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Constraint-based approach to investigate the process flexibility of food processing equipment

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ABSTRACT

Over the last decade the UK food processing industry has become increasing competitive. This leads the sector to maintain high numbers of product variations. 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 existing manufacturing, handling and packaging equipment has the process flexibility to cope. This paper presents an approach for investigating the performance envelopes of machines utilizing a constraint modelling environment. The approach aims to provide the engineer with enhanced understanding of the range of functionality of a given machine and provides the possibility of redesign to process variant product.

1. INTRODUCTION

The research presented in this paper has been commissioned to investigate the capability of food processing equipment to handle product variation. Sethi and Sethi (1990) noted how there are over fifty definitions of flexibility relating to manufacturing. For the purpose of this research process flexibility relates to the ability of equipment to manufacture variant products under the same configuration. Performance is defined as the ability to satisfactorily complete a specified task.
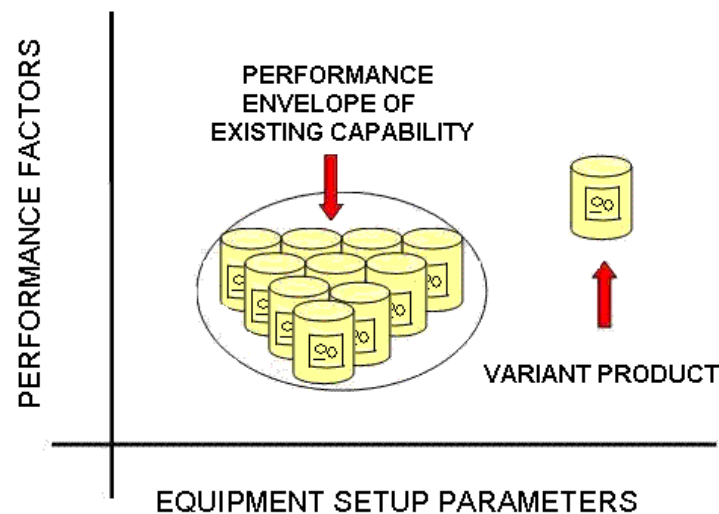

Fig 1. Map of performance envelopes

When considering machine capability, the *envelope of performance* (cf. Figure 1) is the area where the machine will function, using only the inherent design adjustments. This envelope has also been termed as the capacity and capability envelope (Shewchuk and Moodie, 1998). The *envelope of opportunity* is the area where the design will function after external modification to configuration. The approach presented here not only allows the user to analyse the inherent flexibility of the system, but also allow the user to investigate the total envelope of opportunity.

The approach discussed here starts with a parametric model defined within a constraint modelling environment. The combination of program logic and embedded solids associated with this model, are employed to produce multiple instances of the mechanism. These instances are tested against agreed failure modes. The successful performance values returned from functioning instances are used to produce the functional matrix of points. The values from this matrix can then be visually represented to produce the performance envelope for the equipment. Interrogation of these representations, allows the engineer to see if a variant product can be produced using the modelled equipment. The work presented in this paper will contribute to the knowledge of equipment design and performance for the food processing industry. The paper is organised as follows. Section 2 gives an overview of the problem and its related work. Section 3 outlines constraint based approaches and introduces the constraint modeller, Section 4 describes the methodology and Section 5, gives a case study example, Section 6, discusses the approach and its limitations and presents the conclusion.

2. BACKGROUND

The food industry purchases special purpose equipment to process a specific product for its customers. This equipment may have inherent flexibility to cope with limited product variation, although concerns about initial costs restrict manufacturers in purchasing potential flexibilities in new systems (Jordan and Grave, 1995). The product may cease to be commercially viable and a new product may be offered to fills its market space. This was highlighted in the diary industry by Gargouri (2002): due to the dynamic and competitive nature of this sector, new products are continually introduced in an unpredictable way. It was also noted by Erens (1996) that volume and density of variety increase over the products life span. Such changes can be in response to customer demands such as extra percentage for a specific promotion or an additional chocolate bar in a package. In such cases the manufacturer has a piece of equipment but it is not clear whether it can process the new or variant product. An approach is required to investigate this question.

