A CONSTRAINT-BASED MODELLING APPROACH, TO ASSESS THE CAPABILITY OF FOOD PROCESSING EQUIPMENT TO HANDLE PRODUCT VARIATION

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Abstract: *For design and development engineers, difficulties arise ensuring that existing manufacturing equipment has the potential to handle both large product variation and complexity of process. The food processing industry maintains the highest number of product variations, some of which are short lived or seasonal, a factor with which the processing equipment has to cope. This paper presents the idea of "constraint modelling", and identifies it employment in the investigation of the capabilities and optimized performance limits of such equipment. The paper also introduces the concept of multi-instance modelling and its benefits. The approach being employed is illustrated by a number of industrial case study examples, taken from the food processing industry.*

1. BACKGROUND

Marketing and customer demands, pressurizes the food processing industry into maintaining the highest number of product variations; making more product changes than any other of the mass-producing industries. Many of these arise over short periods. Although some of these products are stable over long periods, others are short lived or seasonal. The ability to handle both the complexity of process and large variations in product format creates extreme difficulties in ensuring that the manufacturing, handling and packaging equipment can cope.

The construction of the equipment may mean that certain elements of the machine are constrained for example machine foot print or drive locations, adding to the difficulty of new product handling. At this stage it would be useful to know the function limits of the system. This paper discusses the idea of "constraint modelling". When knowledge of the design area is unspecified or poorly understood, the constraints that limit what can be done are often the most apparent factors.

In machine design and development, the constraints can be applied at various levels. There are *hard constraints* concerned with assembly which ensure that the various parts of a system connect together correctly, and, at a higher level, s*oft constraints* can impose restrictions on kinematic properties. Additional constraints can relate to machine performance, cost, capturing knowledge about design, function and operation. Constraints can provide an understanding, and hence improve agility for the re- design to a configuration that can handle the product variation.

The work presented in this paper shows the capabilities of the constraint modeller while being employed to investigate existing food processing equipment and its capability to process variant products. The modeller's capability as an optimizer and a system limit finder are discussed as well as the concept of multi-instance modelling. The descriptions of these capabilities are supported by three industrial case study examples.

Although the research has been aimed at food processing equipment the techniques can be employed across other processing industries.

2. CONSTRAINT MODELLING

The following section gives an explanation of the concept of constraint based modelling, it also highlights some of previous applications of constraint approaches that have been employed in the engineering domain. The section concludes with a description of how a simple mechanism (four bar linkage) is constructed, and motion applied within a constraint modelling environment.

2.1. Constraint based modelling

With a constraint based modelling approach, the identified parameters and constraints for a design can be specified and their consequences investigated. When dealing with a system, it is very unusual that individual elements or operations are independent of the other elements. As a result, all the goals and the related constraints must be dealt with concurrently and all their inter-relationships taken into account. The aim is to find a configuration that satisfies all the imposed constraints as closely as possible. The constraints can be considered as defining subsets of the universe of all possible designs. The Venn diagram Figure 1 shows the constraints of the system (A-E), visualized as subsets of all possible designs. The feasible solution space is the intersection of all the individual constraint subsets, and the aim is to find (at least) one configuration within the intersection.

When some constraints are in conflict, then the design task is over-constrained and no intersection exists. Given this scenario, the knowledge of the designer is required to determine which constraints can be relaxed without compromising the functionality of the design. This holistic approach allows the representation of design knowledge and, more importantly, enables this knowledge to be expanded or modified at any stage during the design process. In this way, changes in the proposed solution or in the governing constraints of the particular design problem can be dealt with.

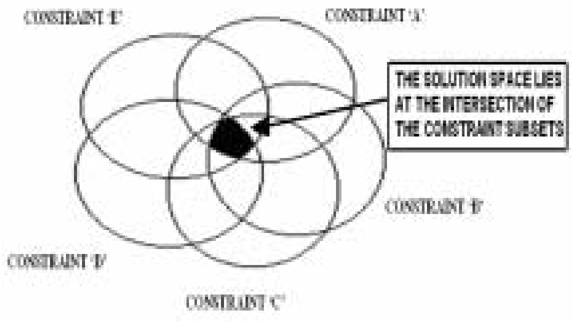


Fig.1.*Overlapping sets of constraints*

2.2. Previous constraint applications

Over the past two decades constraint approaches have become popular in aiding of engineering problems. This section gives a brief overview of how constraint based approaches have been employed across the design, development and planning processes. O'Sullivan [1] presented an interactive constraint-based approach to support the designer at the conceptual design stage. He proposed a computational reasoning environment based on constraint filtering as the basis of an interactive conceptual design support tool. Kenney et al [2] and Mullineux et al [3] described how a constraint modelling environment could be used to aid the conceptual design stage by searching for solution principles and evaluating these principles against the constraint rules.

