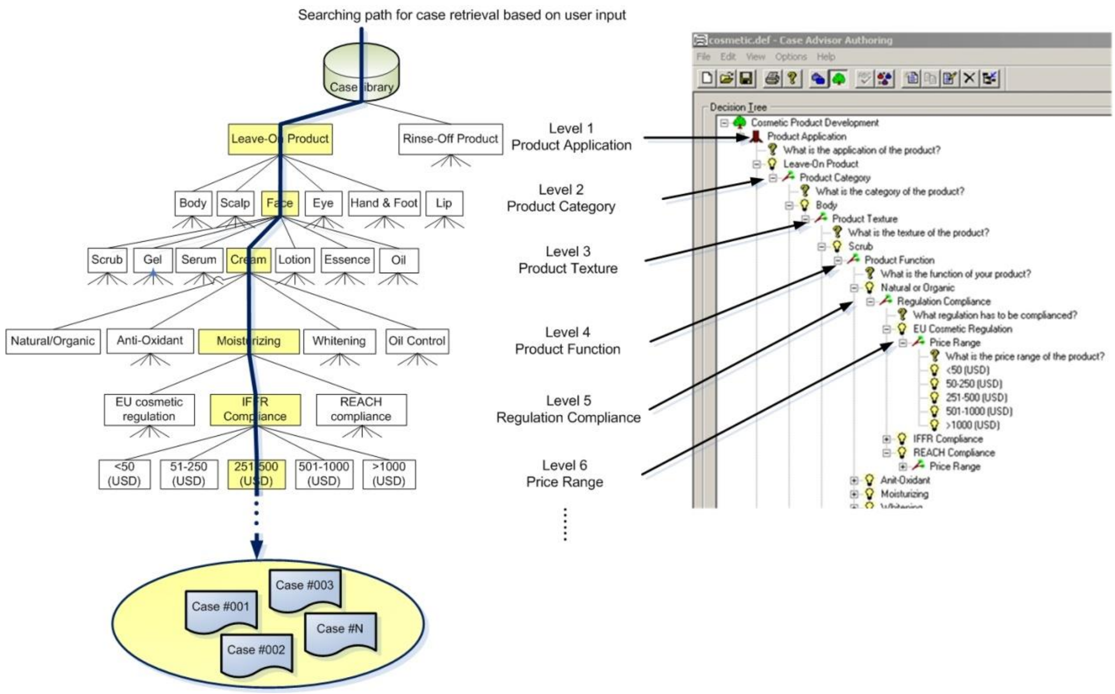


Fig. 4. The structure of the induction tree for case retrieval

After a cluster of cases is retrieved, the nearest neighbor approach is applied to calculate the similarity value of the cases by comparing the scores of the subjective product attributes between the new case and the retrieved cases. In addition, considering that some attributes could be relatively more important, weightings are assigned to the subjective product attributes based on their importance. The similarity value (V) is calculated as:

$$V = \frac{\sum_{i=1}^{n} w_i \times (10 - |S_i^R - S_i^N|)/10}{\sum_{i=1}^{n} w_i}$$