Skewchuk and Moodie (1998) identified three approaches to cope with product variation. The first is to utilize the internal ability of any given system configuration to take alternative corrective action. This could be done with relaxed tolerances on component machine interaction points. Here, the approach does not modify the envelope of performance. If the change is too severe then adjustment must be made to the internal capabilities of the system. This could be performed using adjustments inherit to the design, but as with the first approach, does not change the envelope of performance. Thirdly if the ability of the system cannot cope with the change by utilizing the first two options then changes must be made externally. This would involve shifting the envelope of performance. In this event the authors have sub-divided Skewback and Moodie's definitions into three options, which the approach must deal with:

1. Engineers can either look at ways to develop the flexibility of the existing design so it can cope with the variant product that is increasing the performance envelope, as with figure 2a, this gives the envelope of opportunity (cf. figure1), the total flexible range of the system, or,

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2. more drastically the performance envelope can be shifted to encompass the new product, changing its configuration, but not giving the flexibility to produce the existing products moving from x on figure 2b to y, or
3. The system can be designed so that change parts may be employed to reconfigure the design, and hence allows the design envelope encompass the new product. This moves from x on figure 2b to y, but leaving the option to move back to x.
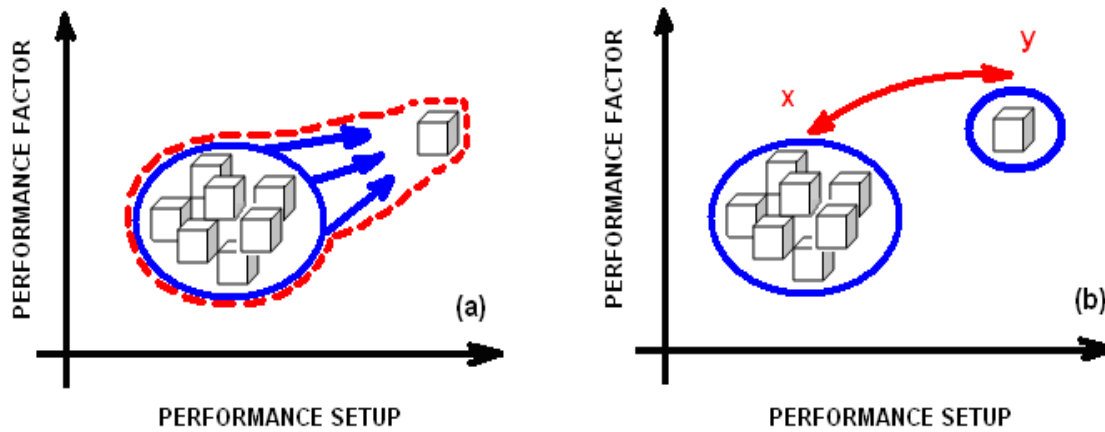

Fig 2. Setup change envelopes

Although many special purpose equipment manufacturers have moved towards pneumatic actuators and servos to translate motion in their equipment, currently manufacturers of packaging and food processing equipment have resisted this trend. This gives highly mechanised equipment which the modelling approach must deal with. The construction of the equipment may mean that certain elements of the equipment are constrained for example equipment 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.

With equipment design and development, the constraints can be applied at various levels These are defined as *hard* and *soft* (Dechter, 2003). Where the *hard constraints are* 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 equipment performance, cost, function and operation. Constraints can provide an understanding, and hence improve agility for the redesign to a configuration that can handle the product variation.