Holland et al [4] have developed an add-on constraint based design technology for Autodesk inventor, also to aid the conceptual design stage. Singh et al [5] presented the benefits to assembly modelling of mechanisms by of incorporating a stand alone constraint based modeller into a commercial computer aided (CAD) design package.

Hicks et al [6] described a methodology using a constraint modelling environment for supporting and analyzing the design of packaging machinery at the embodiment stage. This method showed the ability of the modelling package to analysis the design of a mechanism. Hicks et al [7] continued this approach into optimal redesign of packaging machinery. Their approach bounds maximum and minimum kinematics properties for the given mechanism and optimizes the mechanism to find the best solution. Matthews et al [8] described the utilisation of a constraint modeller to investigate the boundary conditions of an existing system, by varying its geometries.

Constraint based approaches have also come to the fore in the last decade in other areas such as optimization of computer aided process planning (CAPP), for manufacturing. In Li et al [9] and Zhang et al [10] , the constraint are resolved to find the most cost effect sequence to manufacture parts.

2.3. Constraint modelling environment

The design team at the University of Bath has created the constraint modelling software "SWORDS" [11]. The software has its own user language which has been created to handle design variables of several types including structured forms to represent, for example, geometric objects. The language supports user defined functions. These are essentially collections of commands which can be invoked when required. Input variables can be passed into a function and the function itself can return a single value or a sequence of values. Functions are used to impose constraints using an important in-built function which is the "rule" command. Each rule command is associated with a constraint expression between some of the design parameters which is zero (as a real number) when true. A non-zero value is a measure of the falseness of the constraint rule.

In order to investigate the effects of the constraints, they need to be resolved. There are several techniques for doing this, such as those presented in[12] and [13], including, for example, symbolic manipulation and reordering strategies. The method used by the constraint modeller is based on optimization techniques.

Here the constraint modeller uses penalty functions; the squares of constraint relations are effectively added into the objective function to reduce the problem to one of unconstrained optimization. If there are n variables $x1, x2,...,xn$ involved in m constraints. These are denoted as follows.

$$f_j(x1,x2,...xn)=0 \text{ for } 1<j<m \qquad (1)$$

There is no loss of generality in assuming that these are equality relations. Inequalities can be written in this form by use of a ramp function. The objective function is then formed by taking the sum of the squares of these constraints.

$$F(x1,x2,...xn) = f_1^2+f_2^2+...+f_m^2. \qquad (2)$$

During resolution, the expression for each constraint rule (within a function) is evaluated and the sum of their squares is found. If this is already zero, then each constraint expression represents a true state. If the sum is non-zero then resolution commences. This involves varying a subset of the design parameters specified by the user. The sum is regarded as a function of these variables and a numerical technique is applied to search for values of the parameters which minimize the sum. If a minimum of zero can be found then the constraints are fully satisfied. If not, then the minimum represents some form of best compromise for a set of constraints which are in conflict. It is possible at this stage to identify those constraints that are not satisfied and, where appropriate, investigate whether relaxing less important constraints can enable an overall solution to be determined

2.3.1. Mechanism construction

The software environment supports simple wire-frame graphics, such as line segments and circular arcs. These can be defined in world space or associated with a 'model space' [14]. Here a model space is a group of entities with which a transform is associated. This transform dictates how the entities map from their own local coordinates, into world space or into another model space. In this way a hierarchy of model spaces can be set up and used to specify an initial assembly of some components of a design.

The modeller has the capability to use solid objects. These can be embedded within model spaces, so that they can move with other geometry including wire frame entities. Solids have been incorporated into the environment by means of the ACIS library of procedures [21].

As an example, consider the representation of a four bar linkage shown pictorially in figure 2a. In part (b) of the figure, the two fixed pivot points are specified, and the line segments representing the three links are defined, each in a local model space.

In the example, the model space of the link 'L2' is "embedded" in the space of the crank, and the spaces for the crank and link 'L2' are embedded in world space. A partial assembly of the mechanism is achieved by applying the transformations to the links in each space. This is shown in part (c) of the figure. If the space of either the crank or the link 'L2' is rotated, the hierarchy of their spaces ensures their ends remain attached.