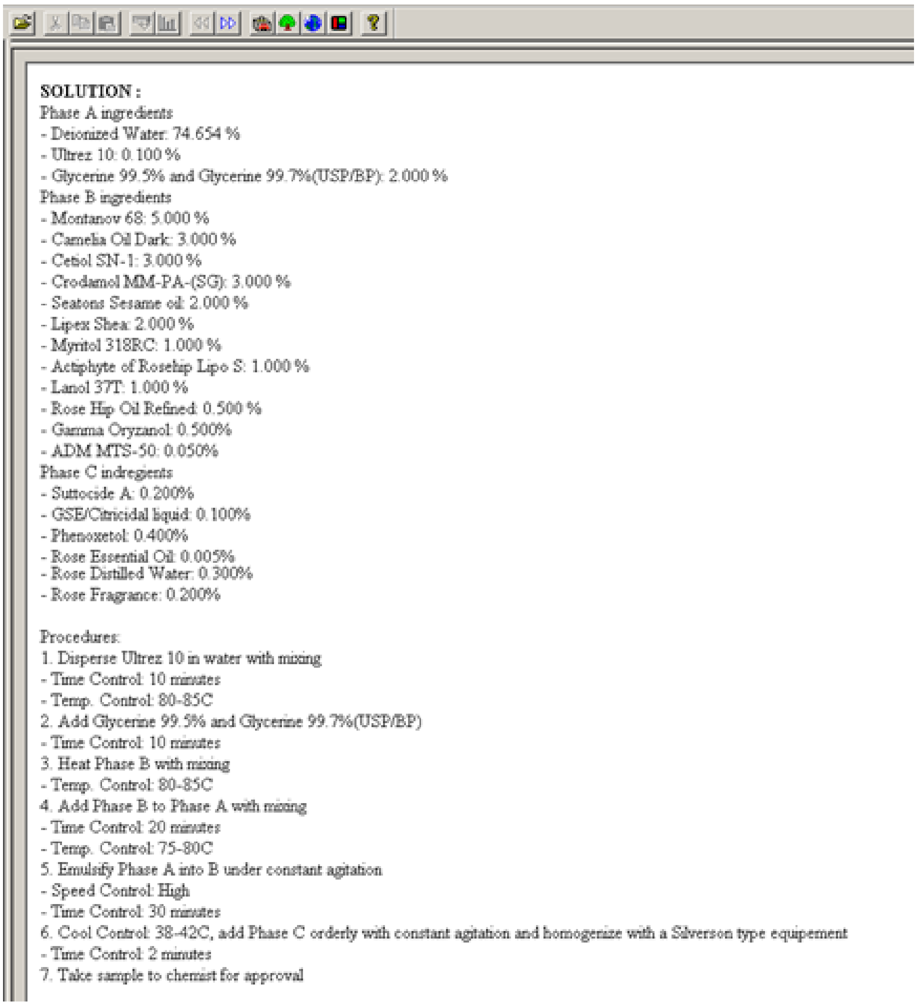
where w_i is the weighting of the subjective product attribute i, S_i^R is the score of the subjective product attribute i in the retrieved case, and S_i^N is the score of the subjective product attribute i in the new case, for $i = 1, 2, \ldots n$. Table 1 is an example showing the details of the subjective product attributes in a retrieved case and according to this case, the similarity value is

= (1x0.9 + 5x0.8 + 3x0.6 + 1x1 + 3x0.9)/(1+5+3+1+3) = 0.8.

Table 1. Scores of the subjective product attributes in a retrieved case

Subjective product attribute	Weighting (w)	Score in the retrieved case (S^R)	Score in the new case (S^N)	$(10-\lvert S^R-S^N \rvert)/10$
Softness	1	7	6	0.9
Smoothness	5	6	8	0.8
Spreadability	3	8	4	0.6
Greasiness	1	5	5	1
Stickiness	3	3	2	0.9

After the calculation of the similarity values of all the retrieved cases, the cases are ranked according to their similarity values and then displayed to users. Users are able to view the content of each case and select the most appropriate one for assisting them in developing a new product. The content of the selected case, as shown in Fig. 5, provides the users with insights on the use of ingredients and the process conditions for the formulation process. To ensure product safety, the ingredient formulae have to be verified by experiments and passed a variety of tests.


SOLUTION :
Phase A ingredients
- Deionized Water: 74.654 %
- Ultrez 10: 0.100 %
- Glycerine 99.5% and Glycerine 99.7%(USP/BP): 2.000 %
Phase B ingredients
- Montanov 68: 5.000 %
- Camelia Oil Dark: 3.000 %
- Cetiol SN-1: 3.000 %
- Crodamol MM-PA-(SG): 3.000 %
- Seatons Sesame oil: 2.000 %
- Lipex Shea: 2.000 %
- Myritol 318RC: 1.000 %
- Actiphyte of Rosehip Lipo S: 1.000 %
- Lanol 37T: 1.000 %
- Rose Hip Oil Refined: 0.500 %
- Gamma Oryzanol: 0.500%
- ADM MTS-50: 0.050%
Phase C indregients
- Suttocide A: 0.200%
- GSE/Citricidal liquid: 0.100%
- Phenoxetol: 0.400%
- Rose Essential Oil: 0.005%
- Rose Distilled Water: 0.300%
- Rose Fragrance: 0.200%

