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A life cycle based method to minimise environmental impact of dairy production through product sequencing

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Abstract

The trend of increasing the number of dairy products for sale affects their environmental impact in a life cycle perspective. During dairy processing, the production schedule is affected by more frequent product changes, hence also cleaning operations. This causes more milk waste, use of cleaning agents and water. The amount of milk waste depends on the product change technique used, which is determined by the characteristics of the product. A method was designed to calculate the sequence, which, for a given set of yoghurt products, minimises milk waste. A heuristic method, based on the strive to minimise production waste combined with production rules, was worked out. To determine whether the heuristic solution gives the best possible sequence from an environmental perspective, an optimisation was also made. The analytical method used for optimisation was able to handle 21 products and verified the heuristic method for a waste minimised sequence up to that level. It is also highly probable that for sequences including a greater number of items waste can be minimised with the same heuristic method. A successful demonstration of the possibility to make a more complete environmental assessment was fulfilled by connecting the sequencing model to conventional life cycle assessment methodology.

Keywords: Production scheduling; Minimisation; Yoghurt; Environment; LCA

1. Introduction

The number of milk products for sale is rising. In fact the dairy sector leads Europe in terms of innovative markets in the food sector, followed by ready made meals [1]. This development is driven both by the industry and by customer demand. The milk produced at farms has to be processed promptly into products at the dairy. Since changing the volume of milk production at a dairy farm is a slow process, it is neither possible to adjust the amount of incoming milk to rapidly changing market requirements, nor can milk be stored for long periods of time. As the volume of milk to the dairy cannot easily be adjusted, the mix of outgoing products is changed instead. A larger variety of products makes it easier to balance the outflow from the dairy with the inflow. In addition, increased dairy product diversity is driven by the industry's effort to stimulate greater demand for its produce, and consumer demand for new types of products.

At the same time environmental concern in society has grown strong. From a life cycle perspective, diversity affects the environmental impact of dairy products in different ways. At the dairy, production scheduling becomes a key activity, influencing a wide range of issues with environmental implications, such as waste of product, need for cleaning of production equipment

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and waste of packaging. Also consumers may generate more waste as they buy a wider variety of products in smaller packages. With a broader spectrum of products in the fridge, more products may be wasted because they are not used in time. Waste also occurs because some product is always left in the container, and because smaller containers lead to an increase in packaging waste. The risk of increased waste of milk, in both dairies and households, consequently may lead to increased raw milk production.

The production of different dairy products is affected by increased product diversity to varying degrees. For example, the production of consumer milk, milk powder and cheese are not affected to any large degree. This depends on a high production volume of consumer milk, that only one type of milk powder is produced and the long storing time and shelf life of cheese. This makes production of the same cheese during several days possible, with no interruptions for product change reasons. Cultured products such as yoghurt, on the other hand, have the largest variation. The wide variety of products combined with a relatively short shelf life (23 days) leads to several changes of flavours in the same production equipment in just one day. Such changes always cause a certain amount of product waste which cannot be recycled into the process but instead becomes either animal feed or waste. Production of cultured products such as yoghurt is therefore most interesting for a product diversity study.

This paper concentrates on how adverse environmental effects depending on increased product diversity may be counteracted at the dairy production unit level. The activity of product scheduling including sequencing of products then comes to the fore. This paper describes an inter-disciplinary approach, making use of both production scheduling and environmental systems analysis to counteract the adverse environmental consequences of the ongoing development towards increased product diversity. Production scheduling at Swedish dairies today is not considered an environmental issue. Instead it is in general based on economy, food safety, utilisation of process equipment, labour working hours or sometimes simply the habit the way things are done. Heuristic methods are in general used for sequencing. They are often implemented as a computerised algorithm, but man-made sequences based on experience are used as well. It has not come to our knowledge that mathematically optimised sequences are used in dairies presumably depending on the theoretical difficulties to optimise large sequencing problems.