2.1 Related work

There is a variety of techniques that can be employed to give an understanding of manufacturing systems. Huda and Chung (2002) noted how cost reduction activities have encouraged manufacturing companies to introduce new concepts to improve efficiency. This combination with the advances in computational processing power have meant that simulation modelling and analysis has become popular technique to investigate these scenarios. Zakarian and Kusiak (2001) investigated the use of dynamic simulation and IDEF models for process analysis. Barton and Lee (2002) presented an intuitive frame for hybrid (continuous and discrete) dynamics systems and discussed the theory of parametric sensitivity. Kazmer et al (2003) models the process flexibility index, which assesses the ability of the design processing variables to effect changes in quality attributes. Thurairajasingam et al (2002) developed a mathematical model for the continuous processing of biscuits. Gindy and Saad (1998) presented a conceptual framework to investigate the flexibility and responsiveness of a

manufacturing cell. Kazmer et al (2001) presented the concept of modelling process windows to aid the tuning of manufacturing setups based on end product quality.

One of the main reasons for the variety in the underlying methods is that particular tools or techniques are frequently driven by the perspective of the particular problem and how it is to be solved rather than a generalised approach for reasoning about the problem. It is arguable that such variety makes the use, integration and exchange, methods and processes particularly difficult and contributes to many of the research challenges facing academia and industry period. Notwithstanding this, there is one method that is emerging as a more generalised approach for modelling and reasoning and has been recently applied to a range of different tasks associated with design and manufacture. This approach is constraint based reasoning or constraint modelling (Freuder and Mackworth, 1994). The approach involves representing what is to be achieved rather than how it is to be achieved, and typical employs heuristic techniques (Dechter, 2003) to fully or partially satisfy the constrained problem. For these reasons, constraint techniques offer an opportunity for a more generalised approach to modelling and reasoning about products or equipments during design and manufacture, which could support a more unified model for the entire design and manufacturing process. Typical examples follow in the next paragraph.

In the design of systems, O'Sullivan (2002) presented an interactive constraint-based approach to supporting the designer at the conceptual design stage. Hicks et al (2001) described a methodology using a constraint modelling environment for supporting and analysing the design of packaging machinery at the embodiment stage. Martinez and Felez (2005) developed a constraint based approach to detailing designs. Their method defines the constraints and geometry of a two dimensional sketch and relates this to the complete dimensioning of the sketch. Hicks et al (2003) used a similar approach for 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. 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 (2004) and Zhang et al (1997), the constraints are satisfied to find the most cost effect sequence to manufacture parts. Constraint based approaches have been employed for biomechanical applications. Feikes et al (2002) proposed the use of a constraint based approach to overcome the limitations of a mechanism based solution for calculating the displacement of a three dimensional geometric model of the knee joint.

3 CONSTRAINT MODELLING ENVIROMENT

The constraint modelling software used here (Mullineux, 2001) 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 satisfied. There are several techniques for the constraint satisfaction problems (CSP), such as those presented in Ge et al (1999) and Anderl et al (1996), including, for example, symbolic manipulation and reordering strategies. The method used by the constraint modeller is based on optimization techniques Fletcher (2000). It uses penalty functions; the squares of constraint relations are added to form the objective function and this reduces the problem to one of unconstrained optimization. If there are n variables x1, x2,…,xn involved in m constraints.

These are denoted on equation 1.

$$f_j(x_1, x_2, \ldots x_n) = 0 \text{ for } 1 < j < m \qquad (1)$$

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, as equation 2.

$$F(x_1, x_2, \ldots x_n) = f_1^2 + f_2^2 + \ldots + f_m^2. \qquad (2)$$

During satisfaction, the expression for each constraint rule 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 the satisfaction process 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.

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' Leigh et al (1989). 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 Corney (1997).