Procedures:
1. Disperse Ultrez 10 in water with mixing
- Time Control: 10 minutes
- Temp. Control: 80-85C
2. Add Glycerine 99.5% and Glycerine 99.7%(USP/BP)
- Time Control: 10 minutes
3. Heat Phase B with mixing
- Temp. Control: 80-85C
4. Add Phase B to Phase A with mixing
- Time Control: 20 minutes
- Temp. Control: 75-80C
5. Emulsify Phase A into B under constant agitation
- Speed Control: High
- Time Control: 30 minutes
6. Cool Control: 38-42C, add Phase C orderly with constant agitation and homogenize with a Silverson type equipement
- Time Control: 2 minutes
7. Take sample to chemist for approval

Fig. 5. Content of a case

4.4 Policies Design with FPDM

During the formulation process, how the ingredients are mixed under different conditions will affect the quality of the products. Solely based on the content of the case retrieved is not sophisticated enough for users to determine the appropriate formulation process conditions, such as the heating temperature, operation time and blending speed. In view of this, the FPDM aims at determining the appropriate parameter settings to be used in formulating chemical products.

4.4.1 Definition of fuzzy characteristics of parameters

Knowledge acquisition from domain experts is undertaken in order to identify the input and output parameters of the FPDM. In this case study, the blending operation in the Emulsifying Department is referred to. Examples of the input parameters include the capacity of the batch tank and the pH value of the product, while the output parameters are the blending temperature change and the blending speed change.

Compared to other artificial intelligence approaches, fuzzy logic uses qualitative descriptions to provide quantitative values. Therefore, domain experts are required to describe each parameter using fuzzy sets and membership functions. They have to determine some conventional linguistic terms, such as “low” and “high” to describe the quantitative values of the parameters, and define the fuzzy characteristics of each term by means of membership functions, such as the triangular and trapezoidal membership functions. Fig. 6 shows some examples of the membership functions of the parameters.

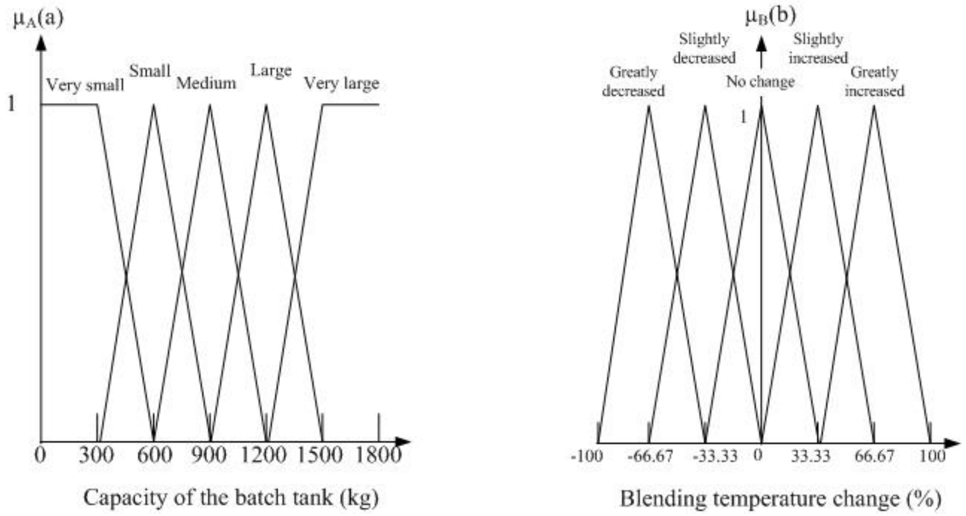


Fig. 6. Membership functions of parameters

4.4.2 Collection of fuzzy rules

Since fuzzy logic relies on a rule base to relate the input and output parameters, a set of IF-THEN fuzzy rules have to be collected before execution of the FPDM. The fuzzy rules are defined directly from domain experts who need to be aware of the completeness, consistency, simplicity and non-redundancy of the rules. Furthermore, the rules obtained are checked at the management level before storing in the rule-based repository, and evaluation of the rules is carried out regularly.