Production scheduling has received much attention in the literature, although few papers include environmental considerations. Various models, algorithms and optimisation tools have been used for solving production scheduling problems in the food sector. A heuristic simulation model based on operations research applied to a theoretical convenience food system was developed by Guley and Stinson [2]. Their purpose was to determine the most efficient production schedule by finding the best way of selecting the sequence of items processed in the same equipment when two or more menu items are competing for priority. Another heuristic simulation model, based on network representation, was devised for the bacon industry [3]. The purpose and heuristic rules are of the same kind as in the study by Guley and Stinson [2]. To enable improvement of production scheduling, from the perspective of fulfilling customer needs, a model based on finite capacity planning was used for low fat spreads and cider [4]. Alternative designs for milk powder production were analysed with both a process design tool and tools for economic analysis [5]. A similarity between most scheduling studies is that they use either a cost based criterion or a system performance criterion. Only two studies were found that took the environment into account. Minimisation of process-sequence dependent changeover waste (as an environmental issue) in product scheduling was conducted in a study of a theoretical batch production unit [6]. Although the procedure optimises a target function that accounts for the amount of product changeover waste, it does not include any other explicit environmental parameters or categories. The second study introduces a methodology for incorporating ecological considerations into the optimisation of design and scheduling of batch processes [7]; this includes a case study of a cheese making dairy. The optimisations were based on both process economics and environmental impact. The relation between a production of a great number of products and the environment was not investigated in the study by Stefanis et al. [7], as only two products were included in their study. Studies of production scheduling that include environmental considerations are thus very limited, in dairy industry as well as in other food industries.

To be able to search for the sequence of products that is optimal from an environmental perspective the target function (also called optimisation criterion) must be carefully selected. Studies of life cycle assessment literature gave us the function. Life cycle assessments have been made for a number of dairy products, including milk [8], milk powder [9], coffee cream [10], soured milk [11], butter [12], soft cheese [13] and semi-hard cheese [14]. Although the system boundaries differed in these studies, a consistent finding in all studies that included farming was that agriculture had the greatest environmental impact. An example from the study of semi-hard cheese by Berlin [14] shows that on a life cycle basis the farm contributed 94% to global warming, 99% to acidification and 99% to eutrophication. Consequently it was identified, for the remaining parts of the life cycle of dairy products (the dairy, retailer, consumer household, waste treatment and also all connected transports) that the action which would offer the best outcome from an environmental perspective was the minimisation of milk waste. For the sequencing problem, minimisation of milk waste would also give a minimised use of cleaning agents and use of water for cleaning during a product change in the sequence, depending on the techniques used for product changes. Therefore, the choice of target function fell on milk waste.

The goal of this study is to find a practical method to calculate a sequence of a great number of cultured products which is optimal or close to optimal, from a waste minimisation perspective, with existing process equipment. Furthermore, to show the full environmental implications of the waste minimisation, we connect the sequencing model to conventional life cycle assessment (LCA) methodology.

Optimising a sequencing problem of this kind involves searching through a vast number of potential solutions. In practice, this is only possible for a limited number of products [15]. Hence, a heuristic method was developed which was able to handle a large number of products. The paper aims to show that the sequence achieved with the heuristic method with a high probability is also the optimal solution. This was achieved through validation of the sequence obtained with the heuristic method with a mathematically optimised sequence for as many products as possible. Production of yoghurt was taken as an example to test the proposed method.

Production scheduling includes deciding the sequence in which products are made, according to a list of requirements for the production system and the allocation of equipment to products. There are several alternatives for a schedule since there are many constraints. Constraints such as process equipment, maximum production rates, employee working hours, volume of each product and product specific characteristics need to be taken into account in the schedule. This paper concentrates on one of the constraints in a schedule: the product specific characteristics. The characteristics of each product are important when different products are processed in a sequence, since the technique chosen for preventing their interaction during a change depends on these characteristics. The product characteristics are a combination of: the yoghurt base, with related bacterial culture and fat content; the additives to the product, with correlated flavour, colour or allergenic potential; and how much it sticks to the surface of the equipment.

2. Method

An environmentally preferable product sequence makes as few product changes as possible and when a product change is required the right technique causing least impact is selected. It is during product changes that environmental impact occurs, in terms of waste of product and use of cleaning agents and water. To be able to design a method which would find the production sequence offering lowest environmental impact, we wanted to find an optimal or close to optimal practical solution from an environmental, interpreted as waste minimisation, perspective. A heuristic method was developed to meet the requirement of sequencing a large number of products. A drawback with a heuristic solution is that it cannot be guaranteed that it is also optimal [16]. Therefore, we decided to validate the result of the heuristic method with a sequence achieved through optimisation, with as large a number of products as could be handled with the optimisation method within a reasonable time. The demonstration of the possibility to make an environmental assessment of the production sequence was made with LCA methodology. A description of the heuristic method that we developed, the optimised solution we identified and the LCA of a production according to a sequence follows below. A description of the dairy selected for the case study can be found in Appendix A.1.