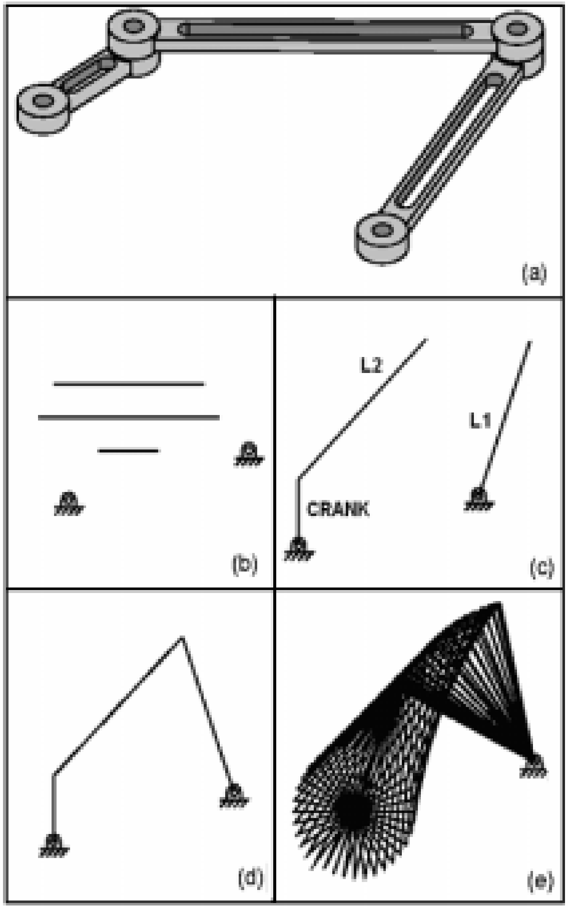


Fig.2. *Assembly of four-bar mechanism*

To complete the assembly, the ends of the link 'L2' and driven link 'L1' have to be brought together. This cannot be done by model space manipulation alone, as this would break the structure of the model space hierarchy. Instead a constraint rule is applied whose value represents the distance between the ends of the lines. The user language has a binary function `'on'` which returns the distance between its two geometric arguments, to assembly 'L1' and 'L2' the constraint rule is expressed as follows,

```
rule( l1:e2 on l2:e1 );
```

where the colon followed by *e1* or *e2* denotes either the first or second end-point of the line. In order to satisfy this constraint rule, the system is allowed to alter the angle of rotation of the model spaces of the coupler and driven links. When the rule is applied then the correct assembly is obtained as in part (b) of the figure. When the space of the crank link is rotated and the assembly of the other two links is performed at each stage. A step-wise simulation of the motion is obtained, as in part (e). If solid objects representing the link are constructed, these can also be included in the model spaces as shown in part (a).

3. CONSTRAINT APPROACHES

The following sub-sections describe three constraint modeller approaches being employed to aid in the investigation of the equipment and its capabilities to handle a variation in product. These are process limitation analysis, optimization and multi-instance modelling.

3.1. Process limitation analysis

In order to determine the ability of existing equipment to handle a chosen range of products, the product characteristics need to be evaluated against the capabilities of the plant. This can be undertaken by modelling the machines and processes within a constraint modelling environment. Within such an environment the performance limits of each machine configuration can be determined and these parameters compared to those of the product.