As an example, consider the representation of a four bar linkage shown pictorially in figure 3 (f). In part (a) 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 'coupler' i.e. 'M2' (c) is "embedded" in the space of the crank 'M1', and the spaces for the crank and link 'driven' 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 'driven' is rotated, the hierarchy of their spaces ensures their ends remain attached.
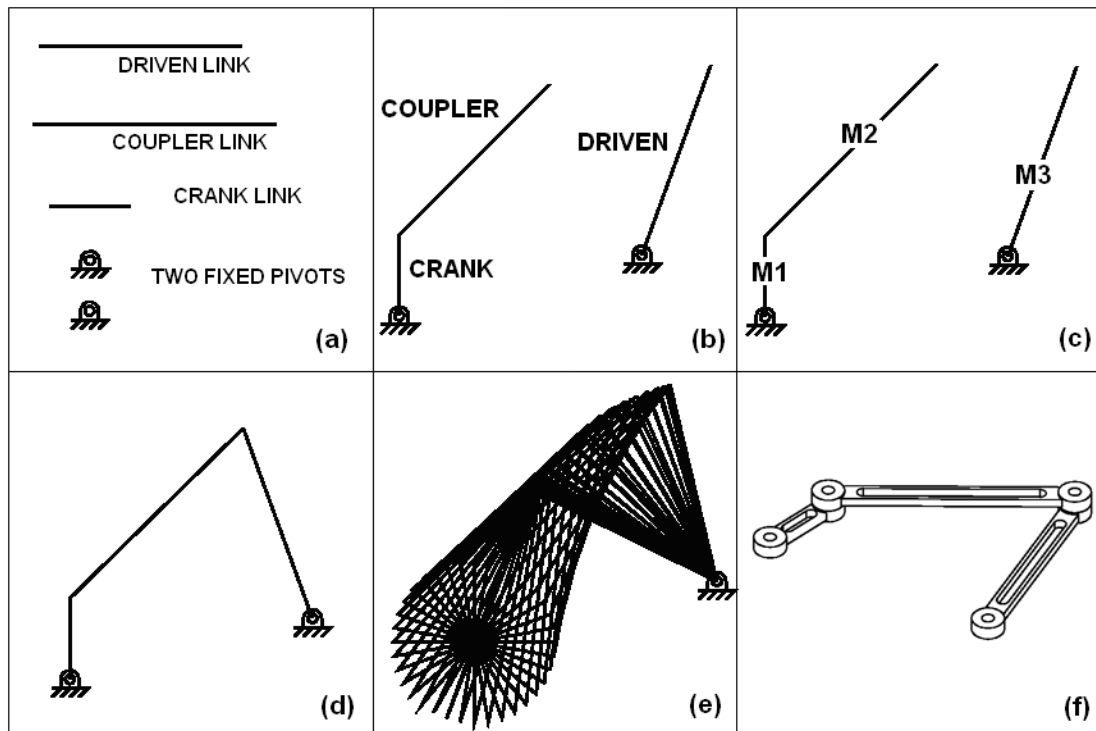
Fig 3. Construction of a linkage

To complete the assembly, the ends of the link 'coupler' and driven link 'driven' have to be brought together. This cannot be done by model space manipulation alone; this would introduce a loop into the tree 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 'coupler' and 'driven' the constraint rule is expressed as follows,

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rule( coupler:e2 on driven:e1 );
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where the colon followed by e1 or e2 denotes either the first or second end-point of the appropriate 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 model 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 (f).

4 ENVELOPE MODELLING APPROACH

The process for establishing the performance and opportunity envelopes can be divided into five steps. These are described in the following section.

4.1 Step 1: Establish, verify and validate the model

The validation of the model is the process of making sure the model represents reality, where as the process of verification identifies that the model operates as the designer or customer intents. The physical measurements of the system are recorded in combination with high speed video footage of the equipment operating. The mechanism is then parametrically

modelled using the constraint modelling package, as described in section 3. The resultant model is then compared against the high speed video footage to verify and validate the functionality.

4.2 Step 2: Define failure modes

While investigating industrial examples, a study was undertaken to determine which factors caused machinery from the food processing and packaging industries to fail. The identified factors are shown below on table 1.