After the input parameters are fuzzified and converted into input fuzzy sets, relevant fuzzy rules are triggered for determining the output fuzzy sets. For each triggered rule, the output fuzzy sets construct an individual fuzzy region based on the membership functions, and a consequent fuzzy region is a combination of the individual fuzzy regions of all the triggered rules. Fig. 7 illustrates how a consequent fuzzy region of an output parameter is obtained. The suggested quantitative value of the output parameter can be obtained by calculating the centre of area of the consequent fuzzy region.

With the use of the FPDM, users are provided with knowledge support when they have to determine the appropriate blending temperature and speed for the formulation of chemical products. The knowledge obtained allows them to effectively develop and manufacture products with the desired properties, minimize chemical disposal incurred in the process as well as improve the efficiency of energy use with optimal parameter settings. The learnt parameter settings form part of the content of the new case and are stored in the case library for future use. As a consequence, a sustainable improvement in chemical development and production can be achieved in the long term.

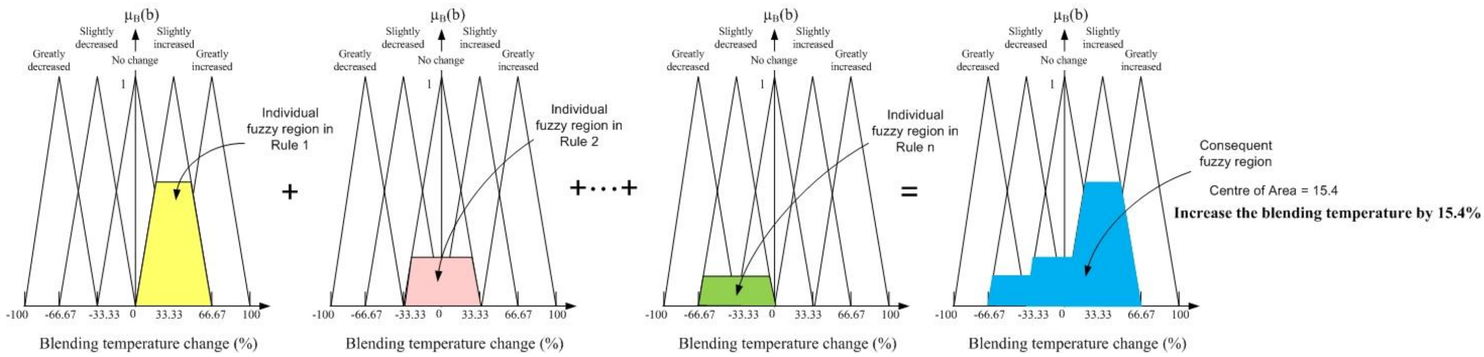


Fig. 7. Determination of quantitative values of an output parameter based on centre of area

5. Results and Discussion

In this section, the results obtained from the case study are presented. Three product items are selected for the pilot run of the model. The number of trials and the amount of chemical disposal incurred in the development process of each item are measured. The results obtained are shown in Table 2.

Table 2. Results obtained after the use of the decision support model

Product	Reduction of number of trials	Reduction of chemical disposal
(i)	9%	24%
(ii)	13%	22%
(iii)	7%	11%
Average:	9.67%	19%

It is found that the ROS model supports sustainable chemical product development and production by offering a series of benefits which include:

(i) Reduction of number of trials by referring to how similar products were formulated

The ROS model provides knowledge support for the chemists and formulators while they are developing new chemical products. With reference to the ingredients in formulating similar products previously, the average number of trials during product development is reduced by 9.67%. As the desired product performance requires the selection of the appropriate chemical ingredients, the chemists and formulators can retrieve and refer to the formulae used in the similar past cases when they are selecting ingredients for product formulation. As a result, the number of trials for verifying the formulae of the new products is reduced.

(ii) Reduction of chemical disposal with a faster track of ingredient formulae

Chemical disposal, which was usually wasted in different trials without the use of the CBR, is reduced by 19% after the implementation of the ROS model. Traditionally, chemical product development is an iterative process, as products, practically, are designed though experiment-based trial-and-error approaches. The potential search space is very large as this involves the generation and screening of an enormous number of chemical ingredients. As a consequence, a significant portion of ingredients, toxic materials and pollutants could be wasted or emitted during the trial-and-error processes. On the other hand, the ROS model, with the integration of CBR and fuzzy logic, provides users with faster tracking of the ingredient formulae. Users input the desired requirements of the new product to be developed and they will then be provided with ingredient formulation solutions based on similar past cases, greatly reducing the potential search. In this sense, the ROS model facilitates sustainable product development and production in the chemical industry by minimizing the waste associated in the process.