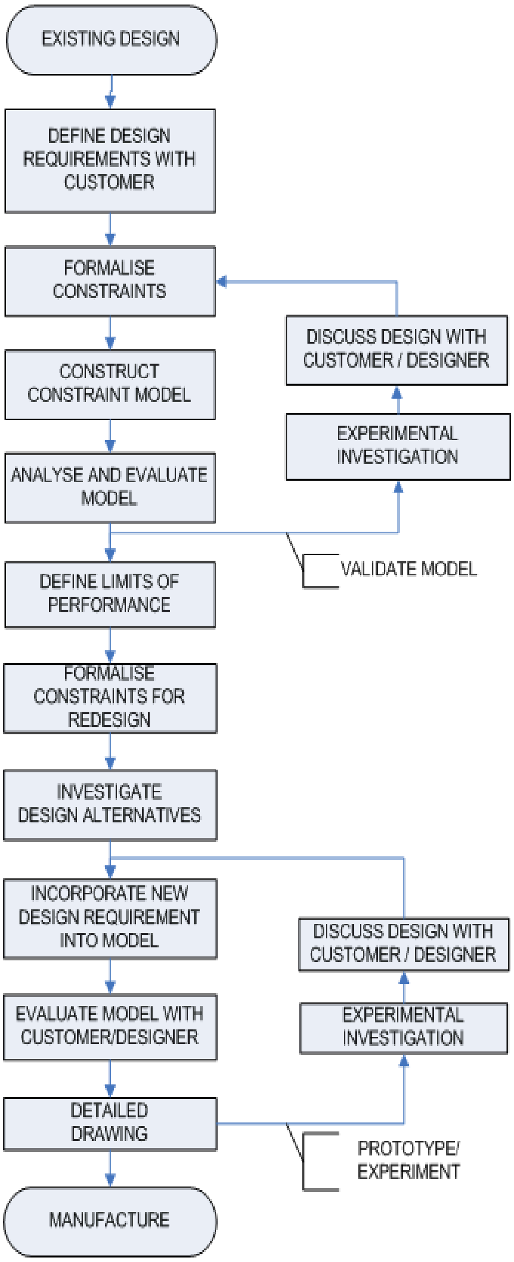


Fig.3. *Constraint modelling process*

If the machine cannot meet the necessary requirements, the modeller can be used to modify the model configuration to seek a successful solution. This may be achieved by the simple searching of the design variables or by creating and evaluating a range of different possible machines through multi-instance modelling. The performance of these modelled machines can then be assessed against the food product characteristics to determine the suitability of each.

Process limitation analysis involves several stages. Firstly the existing system is modelled based on measurements of the physical parts. A constraint model is then created to obtain a simulation of the motion, as with the four bar linkage example shown in section 2.2. This is compared with the real system by way of validation (high speed video techniques can be employed for this). In the second stage, the constraints on the functionality of the mechanism are identified.

The flowchart figure 3 (adapted from Hicks [7]) shows the generic constraint modelling approach. The flowchart shows feedback loops at two stages. These are important within the evaluation process as they increase the understanding of the existing design and the needs of the variant product with respect to any potential new design.

3.1.1. Sensitivity analysis

Sensitivity analysis is the procedure of varying the model input parameters and examining the relative changes in model response. When smalls change in a parameter of a system result in relatively large changes in the outcomes, the outcomes are said to be sensitive to that parameter.

Within the constraint modeller the combined values of the constraints gives a measure of “goodness” of the design and its sensitivities of this to change in the parameters which are found. If S represents the measure and x is the design parameters, sensitivities can be determined either as the vector of first order quantities. $[\delta S/\delta x]$ or as a matrix of second order ones $[\delta^2 S/\delta x \delta xj]$.

Such analysis is useful to the designer in deciding how appropriate and reliable a variant design arrangement will be.

3.2. Optimization

Constraint-based modellers are valuable in managing design applications where the precise rules are ill-understood; this is a specific problem when an existing design has to investigate in respect to handle a new product. Such new designs often add new and unexpected problems into the design problem. The constraint modeller can then be employed to optimize the global problem imposed by these new constraints and deliver an optimal solution.

The following example, shows a pair of simultaneous equations.

$$a + 2b = . \qquad (3)$$

$$a + 3b = 5 \qquad (4)$$

The variables *a* and *b* can be globally defined in the language with the following declaration statement.

```
dec real a, b;
```

The equations 3 and 4 are set as the constraint rules. Each rule statement is associated with the expression involving the variables which is deemed to be true when it is zero.

```
function solve_equation
{
var a,b
rule a + 2b = 4
rule a + 3b = 5
}
```

When the function is invoked with the command

```
solve_equation ()
```

When the optimisation process requires the user to state multiple variables. The modeller allows the user to use a ‘weight’ individual these variables, to aid the process. From the above mathematical example, it is simple to see how parameters such as volume, pressure and force could be substituted for the variables and optimised. Such an example is shown in the case studies in section 4

3.3. Multi-instance modelling

The original version of the constraint modeller has the capability to model and analyse a wide range of plant and machines. Previous research had been performed on the inclusion of higher order modelling and resolution. The current work allows the system to create and analyse a number of model variations based upon the same design rules. These allow differing characteristics to be investigated simultaneously and compared against selected critical product characteristics. The process is divided into three stages, which are described following.

3.3.1. Initial stage

The procedure is to develop a parametric model of the system within the constraint modelling environment. The physical measurements for the system are recorded in combination with high speed video footage. With the system modelled, it is validated and updated so that it matches the characteristic of the observed system.

3.3.2. Secondary stage

The stage is involves the multiple instances for the analysis process. There are two possible approaches for this.

1. The designer / development engineer select specific element from the system and its characteristics iteratively modified on given performance criteria. Such as cam profiles. or
2. All element of the system are varied sequentially then simultaneously such as link dimensions.

3.3.3. Tertiary stage

At this point the model is run repeatedly for different configurations (instances), with each being tested for successful operation. The successful operation can be judged against designer and/or customer failure or performance requirement. Successful instances can be logged in a matrix. With the matrix defined, a crude method to test whether a new product configuration is such that it lies within the limits of mechanism is to search for the closest point to the new configuration [8].

