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AN EXTENDED PRODUCT MODEL FOR CONSTRAINT-BASED REDESIGN APPLICATIONS

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ABSTRACT
This paper presents an extended product model to support the constraint-based redesign process of production machinery to handle product variation. The paper highlights the deficiencies of existing product models (e.g. CAD models), namely such models provide good geometrical and topological information, but offer limited support information for the redesign process, specifically excluding factors such as, performance capabilities, constraints, and the reasoning behind decisions. The research aims to encapsulate the information generated during the redesign process within a new extended product model, so that it can be revisited throughout the whole product life. The proposed extended product model expands current CAD models beyond physical entities, including geometrical and topological information, performance limits, alternative concepts and solutions, and change parts. It adopts a hierarchical structure, to provide specific levels of detail, according to different specialist expertise and stages in the product lifecycle. It also defines the model elements with design constraints, design activities, supporting resources, decisions made and design rationale in the redesign process, no matter what type of document is used. The proposed extended product model is illustrated with a case study example from the food industry.

Keywords: Extended product model, constraint-based design, processing equipment, constraints, design information.

1 INTRODUCTION
With the trends in global competition, manufacturing companies today are facing unprecedented demands to become leaner and more agile with their production processes. In addressing these requirements, such companies need to constantly develop and improve the performance capabilities of existing machinery, and to design new machines and systems. Several approaches have been proposed for machine redesign, for example the constraint-based approaches [1, 2]. However, at present, such redesign tasks can not be carried out efficiently in many companies; the inhibiting factors to this include the following:

- It requires expertise and significant time for new design engineers to understand a machine. Current representations for machines, i.e. various product models [3], mainly provide geometrical and topological information, such as assembly relationships, shapes and dimensions. These lack necessary information for redesign tasks, such as performance capabilities and constraint rules.
- Previous redesign processes, including design activities, decisions-made and corresponding rationale, are still recorded in text documents (e.g. design reports, meeting minutes) and even retained in employees' memory. It is difficult for new design engineers to assimilate and digest these redesign processes.
- Over time, it becomes impossible to retrace the engineering reasoning and decision making processes which have taken place during any design/redesign process.

To address these problems, this paper presents a new extended product model which is employed to encapsulate the information generated during the constraint-based redesign process, so that it may be revisited by designers at later stages of the machines life. Such information will integrate geometrical information with non-geometrical design information, including performance capabilities, constraint rules, design activities, decisions-made and rationale. The paper is organised as follows. Section 2, gives an overview of the constraint-based redesign process. Section 3, presents existing product models and their limitations and then concludes by presenting the proposed extended product model. Section 4 illustrates the extended product model with a case study example. The discussion takes place, and conclusions are drawn, in section 5.

2 CONSTRAINT-BASED MACHINE REDESIGN

When design engineers, are considering the redesign of production machinery (such as those producing food stuffs), to gain an understanding of its capability to process product variation. Knowledge of the precise rules which need to be applied, are generally not well understood. More evident are the “constraints” which limit what can be done [4]. These “constraint rules” represent relations between the design parameters which must be satisfied if the design is to be successful. They may include simple relations between the geometry of parts, and representations of performance and physical requirements of any design. Constraints may also be imposed by resources. In this way the design of the artefact is not process led but goal orientated. When dealing with a system, it is very rare that single elements or operations are independent of the other elements. Consequently, all the goals and the related constraints must be dealt with concurrently and all their interrelationships taken into account. The aim is to find the configuration that satisfies all the imposed constraints as closely as possible. There are several techniques for doing this, such as those presented in [5] including, for example, symbolic manipulation and reordering strategies. 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 both the proposed solution and in the governing constraints of the particular design problem can be dealt with. This has not gone unnoticed by previous researchers, and various constraint-based approaches have been employed to aid and assist the design process [5, 6, 7].