(iii) Elimination of difficulties in describing product attributes and machine settings quantitatively

In general, a crucial feature of chemical products is that consumers judge the quality of products based on functionality and performance attributes, rather than technical specifications (Costa, Moggridge & Saraiva, 2006). Considering that some functionality and performance attributes, such as smoothness and greasiness, are subjective, the CIFM is able to capture the subjective attributes quantitatively by allowing the users to describe them in terms of a score ranging from 1 to 10. This facilitates comparisons of the similarity of products and eliminates the difficulties in specifying qualitative product attributes. Furthermore, the fuzzy logic in the FPDM takes the vagueness of human thought and expression into account. Users are allowed to use linguistic terms for describing the product attributes and machine settings, which are more convenient and practical in real-life situations. By so doing, quantitative values are systematically generated by the ROS model in order to determine the appropriate machine settings for sustainable production.

(iv) Continuous improvement for maintaining sustainability

In addition to the use of ingredients, process conditions also affect the resultant quality of chemical products. In the case study, the suggested temperature and speed of the blending operation for chemical production are based on the fuzzy rules stored in the knowledge repository. After regular evaluation of the rules, the learnt process parameters are nearly optimal, resulting in a more efficient use of energy. The parameter settings determined by the FPDM form part of the content of the new case. As every new case will be retained in the case library for future use, it is expected that more potentially useful cases can be stored over time and the chance of obtaining cases with higher similarity values will be continuously increased. When there are new problems to be solved, knowledge support will be provided for the users to make quality decisions by referring to highly similar cases, and, based on the stored knowledge, sustainable consumption and production in the manufacture of chemical products can be continuously maintained in the long term.

6. Conclusions

This paper presents a novel recursive operations strategy (ROS) model integrating business and operations strategies to facilitate sustainable consumption and production in the chemical industry. By aligning business strategy and operations strategy, companies can holistically define their mission and core competencies when formulating operation policies. This applicable ROS model integrating artificial intelligence techniques provides knowledge support for formulating operation policies, which shows significant improvement in waste reduction. During the chemical product development and production process, significant amounts of ingredients were wasted by the traditional practice of trial-and-error. This paper solves this problem by integrating CBR and fuzzy set theories in the operational level so as to determine the appropriate parameter settings for maintaining sustainability. The aim of using CBR is to narrow the search space for obtaining the appropriate formulae from the large number of chemicals available. By so doing, chemical product development becomes more effective, thereby greatly reducing the number of trials and the resultant chemical waste. In addition, fuzzy logic is employed to ensure that the production process conditions are optimal, leading to a more efficient use of energy. The learned process condition is also recorded and stored as part of the new case for future use. In the long term, the quality of the cases stored in the model can be continuously improved, leading to a sustainable improvement in the development and manufacture of chemical products. On the other hand, the fuzzy logic results greatly depend on the quality of the fuzzy rules. Thereby, regular evaluation of the fuzzy rules is encouraged. Further work will focus on the use of hybrid data mining approaches for the automatic generation of fuzzy rules.

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References

Adamides, E.D. (2015), Linking operations strategy to the corporate strategy process: a practice perspective, *Business Process Management Journal, 21(2*), pp.267 - 287

Avramenko, Y., Kraslawski, A. (2006). Similarity concept for case-based design in process engineering. *Computers and Chemical Engineering 30*(3), 548-557.

Barber, J. (2007), Mapping the movement to achieve sustainable production and consumption in North America, *Journal of Cleaner Production*, *15,* 499–512.

Brown, S. and Blackmon, K. (2005), Aligning manufacturing strategy and business level competitive strategy in new competitive environments: the case for strategic resonance, *Journal of Management Studies 42 (4)*, 793-816.

Chang, C. T., & Hwang, J. R. (1996). A multiobjective programming approach to waste minimization in the utility systems of chemical processes. *Chemical Engineering Science 51*(16), 3951-3965.

Charpentier, J. C. (2009). Perspective on multiscale methodology for product design and engineering. *Computers and Chemical Engineering 33*(5), 936-946.