2.1. Heuristic method

Heuristic methods are intuitively designed and do not guarantee an optimal solution. However, if well designed they can give good approximate solutions, and are often used for very large problems [16]. There are several alternatives for heuristic solutions in general and for sequences of cultured dairy products in particular as the product changes are made with several constraints. The heuristics developed in this study were partly based on constraints, i.e. rules, used in a yoghurt producing dairy. These rules were established from a process perspective, not an environmental one. In addition to these rules, or constraints, the heuristics were developed with the aim to cause as little waste of product as possible. More specifically the heuristic method was based on the characteristics of each product, which determine the choice of technique selected for a product change. The techniques were cleaning, rinsing and the pushing principle. Cleaning caused the most waste and use of cleaning agents and water. Rinsing caused less waste, no use of cleaning agents but used the same amount of water as the cleaning technique. Least waste and no use of either cleaning agents or water was the result of a change with the pushing principle. Therefore the best schedule from an environmental perspective would use the pushing principle the most, while rinsing and cleaning were used as seldom as possible. However, there were the processing rules that must be followed. Cleaning must be done after a change of base, after a product containing rhubarb, after a product containing vanilla, and at the end of the working day. Rinsing is done after products containing sun fruit (a mix of pineapple, mango, peach and passion-fruit), elderberry and honey, which are considered to have allergenic potential. Otherwise the pushing principle is used, with pale coloured products preceding dark ones.

The first step in the heuristic procedure designed was to make a matrix of all of the products that were going to be sequenced and list their individual characteristics. After that the products were sorted in the following priority:

1. Yoghurt base.
2. Presence of rhubarb.
3. Presence of vanilla.
4. Presence of allergenic substances.
5. Increasing colour.

The sorting procedure starts with grouping according to the yoghurt base. Within each base, products containing rhubarb and vanilla were placed last. Products with allergic substances were next to the last. Finally, the rest of the products within the base group were sorted by increasing colour, pale ones first and the dark ones last. This sorting procedure was the heuristic method for production scheduling developed.

2.2. Optimisation

To find the optimal product sequencing solution involves searching through all possible combinations of the manufacturing order of a set of products. Our problem was similar to the "travelling salesman problem" (TSP): given a set of N cities, find the shortest route connecting them all, with no city visited twice [15]. For this problem, the cities were interpreted as yoghurt types and the routes connecting them were weighted according to the waste volume obtained during the product change. The waste volume was determined by the product change technique (cleaning, rinsing, pushing principle), which was in turn governed by the processing rules. This problem formulation gave rise to a weighted, directed TSP. Moreover, the TSP graph was complete since there was a route between any two products in the graph. It is important to keep in mind that a large TSP is insoluble in practice. According to Sedgewick [15] the limit for a super computer is 25–30 products. The optimisation here was made to validate the heuristic solution for the waste minimised sequence, for as large a number of products as possible. A description of our optimisation solution is presented below. First the original algorithm is described then its refinements are presented in the same order as they were implemented. An example of a four-product solution follows the description to illustrate the development of the algorithm. For more information about TSP, see Sedgewick [15].

For the optimisation our problem was: given a mix of products, find the production sequence that causes the least waste. The waste that occurs during a product change depends on the properties of the two products. The problem has as many as $N!$ solutions for schedules, if N is the total number of products in the sequence. To demonstrate the procedure, an example scheduling four products can be examined. The products are named A, B, C and D. First we made an exhaustive search to check all possible solutions for the scheduling of the four products; this yielded 4! (24) solutions of a schedule.

Fig. 1 shows the exhaustive search for the example. This type of illustration is hereafter called a tree. The circles with the products are termed nodes and the lines connecting them are edges. A solution for a schedule is a path. Each edge is assigned a value. The value is the volume of waste of products resulting from a change of product. A graph of the values assigned to the edges is given in Fig. 2. The path passing all nodes with the lowest sum of values gives the best schedule.