3.4. Approach amalgamation

The three approaches described in this section are not mutually exclusive. The core of the process limitation analysis is common to all three approaches. The final five process boxes and the feedback loop from the flowchart (figure 3) are for all redesign problems. An amalgamated approach gives the designer / development engineer the possibility to produce multiple instances of a system. And test and evaluate them, to assess their potential to process the variant product. The optimizing ability can then be employed to select the most capable instance, against higher level soft constraints such as cost or quality which may be imposed by the customer.

4. CASE STUDY EXAMPLE

The constraint modelling approaches mention in section 3, have been used successfully on a number of industrial applications. Many of these applications have primarily involved understanding and improving parts of existing machines and/or assessing the benefits of proposed design changes.

The following section illustrates three case study examples taken from the food processing industry. Each example is described and the role of the constraint modeller defined as well as the results of its implementation.

4.1. Process limitation analysis

A commercial machine to make tea bags was exhibiting problems in production due to its large vibrations. These were traced to the action of the “flying guillotine” mechanism. The speed of operation meant that the paper supplied from a reel had to be cut into the appropriate lengths while it was moving. The process starts by the creation of a parametric model in the constraint modeller, giving the schematic model of the cutting mechanism as shown in Figure 4a. The ten major components of the guillotine were constructed and embedded in model spaces. The assembly was finally completed by the application of seven constraint rules that maintained point-to-point, point-on-line and point on cam relationships.

The paths of the upper and lower blades are shown as sequences of points in the enlarged view in (b) of the figure. The forward and backward swinging motion of the blades is controlled by a four bar mechanism driven by a cam. The cutting operation is effectively a sliding action driven by a second cam. An initial model of these mechanisms was created using the modeller and confirmed by comparison with high speed video of the physical machine. This confirmed what was suspected by the operators: the opening action of the cutting blades was fast and uncontrolled and this induced vibration in the rest of the machine.

It was decided to investigate modifications to the cams in order to improve the motion of the blades with minimal machine modification. It is these improved paths that are shown in part (b).

Care was taken to ensure that the forward speed of the blades matched that of the paper during cutting and that the upper path passed through to prescribed trigger points at the top of its motion.

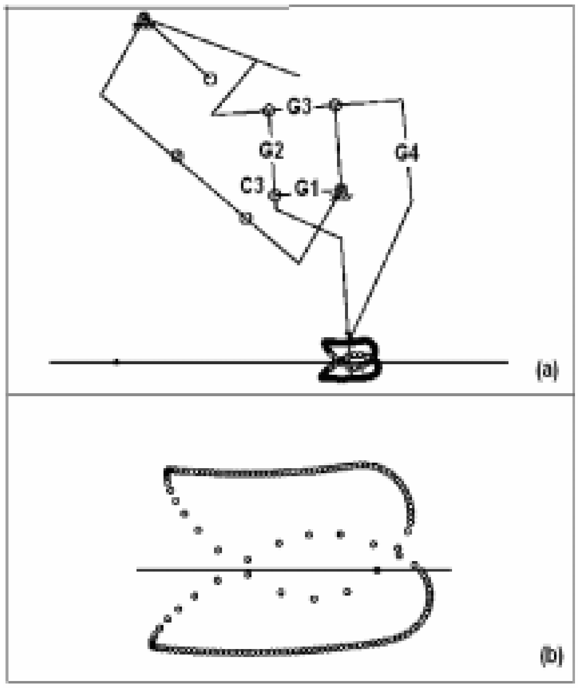


Fig.4. *Flying guillotine*

4.1.1. Results

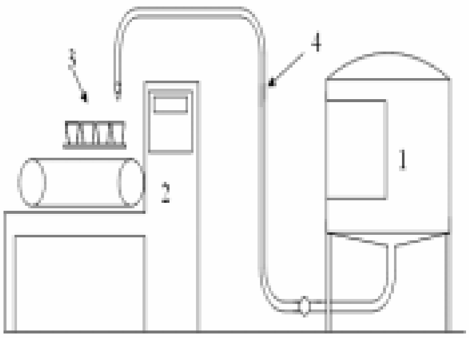
The use of constraints allowed the model to be run “in reverse”: the desired output motion was used to define the cam laws to drive the machine. When the new cams were evaluated, it was found that the peak acceleration of the blades had reduced by more than 95%: a considerable reduction which had not been anticipated by the collaborating company.

Sensitivity analysis performed on the mechanism

It showed a value of almost unity throughout the cycle was obtained for the variation in ‘G4’ (figure 4). As this member is pivoted on the top rocking arm ‘G3’ and carries the upper blade on its lower end, any change in length results in approximately an identical shift in the upper blade position. Analysis also that the group constructed from ‘G1,G2,G3’ contained only one parameter that had a sensitivity less than 1. It is thus this group that limits the performance of the flying guillotine mechanism.