One constraint-based redesign process [2] consists of five stages and involves several types of information, such as high-speed video recordings of machine, simulation models, and text documents. The approach works with a parametric simulation model of the machine established within the constraint-based modelling environment [5]. The constraints are used at two levels. Firstly the constraint-based modelling environment employs numerical optimization of the constraint rules [5] for relationships and connectivity of elements within the model, then constraint monitoring is used, to check for violations in the model operation. The effects of variations within the machine can be investigated by adjusting suitably chosen parameters within the model. Such variations can represent the effects of adjustments within the physical machine and the use of change parts. Working with the designers or users of the actual machine, the possible modes of failure for the machine are established. These modes of failure for the machine become further constraints for the operation of the model. Within the modelling environment, tests for these constraints can be created. There are various ways in which this can be achieved within the modelling environment. For example, one failure mode may be the clashing of parts of the machine with each other or with the product being processed by the machine and interference checking between solid objects within the model can be undertaken. An alternative is bounded boxes, where a box is a rectangular block which contains an object throughout its motion. When a change to product being processed or packaged necessitates a modification to a machine setup and this modification causes the motion to take place outside of the box, then it can be concluded that this processed product cannot be manufactured using this machine. While this is crude, it is an approach that is sufficiently reliable for many applications. These failure modes are used as design constraints for model functionality in the redesign process.

The next stage is to execute the model repeatedly for different configurations (design instances) with each being tested for successful operation. This allows a matrix of successful design instances to be generated. When the model is being tested, performance characteristics [8] can also be collated into the matrix. With the matrix defined, a crude method to test whether a new product configuration lies within the limits of mechanism, is to search for the closest instance to the new configuration. At this point, the performance values can be used to find the best solution. If the values of the new configuration are greater than those recorded within the matrix then it can be assumed that the new product cannot be produced with this mechanism/ machine. The design information recorded in the matrix, can then be employed, to produce a variety of visual representations, for example, convex hulls and surface plots. Such visual representations, offer the designer techniques for interrogating the performance envelope of the machine [2].

This implementation of this approach opens the opportunity of redesigning the original machine so as to maximize its allowable space. Here constraint-based techniques and optimization are used. Now more of the fundamental design geometry can be varied with the aim of increasing the volume of the design envelope obtained when the machine adjustments are varied. This then allows a more general purpose machine to be designed and can permit the number of machines in a given family to be reduced. The approach generates a variety of design information as the process progresses. This ranges from geometry details captured at initial modeling stage, high speed videos of the machines operation, and performance data. Also, the design constraints relating to individual components, mechanism operation and the functional factors can be identified by users and designers. After the redesign process has taken place and any relevant modifications have taken place. The only information that is retained comes from the generated performance envelopes and the constraints employed in model construction.

In general, redesign of production machine using constraint modelling principles consists of two steps:

1. *Capturing the information for the existing machine*: it is likely that manufacturers may have been using a machine for many years, which makes it probable that the machine drawings and specifications may be incomplete, and in any case design representations may be in the form of orthographic projection drawings. Thus, there is often a requirement to re-model the machine, including its physical composition, mechanism and performance capabilities, to identify and understand those aspects of the existing machine. Using the constraint-based approach will generate design information representation in the forms of constraint networks and some variant of a constraint-based model.
2. *Redesigning machines*: in the constraint-based approach, the machines are redesigned based on new functional requirements and constraint rules. To retrieve such information, not only the new configuration of redesign machine, but also the related information in the redesign process, such as constraint rules, limiting model, changed parts, design activities and rationale, all need to be represented and documented.

3 PRODUCT MODELS

3.1 Conventional product models

The essential objective of a product model is to represent the design and engineering aspects for a product in an appropriate format (usually digital), during the configuration, assembly or detail design stages. Product models have become a critical part of today's 3D design/redesign applications. During the last forty years, a large volume of research has focused on product modelling and several approaches have been proposed [9], such as wireframe model, surface model, Constructive Solid Geometry (CSG), Boundary Representation (B-rep), feature-based model and parametric model. Currently, most CAD systems implement a hybrid-modelling strategy combining the best features of the various approaches. For example, NX 3 [10] integrates sheet/surface/solid representations with parametric and feature-based design. However, such CAD representations are centred on geometric and topological depictions of the product, and lack the ability to model high-level design and engineering context and semantics.