As can be imagined from Fig. 1, the tree grows very fast with increasing number of products to be scheduled. Apart from the example, the exhaustive search was able to handle 11 products within reasonable time (7 min) and 12 products required 89 min to schedule. This was not satisfactory, so to enable scheduling more products, we decided to prune the tree. This means cutting off certain branches and deleting everything connected with them [15]. The sum of the values, x, for the first path was calculated. For the following searches, it was

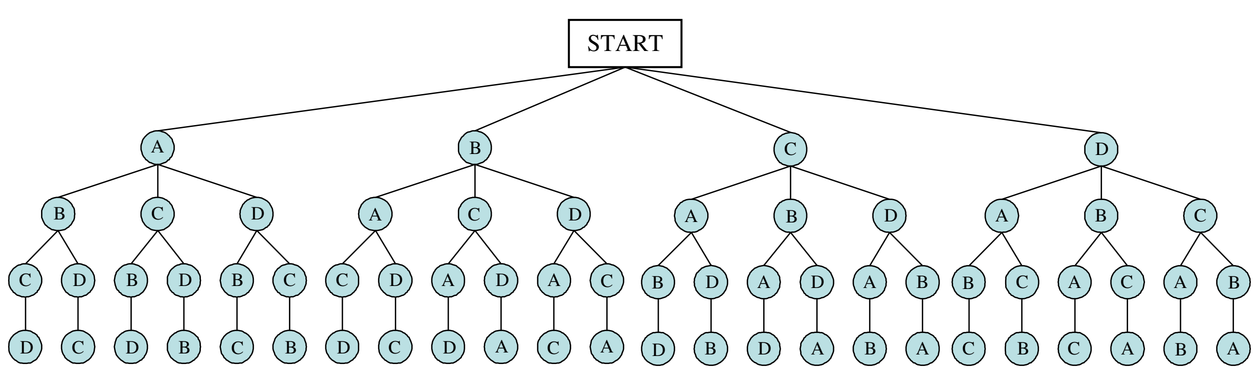

Fig. 1. An exhaustive search for four kinds of products.

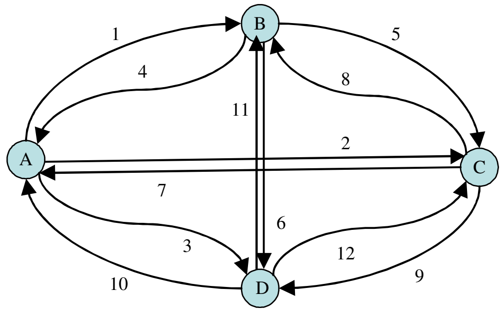

Fig. 2. The assigned values of the four products.

fruitless to continue along any path for which the summed values were greater than x, therefore these paths were pruned. The pruning is most efficient if a low-value path is found early in the search. A pruned tree for the example with a starting path CABD is illustrated in Fig. 3. The number of full paths is reduced by 50% and the number of nodes is reduced by 19% in the example. With this technique to limit the number of full solutions needing to be examined, 13 products were scheduled in a reasonable amount of time (10 min, 14 products required 140 min).

To improve the optimisation even more, we chose a method known as branch-and-bound [15]. We computed a bound of the summed values for a path that began with a given partial path. A path that started with the given partial path got a lower bound by adding the values of the minimum spanning tree of the rest of the path. A minimum spanning tree of a weighted graph is the collection of branches (edges) that gives the sum of values which is at least as small as any other combination of the nodes [15]. For example, the working procedure for the minimum spanning tree is the following: start at A and select the edge with the lowest value. At the next node, select the edge with the lowest value that connects with a node not been visited before. The same procedure is repeated until all nodes have been visited by starting from A. The next step is to start at B and repeat the same process as for A. Then continue with C and D. When the summed value of the path (the value of the given partial path and the value of the minimum spanning tree) is higher than the best path found so far, the tree is cut.

The branch-and-bound technique reduces the number of solutions dramatically. The tree example illustrated in Fig. 4 was reduced by 87.5% of the full paths and the number of nodes revisited was reduced by 80% after using both pruning and branch-and-bound techniques. By using both pruning and branch-and-bound techniques to limit the full searches, we were able to make a schedule of 21 products within a reasonable time (30 min). This was the solution to our problem. Note that the algorithm can still be guaranteed to find the weight minimised schedule.

2.3. Life cycle assessment of a production sequence

The detailed production scheduling method gives the sequence, for a given set of products, which causes the minimum amount of milk waste and a low use of cleaning agents and water. This has environmental consequences in a life cycle perspective. For example, due to a change in raw material requirement, the agricultural part of the life cycle will be affected, which in turn impacts several environmental categories. Therefore, to calculate the total environmental impact, an LCA of the production according to the sequence was performed.