4.2. Optimisation of yogurt flow

There are a number of stages in the typical yoghurt production process. The first is fermentation in which milk and the appropriate culture are allowed to interact in large vats. Once the reaction has taken place, the product is removed and allowed to cool which has the effect of halting the fermentation process. The next stage is the addition of fruit, colours and other additives. Mixing is carried out to ensure homogeneity. The final stage is the filling of the pots and the subsequent storage of these to await shipment. (cf. Figure 5).



1. Holding flask
2. Packing machine
3. Yogurt pots
4. Feed piping

Fig.5. *Yogurt filling process*

The product passes between the various stages via pipe work. Mixing and pumping along pipes both have the effect of damaging the product. Yoghurt is thixotropic and as work is done upon it, it shear thins.

While there is some recovery (over a period of time), the aim is often to try to minimise the amount of processing that is done upon the product. The amount of work required to pump and mix depends upon the temperature. There is a trade-off between ease of processing (and reduction in damage) and need to keep the temperature low in the interests of fixing the reaction and storing the product. One option is to undertake the processing at room temperature and only cool the product in the pots after filling. An alternative is to cool in the pipe as the product is being moved into the filling station.

Given the conflicting requirements, a constraint-based methodology seems well suited to looking for an optimal design of production system. The main difficulty is that the properties of yoghurt do not seem to be well understood. A number of rheological models have been proposed [15] for various food stuffs. These include the Herschel-Bulkley model [16], the power law [17], and Cross's model [18]. While these have all been used to model yoghurt, they lack any involvement of time and temperature which are essential given the nature of the product. To cope with this, a model has been proposed [19] which attempts to relate strain rate ($d\gamma/dt$) to shear stress (τ), temperature (θ), and time (t). This is based upon empirical results but it can be argued [20] that for design purposes very high precision is not necessarily required provided general trends and typical values can be determined.

The relationship is the following

$$d\gamma/dt \;=\; A_0 \exp(\alpha\theta)\, \tau^m\, t \qquad (5)$$

where A_0, α and m are constants (and m is not necessarily an integer) which depend upon the material.

To illustrate the constraint modelling approach, the following design problem is considered. It is desired to pump yoghurt along a pipe (into a filling head) by applying a fixed pressure P and achieving a specifying volume flow rate Q. A temperature distribution is applied along the length of the pipe to try to reduce the temperature as much as possible. What are the dimensions of the pipe and the lowest achievable temperature, given that the maximum value of strain rate must be lower than a specified value to prevent product damage?

4.2.2. Results

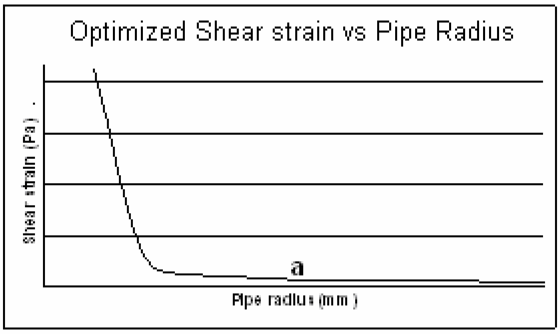


Fig.6. *Optimized shear strain results*

Figure 6 show the relationship between pipe radius and pressure after the optimization process. The letter 'a' on the curve shows the transition point where the shear strain becomes acceptable.