Table 1 Identified failure modes

Failure Mode		Description
Element collision		Clash interaction between elements of equipment
Mechanism deconstruction		Motion cause elements of equipment to pull apart
Displacement		To much or insufficient movement of element to translate required motions
Kinematics		The three time derivatives of motion.
	Velocity	Low or high velocities can cause timing problems
	Acceleration	Excessive acceleration and jerk cause vibrations,
	Jerk	lack of accuracy and advanced wear.
Dynamics		Effects of forces on the motion, increases in speed and product load can cause vibration, increased equipment wear and lack of accuracy

While investigating variation effects to systems, it was found that most of the failures occur with the equipment reaching its limit factors for example insufficient displacement achievable, required motions forces the mechanism apart, or accelerations are too high, inducing vibrations and wear. However product factors also affect the failure responses. For example consider a mechanical gripper and transfer mechanism from a piece of equipment producing a frozen product. Marketing changes now mean the customer is offering to product in a non frozen variant. This affects the mechanism in two ways: the package is softer, so less grip pressure can be applied and speed of transfer is limited due to potential deformation of product. For this reason the failure modes must be agreed with designer/ engineers along with some proper testing of product.

4.3 Step 3: Associate failure detection to model

This section introduces the tasks to detect certain forms of failure as identified in table 1. This ability to detect failures with the modelling environment, fails under three headings; the inability to assemble correctly, satisfactory motion and clash detection. Table 2 highlights the techniques employed within the modeller to identify these failures.

Table 2 Task to detect forms of failure

Failure mode	Detection approach	Description
Inability to assembly correctly	Truth Maintenance	The modeller performs assemblies by minimizing the error in constraint rules which represent the distance between parts. Its ability to do this can be used the access it ability to assemble and stay assembled through motion.
Satisfactory motion	1. Bounding Box 2. Point displacement & Non-excessive kinematics	1. This is where a block contains an object throughout its motion. A check can be invoked to identify interactions between box produced by the motion of the object and another block defined as the expected motion for the object. 2. Models are defined within Cartesian space; the co-ordinates of each element within the model can be mapped while in motion. Conditional statements are employed to investigate maximum and minimum displacements. With motion initiated in the model, this ability is also utilised to calculate the time derivatives of motion.
Clash detection	Embedded solids	The modeller, has the ability to identify the volumes of solid objects. The change in volume is used to detect the interaction between elements of the model

4.4 Step 4: Disturb mechanism under failure modes

Within this research the term disturbance implies the mean parametric variation of the variables defined in the model. These are used to find the successful instances of the model operating under the failure modes. Successful instances are used to produce the functional matrix, along with the successful instance variables recorded, performance values for each instance can also be logged. The data from this is plotted to find either the envelope of performance or opportunity. There are three strategies for the disturbance that can be performed within the modeller. When modelling machine/ mechanisms, for each of these strategies, the maximum geometric sizes for individual elements, is limited by the footprint size of the machine/ equipment, these are defined as the *preliminary limits*. The three strategies are as follows.

- *Program modeller to disturb dimensions of model*: The variables within the model can be programmed to vary in dimensionality. A strategy for the disturbance has to be decided prior to this step. This approach is only suitable for simplistic mechanisms with small amount of variables.
- *Set goal, and allow the modellers optimising function*: the internal optimiser with the constraint modeller can be used when a goal is set for the model. The modeller will iteratively optimise the model; all successfully functioning instances can be recorded to produce a functional matrix.
- *Design for experiment*: with the preliminary limits established for the individual variables, statistical software such as Minitab® (Barbara et al, 2005) MATLAB (Mathworks inc, 2005) can be used to generate a test matrix of preliminary limits to be run through the model. Successful instances from the test matrix can be logged to produce the functional matrix. This is the preferred method statistical tools easily

generate data for large quantities of variables that are associated with complex equipment.