Cheng, Y. S., Lam, K. W., Ng, K. M., Ko, R. K. M., Wibowo, C. (2009). An integrative approach to product development – a skin-care cream. *Computers and Chemical Engineering 33*(5), 1097-1113.

Conte, E., Gani, R., & Ng, K. M. (2011). Design of formulated products: a systematic methodology. *AIChE Journal 57*(9), 2431-2449.

Costa, R., Moggridge, G. D. and Saraiva, P. M. (2006). Chemical product engineering: an emerging paradigm within chemical engineering. *AIChE Journal 52*(6), 1976-1986.

Craw, S., Wiratunga, N., Rowe, R. (1998). Case-based design for tablet formulation, In *Advances in case-based reasoning*. Berlin, Heidelberg: Springer.

Dadhich, P., Genovese A., Kumar, N., & Acquaye, A. (2015). Developing sustainable supply chains in the UK construction industry: a case study. *International Journal of Production Economics 165*, 271-284.

Dantus, M.M., & High, K.A. (1996). Economic evaluation for the retrofit of chemical processes through waste minimization and process integration. *Industrial & Engineering Chemistry Research 35*(12), 4566-4578.

Freeman, H., Harten, T., Springer, J., Randall, P., Curran, M. A., & Stone, K. (1992). Industrial Pollution Prevention! A Critical Review. *Journal of the Air & Waste Management Association*, 42(5), 618-656.

Gadalla, M., Olujić, Ž., Jobson, M., & Smith, R. (2006). Estimation and reduction of CO 2 emissions from crude oil distillation units. *Energy 31*(13), 2398-2408.

Govindan, K., Jafarian, A., Khodaverdi, R., & Devika, K. (2014). Two-echelon multiple-vehicle location-routing problem with time windows for optimization of sustainable supply chain network of perishable food. *International Journal of Production Economics 152*, 9-28.

Gunasekaran, A. & Spalanzani, A. (2012). Sustainability of manufacturing and services: Investigations for research and applications, *International Journal of Production Economics 140*, 35-47.

Haque, B.U., Belecheanu, R.A., Barson, R.J., & Pawar, K.S. (2000). Towards the application of case based reasoning to decision-making in concurrent product development (concurrent engineering). *Knowledge-Based Systems 13*(2), 101-112.

Hassini, E., Surti, C., & Searcy, C. (2012). A literature review and a case study of sustainable supply chains with a focus on metrics. *International Journal of Production Economics 140*(1), 69-82.

Hilaly, A. K., & Sikdar, S.K. (1995). Pollution balance method and the demonstration of its application to minimizing waste in a biochemical process. *Industrial & Chemistry Research 34*(6), 2051-2059.

Hill, M. (2009). Chemical product engineering – the third paradigm. *Computers and Chemical Engineering 33*(5), 947-953.

Jacobs, R., & Jansweijer, W. (2000). A knowledge-based system for reactor section. *Computers and Chemical Engineering 24*(8), 1871-1801.

Karuppiah, R., Peschel, A., Grossmann, I.E., Martín, M., Martinson, W. & Zullo, L. (2008). Energy optimization for the design of cornbased ethanol plants. *AIChE Journal 54*(6), 1499-1525.

Kheawhom, S. & Hirao, M. (2004). Environmentally benign separation process synthesis. *Journal of Chemical Engineering 37*(2), 243-252.

Kim, Y.H., Sting, F.J. & Loch, C.H. (2014). Top-Down, Bottom-Up, or Both? Toward an Integrative Perspective on Operations Strategy Formation. *Journal of Operations Management, 32* (7-8), 462-474

Kristal, M.M., Huang, X. & Roth, A.V. (2010). The effect of an ambidextrous supply chain strategy on combinative competitive capabilities and business performance, *Journal of Operations Management 28 (5)*, 415-429.

Lao, S.I., Choy, K.L., Ho, G.T.S., Tsim, Y.C., & Lee, C.K.H. (2011). Real-time inbound decision support system for enhancing the performance of a food warehouse. *Journal of Manufacturing Technology Management 22*(8), 1014-1031.

Lee, C. K. H., Choy, K. L. and Chan, Y. N. (2014). A knowledge-based ingredient formulation system for chemical product development in the personal care industry.