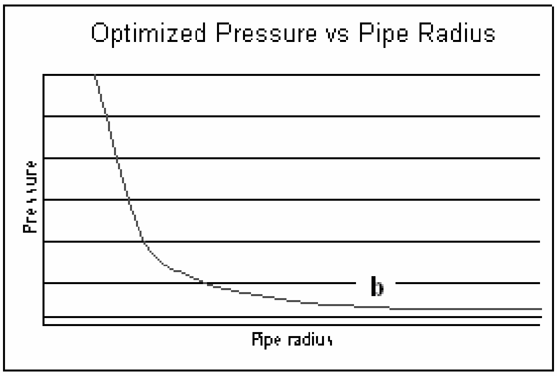


Fig.7. *Optimised radius results*

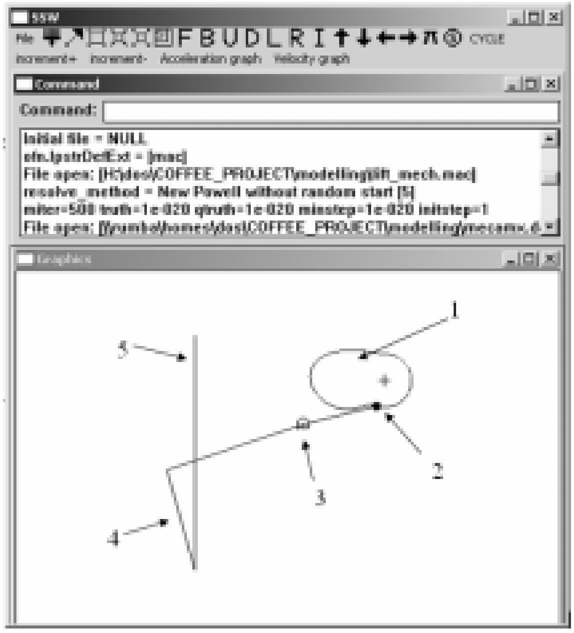
Although the yogurt producer would prefer to reduce costs of the pumping rigs by reducing pipe size, the optimisation process showed detrimental effects to the product. It was also shown in this process that the pressures required to pump the yogurt could not reach the required value until relatively large pipe radius was used. The 'b' on the curve shows the transition point where goal pressure is reached.

To this effect, the optimization process found a point that allowed the minimum pipe diameter with the process inherent feed pressure that did not violate the shear strain properties of the yogurt.

4.3. Multi-instance modelling of elevator

This case study highlights the capability of the constraint modeller to synthesis motion for multi-instance modelling analysis (as noted in section 3.3). The following example is an elevator sub-mechanism from a packaging station. The mechanism is required to push the product through the packaging medium and into to the wrapping station. The elevator of the machine is required to return quickly to the start position, so as not to interact with other parts of the machine.

Figure 8 shows a wire frame model of the mechanism produced in the constraint modeller. Item 1 is the drive cam, 2 the cam follower, 3 cam follower pivot, 4 connection rod and 5 is the elevator block. (constrained to move up and down). The mechanism is now required to process a lower value product, this dictates that the mechanism must now process the new product more quickly to maintain the same level of productivity. An increase from 60 PPM to 120 PPM is needed.



```
Initial file = NULL
ofn.lpstrDefExt = [mac]
File open: [H:\dos\COFFEE_PROJECT\modelling\lift_mech.mac]
resolve_method = New Powell without random start [5]
miter=500 truth=1e-020 qtruth=1e-020 minstep=1e-020 initstep=1
File open: [/grumbo/homes/dos/COFFEE_PROJECT/modelling/mecams.d
```

Fig.8. *Constraint model of elevator*

Figure 9a shows the displacement profile for the existing elevator mechanism. The timing for the lift relates to the rotational movement of the cam. Before considering any modification to this profile, the functional constraints have to be defined. The displacement distance is fixed as it is required to transfer the product from the base of the machine to the packing height. The start and stop points are also critical as they are timed with other sub mechanism within the machine; the product is required to be in place by the time the cam has reached 150°. This leaves the position of the peak of the lift profile as the only factor that can be modified. The lift profile can be described by a sinusoid. To adjust the peak position, the sinusoidal motion law was modified. This modification was calculated to give peak positions from 10° to 150° cam timing. Some of the modifications can be seen in Figure 9b.

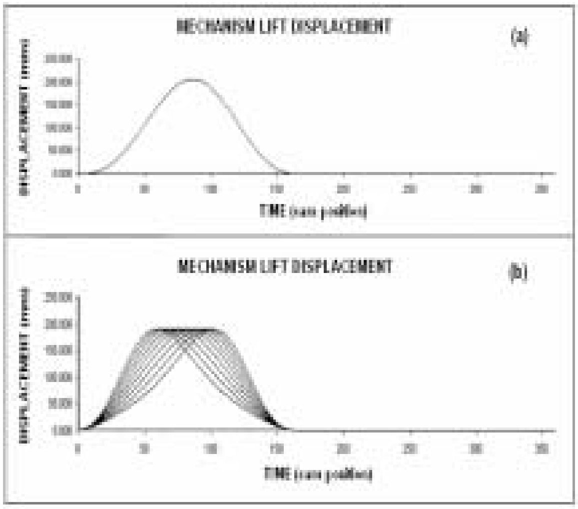


Fig.9. *Displacement profile graphs*

The points from the modified sinusoid are employed as the drive geometries for the end effecter of the elevator. As the elevator is moved, the model space where the cam would be positioned is rotated. With each movement of the elevator, a point is transferred from the end of the cam follower into the cam model space. This can be seen in Figure 10.