The sequence includes the list of products to produce and the techniques used for the change between products. To get the total environmental impact, each activity affected by the choice of production sequence was taken into account with its emissions to water and air; the use of natural resources for extraction and processing of the energy, materials or ingredients are calculated according to life cycle inventory (LCI) methodology [17–19]. The LCI included activities that are affected by the production, the choice of techniques selected for product changes, and the treatment of waste. The product changes are made just before the filling equipment is reached. The filling of containers is designated as product packaging in Fig. 5. Before the yoghurt is

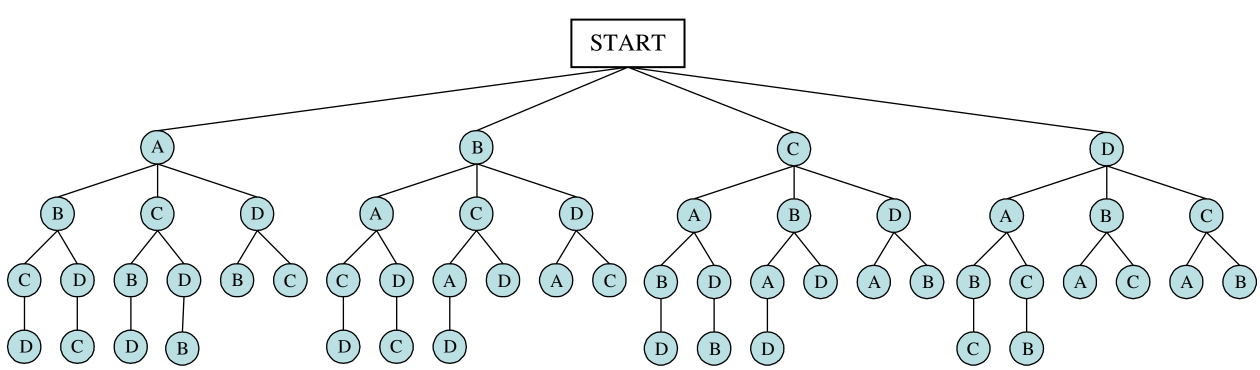

Fig. 3. The product sequence tree pruned by 50% of full paths.

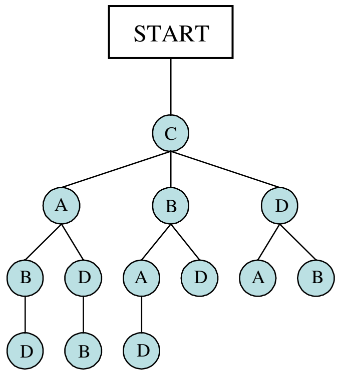

Fig. 4. The tree of the four products after both pruning and branch-and-bound techniques were used.

packed, it is treated for both hygienic and product purposes i.e. milk treatment and product treatment, in Fig. 5. The milk treatment includes pasteurisation and separation. The product treatment covers standardization, homogenisation, fermentation and the specific processing required for each product. The milk production takes place at the dairy farm, which spans the following activities: cultivation and production of feed, seeds, fertilisers and pesticides plus all transports involved. To make product changes, water and cleaning agents are required. Water treatment and manufacture of cleaning agents take place outside the dairy. Water treatment refers to the manufacture of chemicals needed for treatment of water, the water treatment itself and distribution. The cleaning agents used are nitric acid and sodium hydroxide. The data sources applied in the LCI can be found in Appendix A.2.

Some of the milk waste from product treatment (5%) is taken care of in a sewage treatment plant. The remaining milk waste is used as animal fodder, mainly for pigs. The extraction and production of energy and electricity is included for each process in the system. Two flows are leaving the system: yoghurt and animal fodder. In order to be able to compare the environmental impact associated with the waste (i.e. animal fodder) and that associated with the product the environmental impact was partitioned between them on a mass basis.

The contribution of the production according to the sequence to selected environmental categories was calculated according to life cycle impact assessment (LCIA) methodology [17,19–21]. The environmental impact categories used were: eutrophication, acidification, global warming and photochemical ozone creation potentials (POCP).

3. Results

Simulations were made for sequencing the products in an existing dairy, using both the heuristic and optimising methods. An LCA was also made of the production according to the sequence. The results of the simulations and the LCA are described below.