4.5 Step 5. Evaluate and representation results

Step 4 results in a list of successfully functioning points these are recorded individually to form the functionality matrix. The maximum and minimum values recorded for these elements give us the performance envelope of the equipment. Different representation techniques can be used to present data in the functional matrix. Two main options are the convex hull (Shamos and Preperata. 1985) and response surfaces (Khuri and Cornell, 1987) When a new configuration is required and the new point is plotted into the data set, it can be compared with the original hull. If the volume or surface area has increased, then the new configuration lies outside of the limits of the mechanism. In most cases, it becomes obvious that there are, multiple configuration that will process individual products. At this stage the differing characteristics can be investigated simultaneously and compared against selected critical product characteristics. Here a constraint-based optimization approach can be employed to find the optimal instance for the given product. It is also possible at this stage to use the modeller's sensitivity analysis function upon each configuration. Sensitivity analysis (Galan et al, 1999), 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.

5. CASE STUDY

The following problem relates to the investigation into the expansion of the performance envelope (cf. Figure 1) and process flexibility of a candy wrapping machine. This section describes the equipment, defines the problem and shows how the approach described in section 4 is applied.

5.1 Equipment

The case study is the ejection mechanism from a candy wrapping machine (Figure 4). The function of this sub-mechanism is to guide the wrapped candy from the transfer grippers onto a chute where the candy exits the machine. The machine is designed to wrap a lozenge shape hard boiled candy, and has inherent flexibility to accept dimensional inaccuracies in the products manufacture. The original candy has dimensions of 26mm diameter and a central height of 19mm.
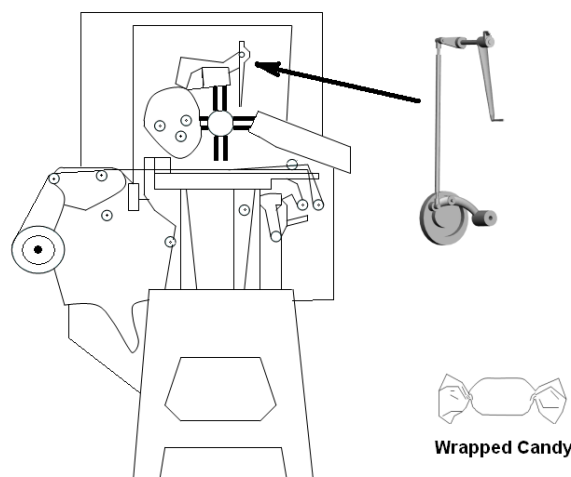

Wrapped Candy

Fig 4. Schematic of wrapping machine

5.2 Problem

If the manufacturer wanted to wrap a candy bar with dimensions of 20mm height, 70mm long and 40mm width, yet maintain the ability to wrap the original product, would it be possible? (This would mean expanding the performance envelope in the nature shown in figure 2a.). Preliminary investigations of other sub-mechanisms show, an ability to process product of a height of 32mm and length of 83mm. The mechanism has topological *hard* constraints. A Geneva mechanism indexes the gripper jaws into a set position. The position of the pivot points for the cam follower and the pushrod to link are fixed. The length of the ejection arm is constrained, as the product is held centrally in the gripper jaws and the index position for ejection is fixed. For the purpose of this example we are not evaluating the cam profile for modification. This leaves the four links as the option to produce the configuration to process the new and old product.

5.3 Modelling and evaluation process

In this study, the physical measurements of the mechanism were recorded in combination with high speed video footage. The mechanism was then modelled using the constraint modelling package. The resultant model was then compared against the high speed video footage to verify the functionality. With the model produced and tested the next stage is to define the factors which stop the mechanism from functioning. The following failure modes have been established for the ejection mechanism.