To solve this problem, various efforts to extend the conventional product models have been attempted recently. MOKA (Methodology and tools Oriented to Knowledge-Based engineering Applications) [11, 12] introduced a formal model which provides the representation of product meta-classes and its views (i.e., function, structure, behaviour, representation, and technology), and relations between them. NIST presented an information modelling framework [13]. The framework consists of four major components: the Core Product Model (CPM) with the capability of capturing and sharing the full engineering context in product development; the Open Assembly Model (OAM) for assembly and system-level tolerance information; the Design-Analysis Integration model (DAIM) as a basis for integrating design and analysis; and the Product Family Evolution Model (PFEM) for the evolution of product families and of the rationale of the changes involved. The IPPOP (Integration of Product – Process – Organisation for engineering Performance improvement) Project [14] aims to integrate the product, process and organisation dimensions of a design project, and adopts versioned product data as the kernel of integrating a process model with product model.

There have been attempts to incorporate constraint representation into product models. Research by Thornton employed a product model to store geometric variables and constraints [6]. The model supported dimensional, geometric, positional and interference knowledge. The aim of the research was to use constraints to support the search for feasible designs solutions. Although this and other methods have succeeded in some aspects, (e.g. the inclusion of engineering context), the requirements of constraint-based redesign application cannot be met effectively so far because of the following:

- As described in section 2, a large amount of work is performed in the constraint-based redesign process in understanding a machine and its performance limits, for example by building simulation models, determining failures modes and identifying the effects of variations. Current product models cannot provide such information for the next redesign process, though some related files, like videos of machine operation, simulation models and text reports may be stored separately.
- Constraints are the key information for machine redesign, but such important information is not recorded in current product models.
- Information about previous redesign processes, including design activities, decisions-made and corresponding rationale are a valuable for designers, but no linkage can be provided directly from this information to the product model.
- The processed product changes, dictate that a machine needs to be redesigned to accommodate new functional requirements. As the processed product evolves over time, thus the machine can be redesigned several times. The machine design history, the change parts and the support information (e.g. simulation models, matrix of functional points and constraint networks) are necessary pieces of information to be recorded though current CAD models only represent the product at this final stage.
- The constraint-based method is performed against new functional requirements and a list of constraints, but the linkages between the changed parts and the constraint rules are lost after redesign process has been completed.

To address these problems, it is necessary to extend the CAD product model for the constraint-based redesign process.

3.2 Extended product model

3.2.1 Structure of model

As discussed above, the extended product model (EPM) as shown in Figure 2 and 3, broadens the conventional CAD models to include the following aspects:

- ***Extension to non-geometrical information***: traditional geometrical models can be described hierarchically, such as the ACIS approach shown in Figure 1 [15], but the information is limited within geometry and topology. The proposed EPM (Figure 2) is extended beyond physical entities, including requirements, performance limits, alternative concepts and solutions (e.g. sketches, parts and features).

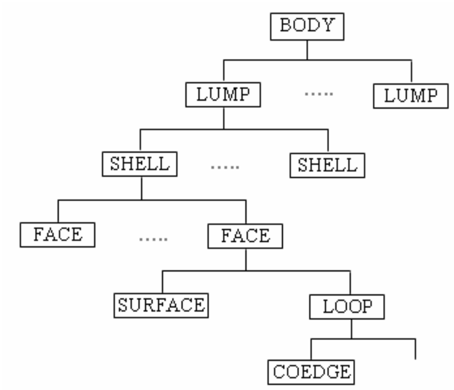

Figure 1 ACIS hierarchy [15]

- ***History of design***: during its lifespan, a machine can be redesigned several times. During each redesign process, there may have been several design iterations. To reflect machine history and iterative development, the EPM not only includes the final design, but also links to or records the previous designs, the conceptual designs, and the alternative design solutions (e.g. parts, features, parameters, and tolerances).The elements in EPM are classified into two types:
    - *Active element*: this element represents information on the product at the current stage;
    - *Inactive elements*: these elements represent previous designs, changed designs, conceptual designs and alternative solutions including underlying constraints and respective variables.