Computers and Chemical Engineering 65, 40-53.

Lee, C.K.H., Choy, K.L., Law, K.M.Y. & Ho, G.T.S. (2014). Application of intelligent data management in resource allocation for effective operation of manufacturing systems. *Journal of Manufacturing Systems 33*(3), 412-422.

Leonidou, L.C., Fotiadis, T.A., Christodoulides, P., Spyropoulou, S. & Katsikeas, C.S. (2015), Environmentally friendly export business strategy: Its determinants ad effects on competitive advantage and performance, *International Business Review 24*, 798-811.

Longoni, A. & Cagliano, R. (2015). Environmental and social sustainability priorities: Their integration in operations strategies, *International Journal of Operations & Production Management 35 (2)*, 216 - 245.

Linnhoff, B. (1993). Pinch analysis – A state of the art overview. *Transaction on IChemE Part A*, 71, 503-522.

Ma, J., Chen, S. & Xu, Y, (2006). Fuzzy logic from the viewpoint of machine intelligence. *Fuzzy Sets and Systems 157*(5), 628-634.

Muñoz, M.J., Rivera, J.M., & Moneva, J.M. (2008). Evaluating sustainability in organizations with a fuzzy logic approach. *Industrial Management & Data Systems 108*(6), 829-841.

Nand, A.A., Singh, P.J. & Power, D. (2013). Testing an integrated model of operations capabilities: An empirical study of Australian airlines, *International Journal of Operations & Production Management 33 (7)*, 887-911.

Nazzal, D., Batarseh, O., Patzner, J., & Martin, D.R. (2013). Product servicing for lifespan extension and sustainable consumption: an optimization approach. *International Journal of Production Economics 142*(1), 105-114.

Nikolopouulou, A., & Ierapetritou, M. G. (2012). Optimal design of sustainable chemical processes and supply chains: A review. *Computers and Chemical Engineering 44*, 94-103.

Nuner, B., Bennett, D. & Shaw, D. (2016). Green operations strategy of a luxury car manufacturer, *Technology Analysis & Strategic Management 28(1)*, 24-39.

Oltra, M.J. & Flor, M.L. (2010), The moderating effect of business strategy on the relationship between operations strategy and firm's result, *International Journal of Operations & Production Management 30 (6)*, 612-638.

Ordoobadi, S.M. (2008). Fuzzy logic and evaluation of advanced technologies. *Industrial Management & Data Systems 108*(7), 928-946.

Pusavec, F., Krajnik, P., Kopac, J. (2010), Transitioning to sustainable production–part I: application on machining technologies, *Journal of Cleaner Production*, *18* (2), 174–184

Schoenherr, T. (2012). The role of environmental management in sustainable business development: A multi-country investigation, *International Journal of Production Economics 140 (1)*, 116-128.

Shavarini, S.K., Salimian, H., Nazemi, J., & Alborzi, M (2013). Operations strategy and business strategy alignment model (case of Iranian industries), *International Journal of Operations & Production Management, 33(9)*, pp.1108 - 1130

Simpson, D. & Samson, D. (2010), Environmental strategy and low waste operations: exploring complementarities, *Business Strategy and the Environment 19(2)*, 104-118.

Slack, N., Lewis, M. (2011), Operations Strategy (3rd ed.) Pearson Education Limited, Harlow, England

Sun, Z., Li, Lin, Bego, A., & Dababneh, F. (2015). Customer-side electricity load management for sustainable manufacturing systems utilizing combined heat and power generation system. *International Journal of Production Economics 165*, 112-119.

Teece. D.J. (2010). Business models, business strategy and innovation, *Long Range Planning 43(2-3)*, 172-194.

Tseng, M.L. (2010). Using linguistic preferences and grey relational analysis to evaluate the environmental knowledge management capacity. *Expert Systems with Applications 37*(1), 70-81.

Tseng, M.L., & Chiu, A.S.F. (2013). Evaluating firm's green supply chain management in linguistic preferences. *Journal of Cleaner Production 40*, 22-31.

Wibowo, C., & Ng, K. M. (2004). Product-centered processing: manufacture of chemical-based consumer products. *AIChE Journal 48*(6), 1212-1230.