3.1. Simulation of the production schedule

As the method which gave an optimised solution with respect to milk waste was able to handle 21 products, we

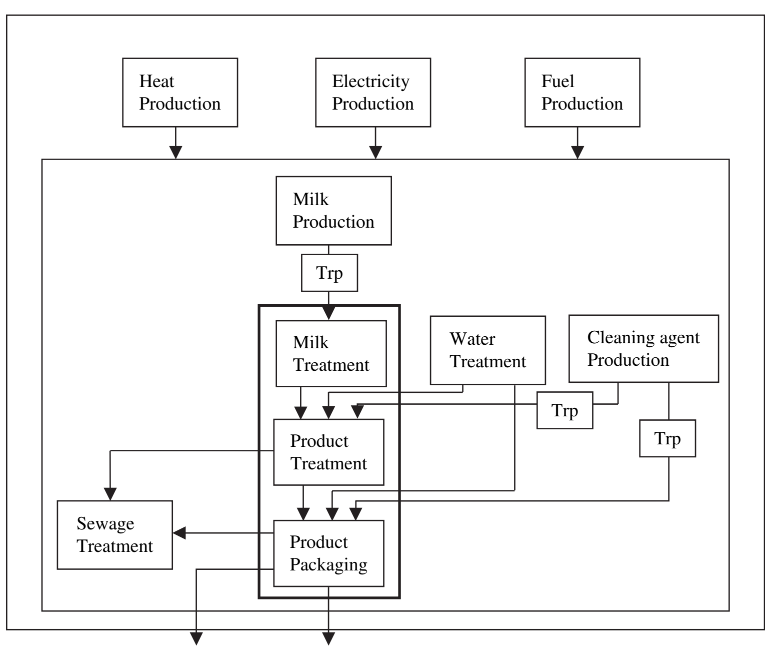

Fig. 5. The system for production according to the dairy production sequence in a life cycle perspective.

chose to limit this test case study to 20 products. We simulated the sequence with both the heuristic and the optimised solutions and then compared the results. The sequenced products were composed of six different bases (designated Base A to Base F). The products were: Base A: rhubarb, apple and elderberry; Base B: peach/orange, raspberry and apple/pear; Base C: blueberry, peach and strawberry; Base D: sun fruit, raspberry/rhubarb, pear, strawberry and banana; Base E: rhubarb/cardamom, strawberry and raspberry; and Base F: honey, apple/cinnamon, vanilla and strawberry. The assigned value used for a product change in the method was the same as the total amount of product waste resulting from a product change, which included the mixed zone product (depending on the technique) and the yoghurt in discarded cartons. Cleaning was given a value of 219, rinsing 86 and the pushing principle 74. A product change from a strongly coloured product to a pale one had a value of 86 (the pushing principle was used, but a larger amount of mixed product was estimated than for the ordinary pushing principle).

The heuristic solution for the sequence generated the same result as the optimal sequence independently of the products' starting order. Several starting orders were tested and the simulated result from both of the solutions always gave the same sequence. Accordingly, we can state that the heuristic method gives the optimal sequence from an environmental perspective (that is a waste minimised solution) for all sequences including up to 20 products. This implies that the method used will also find optimal solutions for all production sequences including fewer products, since all possible combinations are tested in the algorithm. The same sequence was also obtained using both the optimising and the heuristic methods when the number of products was increased to 21, which was the limit for the optimisation. There is strong reason to believe, although it may not be mathematically proven, that the heuristic solution for a sequence including more than 21 products will also be the optimal one, as there is no known event that occurs in the sequence that relates to the number of products. The resulting sequence of the simulation is given in Table 1. The weight of the milk waste generated during production of this sequence is 2179 kg. This is 5% of the weight of the sequence total produce.

3.2. The LCA of the production sequence

To determine the total environmental impact from the production according to the production sequence chosen, an LCA can be carried out as demonstrated in Section 2.3. This means that the detailed scheduling model can be successfully included in a broader life cycle context. An example of results from such a combined model is illustrated in Fig. 6, where the yoghurt waste environmental impact contribution is related to the total environmental impact of the production according to the sequence.