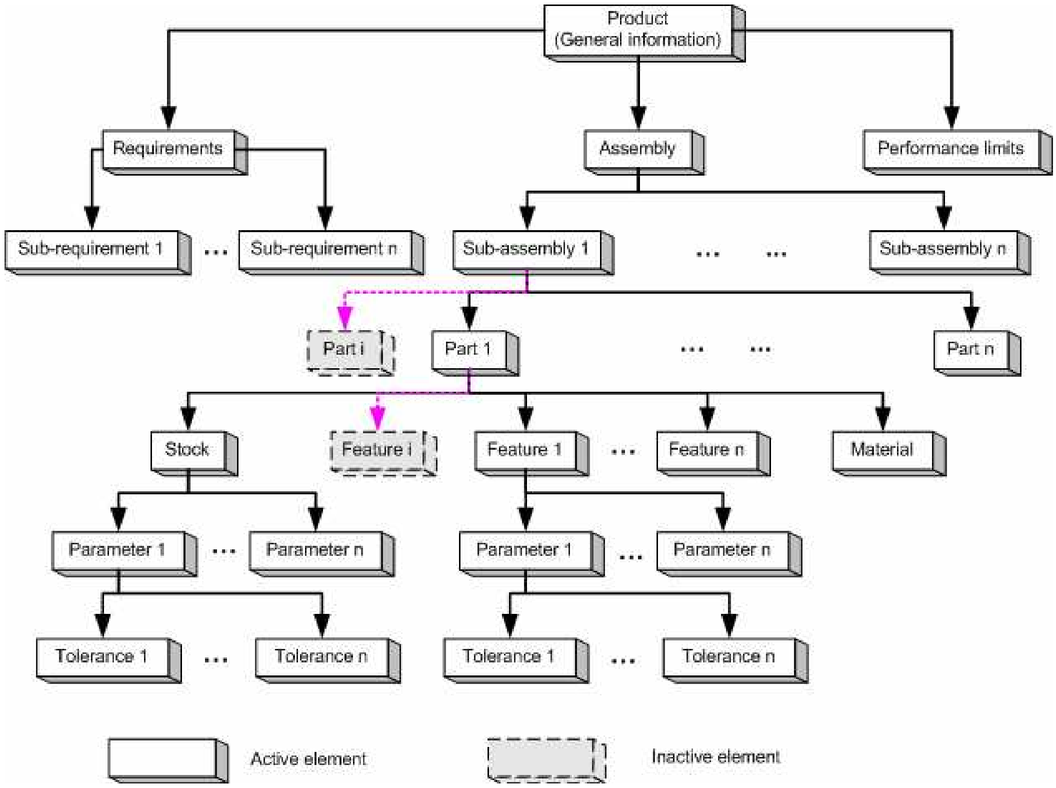

Figure 2 Architecture of extended product model

- ***Linkages among the information in the design process***: As shown in Figure 3, a specific element (e.g. an assembly, a part, a feature, a parameter or a tolerance) of the EPM can be linked to its previous design, alternative solutions, specific constraints, specific activities, specific rationale, or specific support information resources. The directly linkages enable users to revisit and to retrieve the design history, the constraints, the redesign process which was performed, internal rationales and various supporting sources, and therefore benefit designers, especially for the new designers. The following linkages are defined in the proposed model:
    - *Version-linkage (VER-LINK)*: the linkages between an active element and its historical development (e.g. the modified part links to its previous version);
    - *Virtual-linkage (VIR-LINK)*: the linkages between an element and its alternative concepts/solutions (e.g. the assembly links to sketches in conceptual design) ;
    - *Constraint-linkage (CON-LINK)*: the linkages between an element and its relevant constraint rules (e.g. length of pushrod links to min/max length rule);
    - *Input-linkage (INP-LINK)*: the linkages between an element and the activities that regard the element as an input (e.g material links to activity A as it is an input of activity A);
    - *Output-linkage (OUT-LINK)*: the linkages between an element and the activities that regard the element as an output (e.g. length 400mm links to activity B as it is designed in activity B);

- *Rationale-linkage (RAT-LINK)*: the linkages between an element and its relevant rationale (e.g. a modified part links to reasoning, why new design solution sort);
- *Resource-linkage (RES-LINK)*: the linkages between an element and its relevant supporting resources (e.g. the assembly links to simulating model).