Table 3 Ejection mechanism failure modes

	Failure mode type	Description
a	Kinematic	Ejection arm velocity profile too high
b	Mechanism Deconstruction	Breakage in mechanism
c	Collision	Pushrod interacts with frame of machine
d	Collision	Eject arm interacts with pushrod
e	Displacement & Collision	Ejection arm movement insufficient or incorrectly orientated to remove the candy from jaws
f	Displacement	Ejection arm rest position too far forward
g	Displacement	Ejection arm max position

Figure 5 shows the ejection mechanism modelled in the constraint modeller. The ejection mechanism comprise of a cam driven four bar chain with two fixed pivot points. The circular form at the base of the model is the drive cam. The cranked arm attached to the fixed pivot point and resting on the drive cam is the cam follower. The upright line is the pushrod. The link is the line spanning the top of the pushrod and the top fixed pivot point. The line descending from the top fixed pivot point is the ejection arm. The model is drawn in wire-frame construction, but for the failure mode detection for 'c,d,e' Table 3, solid are embedded into the model. The solid elements added to the model are the vertical rectangular and square block to the left, which models the machine frame. The rectangular block to the right of the model is the new candy held in the machine jaws. The upright block on the pushrod is the body of the pushrod and the cylinder disc at the end of the ejection arm is used to check ejection arm contact to the candy and pushrod. The inbuilt 'Truth' function is employed to detect mechanism deconstruction and geometric positioning was used to detect maximum and minimum position and the velocity of the ejection arm.
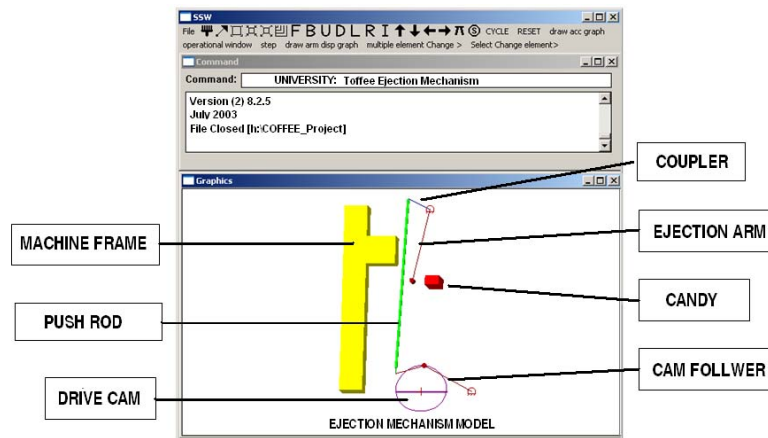
Fig 5. Constraint model of mechanism

The values from disturbance to the elements are recorded individually to give the function matrix. From the matrix a scatter plot is produced in MATLAB, this plot is then used to generate the convex hull shown in figure 6. Figure 6a shows the performance envelope produced for the original candy, with the new candy failure mode limits assigned to the model 6b is produced.
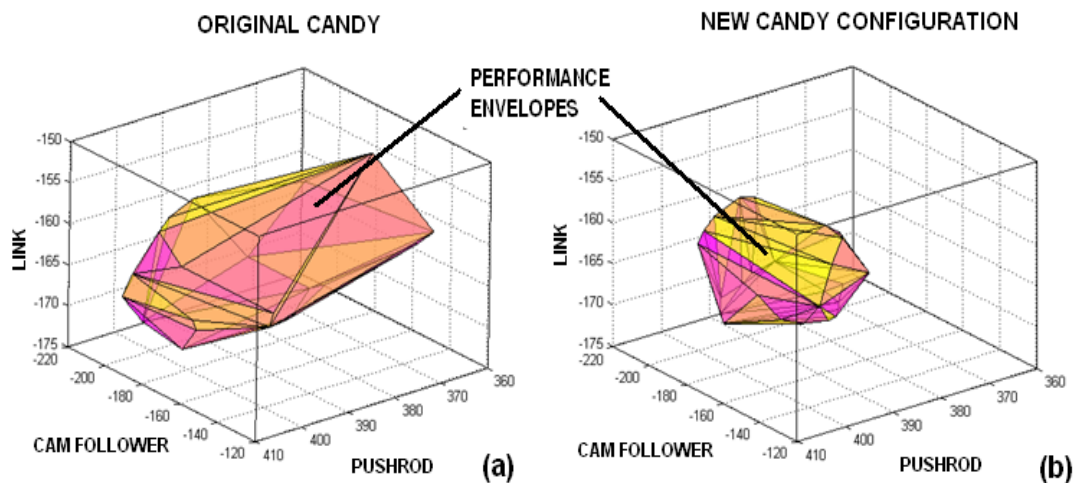