Table 1
The optimal sequence of the production order

Optimal sequence
Base A: apple
Pushing principle
Base A: elderberry
Rinse
Base A: rhubarb
Cleaning
Base B: peach/orange
Pushing principle
Base B: apple/pear
Pushing principle
Base B: raspberry
Cleaning
Base C: peach
Pushing principle
Base C: strawberry
Pushing principle
Base C: blueberry
Cleaning
Base D: banana
Pushing principle
Base D: pear
Pushing principle
Base D: sun fruit
Rinse
Base D: raspberry/rhubarb
Cleaning
Base E: strawberry
Pushing principle
Base E: raspberry
Pushing principle with decreasing colour
Base E: rhubarb/cardamom
Cleaning
Base F: strawberry
Pushing principle
Base F: apple/cinnamon
Pushing principle
Base F: honey
Rinse
Base F: vanilla
Cleaning

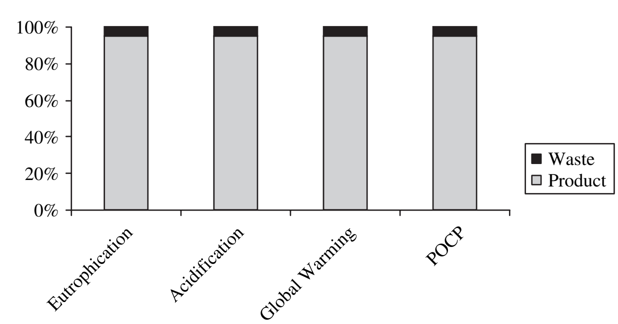

Fig. 6. Environmental impact associated with the milk waste in relation to the environmental impact associated with the yoghurt products.

4. Discussion and conclusion

The raising environmental impact caused by dairies depending on the ongoing diversity of cultured dairy products can be counteracted. This study describes the construction of a practical method to achieve the environmentally optimal or close to optimal sequence of products which causes as small impact as possible on the environment during production in the existing equipment. A heuristic solution of the sequencing problem was worked out. In general a heuristic solution cannot be guaranteed to be optimal. To achieve the best possible heuristic solution, we also made a waste optimised solution for the sequence. There are limitations in how many products may be handled by an optimisation method for this type of problem, since the problem grows with $N!$ where N is the number of products. For most problems the running time for an algorithm will be improved using a faster computer. This holds true for problems affecting the running time with polynomial factor but not with problems such as this where the running time is affected with a factorial factor [15]. With the method used, it was possible to optimise sequence of 21 products and get a result within a reasonable time. Since the same sequence for the same 21 products was obtained with the heuristic method, it may be concluded that the heuristic method gives optimal solutions for sequences including up to this number of products. Sequences obtained with the heuristic method for a larger number of products are probably also waste minimised since the heuristic rules do not depend on the number of products.

To be able to show the full environmental implications of a production according to the sequence this study also successfully demonstrated the possibility to connect the sequencing model to LCA. The test LCA study highlighted the environmental impact associated with the milk waste in relation to the impact of the products.

The heuristic method was designed to be general enough to be useful for any dairy producing cultured products. The generality was achieved through including most of the production rules used in Swedish dairies. If implemented in a specific dairy no change of the method is required, even if not all of the rules are used. It is usual for a dairy to use fewer rules than this method does. If for example the rhubarb jam is pre-worked, which means that the long fibres are shortened, the risk of sticking to pipes surfaces is reduced. Then the "presence of rhubarb" rule can be disregarded and the product may instead be sorted only according to the "colour" rule. The LCA of the production according to the sequence was also constructed to be general for Swedish purposes. The data used for the calculations originated from the most common techniques used for processing and cleaning. We also used average values when that was possible.

The method is going to be used in a forthcoming case study for an evaluation of production sequences, which includes both the product order, frequency of production and an environmental assessment.

To combine environmental systems analysis with production scheduling is a new approach to product sequencing for the dairy industry. It is also a text-book example of a cleaner production approach where environmental impact may be improved at the same time as economic resources are saved.

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Appendix A

A.1. The dairy selected for the case study

The dairy selected for the case study had a weekly production of 380 000 kg of yoghurt products. The yoghurt section used 13 yoghurt bases, which were further refined to 55 products. The dairy was originally built for processing drinking milk products alone. Since the yoghurt section was added later, its design was not ideal. For example, the yoghurt base was transferred a long distance to reach the filling machine, which led to a large amount of mixed zones product to be removed by rinsing and cleaning operations. For a cleaning operation, 195 kg was estimated as mixed zones product, for rinsing 62 kg and for a product change according to the pushing principle 50 kg. The amount of mixed zones product was calculated from the diameter and length of the pipe. For each yoghurt product manufactured, approximately 24 filled containers (1 kg each) were discarded. The first 10 and the last five produced were disposed off because the dairy wants to eliminate the risk of substandard content. Six containers were sent to the dairy laboratory. The remainder was used for flavour, colour and consistency tests by the operator during manufacturing. A full cleaning operation was executed at the end of the day, which means that, in addition to the pipes and filling machine, each yoghurt base tank was also cleaned.