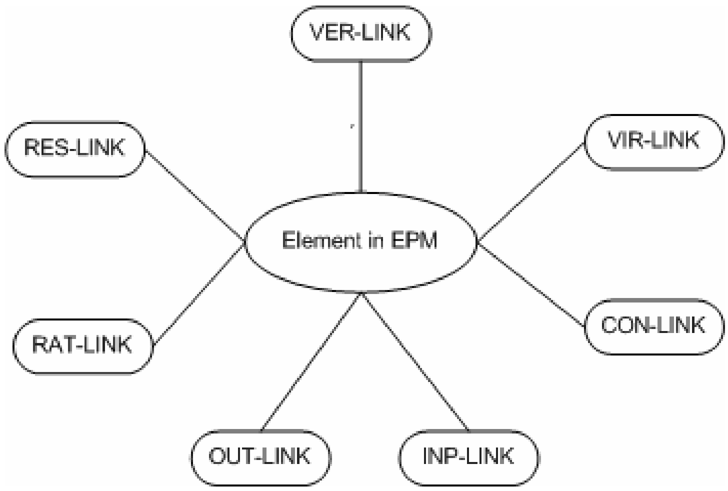

Figure 3 Definition of elements in the extended product model

3.2.2 Implementation of model

The proposed extended product model has been implemented within a commercially available design software package: Unigraphics NX3 [10]. The prototype system is founded on a NX3 model, with the API NX Open being employed to attach non-geometrical information (e.g. performance limits and requirements); reference previous design (e.g. alternative solutions, changed parts); and link to relevant information in design process (e.g. constraints, supporting resources, relevant activities and rationales). A program has been developed using C, which is embedded to assist the opening/running of external resources automatically. In addition, the UIStyler dialogue in NX3 has been utilised to develop the user interface. Figure 4 below shows the developed NX3 user interface input menus, for the proposed extended product model.

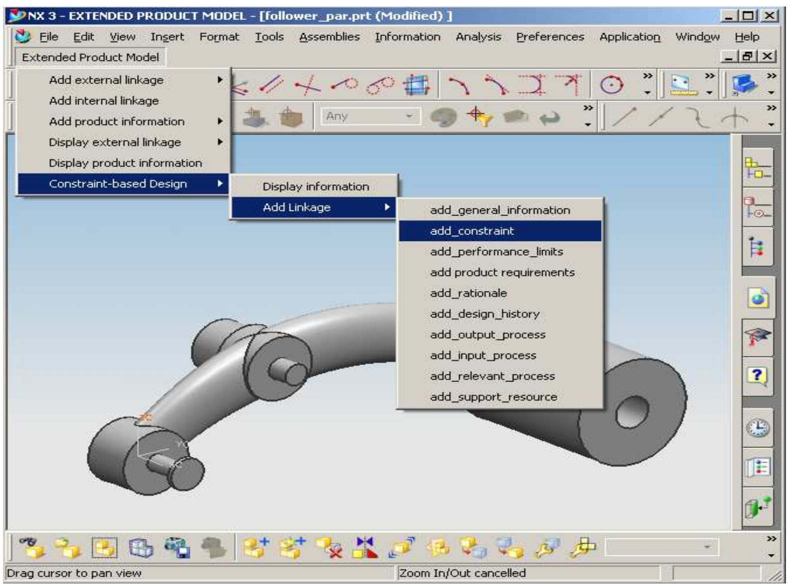

Figure 4 Information input Interface

Figure 4 shows the ten input factors that the user can employ in the creation of the extended product model: general information, constraints, performance limits, product requirements, rationale, design history, output process, input process, relevant process and support resource. Once the user selects the factor they require, the user is taken to the input windows, where they are prompted to enter the specified information: constraint, performance capabilities, rationale etc, and links, to the supporting files to the specific elements (e.g. product, component and face etc). Figure 5 shows the information retrieval interface implemented in the NX3 environment