Fig 6. Convex hulls of performance envelopes

The parameters to produce the new failure mode specification were added to the model, these constrained the motion for both the old and new candy. The envelope produced encompassed regions where both products could be produced. The fact that points can be plotted and a hull produced, indicates that a configuration exists that will produce both products, although the performance envelope is greatly reduced, and shown to be a sub-region of the original products convex hull. By implication the system should be capable of processing all products that lie 'chained' (Jordan and Grave, 1995) in the product family in between. To test this, two further products were modelled in the system. A product with a large width, that the mechanism should not be able to handle and another product, with dimensions that lie half way between the new product noted in the problem section and the original product. The resultant hull can be seen in figure 7, here the convex hull for the original product is also plotted. The approach shows that as the size of the product increases, the performance envelope decreases.
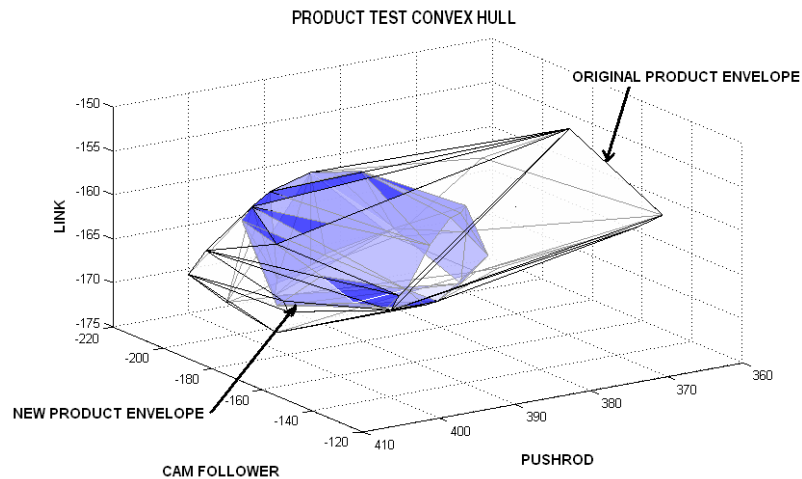
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Fig 7. Test convex hull

An additional factor from the modelling shows, that in the original configuration the link dimension was close to its minimum limit. If a reduction adjustment to this link was required for a variant product change, it is likely that the cam follower and pushrod would need modification as well. One limitation that has become evident in the representation of the envelopes using the convex hulls is, the hull plots the minimal convex shape containing the given data, it can envelop is that a void in the points where the equipment does not function successfully. For this reason the convex hull is only an approximation of the region of acceptable working. Although in previous case studies this has not been a problem, as the analysis and optimization is performed on the raw data produced in the functional matrix.

6 Conclusion

The research approach illustrated in this paper aims to provide the engineer with a greater knowledge and understanding of the performance envelope for a given piece of equipment. The specific outcomes of this work are shown to be. That it allows the engineer to investigate the capability of processing equipment, offering the opportunity to examine the redesign to handle product variation. The holistic Constraint-based modeller approach offers the possibility to perform sensitivity analysis on the design and to optimize it, when resources are in conflict. The research described in this paper is part of an ongoing project into the assessing the capabilities of existing food processing equipment to handle variation in product and packaging. The emphasis of the work presented here has been on discrete mechanical performance. It is planned to extend the technique for technologies that deal with more continuous flow type applications

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