A.2. Data sources used for the LCA calculations

The inventory of data sources used in the LCA calculations of the production sequence can be found below.

The data sources for the selected environmental impact categories in the LCA are the last part.

For production at the dairy energy is required. We have used energy requirement data specified for each step during milk treatment, product treatment and product packaging. For each step a mean value of three Norwegian yoghurt producing dairies of various sizes has been calculated [22]. At most dairies, both electricity and natural gas are used as energy sources. An average of the 30 dairies within Arla Foods, in Sweden, showed that 33% of the energy used was electricity [23]. The Swedish mixture of energy sources for electricity production was used. The sources used are: hydropower 46.8%, nuclear power 46.55%, oil condensing power 2.70%, combined power/heat, renewable fuels 1.70%, coal condensing power 1.55%, combined power/heat, natural gas 0.50%, gas-turbines 0.10% and wind power 0.10% [24]. Data on emissions to air and water, and the waste arising from the life cycle of energy were found in Brännström-Norberg et al. [24]. The electricity was considered to have a grid loss of 5%. To estimate the total energy requirements of a dairy, it was assumed that the remaining two-thirds of the energy use consisted of natural gas. Data for extraction, refining and combustion of natural gas were found in Bakkene [25] and Frischknecht [26].

The data used for milk production at the dairy farm are mean values from 17 conventional farms situated at the west part of Sweden [27,28]. They were all specialised in milk production. The data included all activities at the dairy farm but also production of fertilisers, diesel, pesticides and seeds, cultivation of oil/starch crops and sugar beets, extraction of industrial feed co-products, processing at the feed industry as well as all transports. The fuel consumption used for the milk transport from the farm to the dairy was 0.14 MJ/kg milk [29].

There are several different methods used for cleaning among dairies. The method of conventional alkaline/acidic cleaning with sodium hydroxide (2.5 kg/cleaning) and nitric acid 1.2 kg/cleaning) followed by hot water disinfection (90 °C), the one most commonly used [30], was used in this study. The alkaline cleaning consists of a 1% NaOH solution with temperature of 75 °C. The acidic cleaning consists of a solution of 1% HNO_3 and a temperature of 65–70 °C. The water consumption for a cleaning is 1000 l and the energy consumption is 110 kWh per cleaning [30]. Average European data for production of sodium hydroxide was chosen [31]. The transport distance from the sodium hydroxide production to the dairy was assumed to be 100 km with a medium sized truck. Ammonia and air are required for the production of nitric acid. Data from a Swedish producer of nitric acid were used [32]. West European average data for production of ammonia were used [32], and a transport distance of 1400 km was chosen as representative. For production of ammonia, natural gas is required. Data used for natural gas production were found in a database [33]. The transport distance for the nitric acid to the dairy was assumed to be 100 km with a medium sized truck. The same database was the data source for the transportation [33].

The data used for water treatment was found in a study of a surface water treatment plant in Sweden [34]. This treatment plant disinfected the water with chlorine and ozone. The resource use for production of drinking water was: aluminium sulphate 30 g/m^3 water, lime 30 g/m^3 water, carbon dioxide 28 g/m^3 water, and sodium chlorite 1.7 g/m^3 water. The use of oil and electricity, as well as emissions to air and water, from production of chemicals was stated in Tillman et al. [34]. The energy requirement for water distribution is closely related to the topography. The mean value of seven municipalities in Sweden, 2.2 MJ electricity/m^3 water, was used [35].

The cleaning values at the sewage treatment plant chosen as data source were BOD5 96%, COD 89%, total phosphorus 91% and total nitrogen 58%. The electricity required to treat the dairy's waste water was 0.26 kWh/m^3 incoming water. The data come from a Swedish sewage treatment plant that in the year of 2000 treated sewage corresponding to 781 284 personal equivalents [36].

Equivalence factors for following categories were used during the environmental impact categories calculation; eutrophication [37], acidification [38], global warming 100 years [39–41] and POCP [38,42].

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