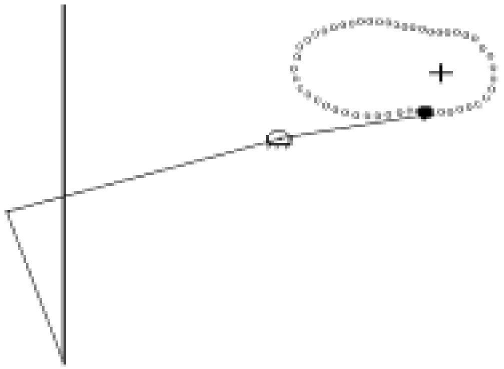


Fig.10. C*am generation in modeller*

Here the open dots representing the transferred points. To add clarity to the figure only 48 points are shown transferred. In the actual case study 1080 points were transferred. Cams profiles in the modeller can be constructed using the B-spline form, the curve is defined by a set of control points, these being the transferred points noted. Each cam profile was saved sequentially in a text files. Some of the multiple instances of the cams can be seen in plotted in figure 11.

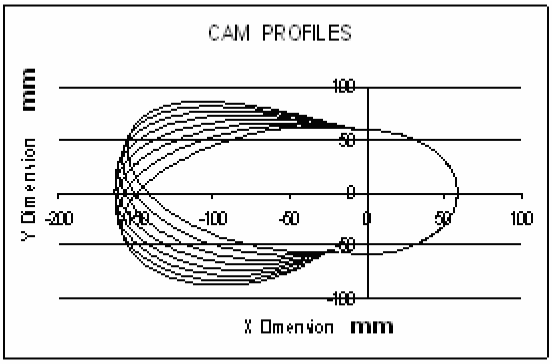


Fig.11. *Multiple instances of lift cam*

These files were read back into the modeller and the run as the drive cam. The acceleration, jerk and velocities were then logged for against each profile and compared.

4.2.3. Results

For visual representation of the results the peak acceleration and velocity values, are plotted against production speed (parts per minute PPM). These can be seen in figures 12 and 13.

Figures 12 shows an acceptable range of velocities when the peak cam value is between 75º and 95º

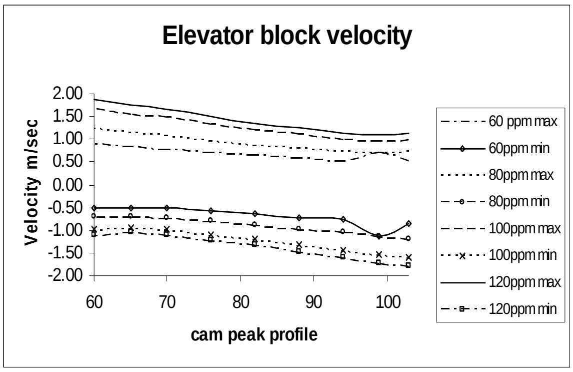


Fig.12. *Elevator velocities*

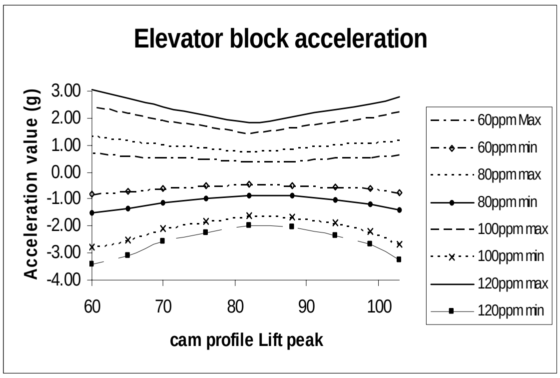


Fig.13. *Elevator acceleration*

It can be seen from the figure 13 that the lowest achievable accelerations for 120 PPM are at 82°. The results show that there is a window of 82° to 84° for the cam peak profile

5. DISCUSSION AND CONCLUSION

The constraint modelling approach enables design knowledge or design rules to be represented within the modelling environment. This set of rules can be refined as the design progresses and provides a set of requirements, against which a design solution can be continually checked. The approach allows a designer to explore the boundaries of a design task and so to gain a greater knowledge of these limits to design and performance. This has benefits both in the case where a design challenge is being met for the first time and when an existing design is being evaluated and enhanced to handle process variations in product.

The approaches described in this paper have been applied to a number of case study examples which have demonstrated the benefits of the technique, This is not just for the modelling activities and refinement of design, but also for aiding development and understanding of existing design problems. The use of multi-instance constraint modelling is in its infancy at this stage but future work is aiming at progressing this approach for investigated the optimal design solution for existing equipment to process variant products.

Although the work presented here has been applied to studies from the food processing industry, the techniques can equally be applied to other industrial sectors.

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