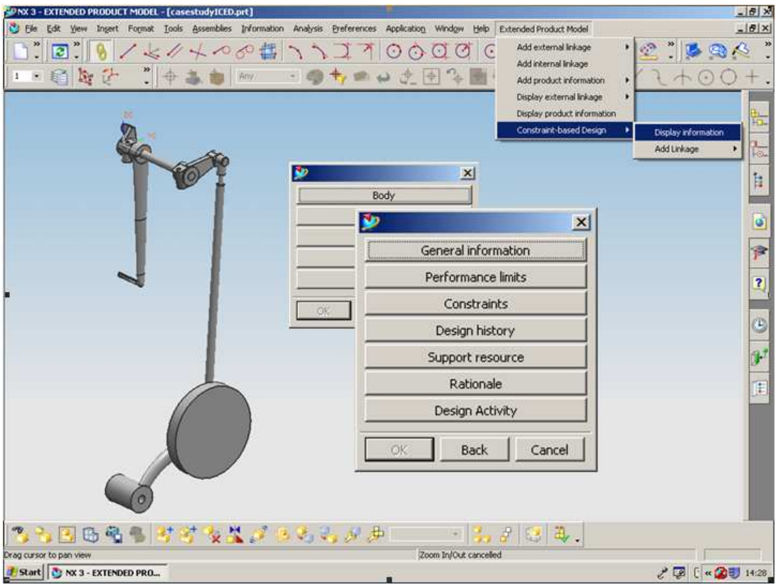

Figure 5 Information retrieval interface

4 CASE STUDY

The case study presented here is the ejection sub-mechanism from a candy wrapping machine (Figure 6a). The function of this sub-mechanism is to guide the wrapped candy from the transfer grippers onto the 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 product's manufacture. The original candy has dimensions of 26mm diameter and a central height of 19mm.

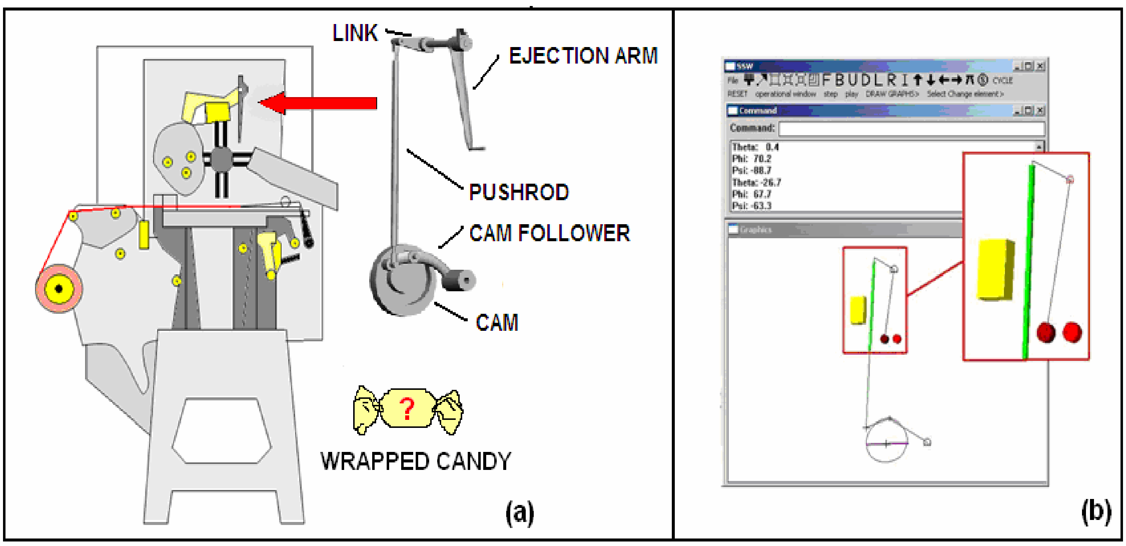

Figure 6 Schematic of machine and constraint-based model

4.1 The redesign problem

The redesign problem being considered is: if the manufacturer wanted to wrap a rectangular candy bar with dimensions of 20mm height, 70mm long and 40mm wide, yet maintain the ability to wrap the original candy bar, would it be possible? The preliminary investigations of other sub-mechanisms of the machine show, process flexibility to manufacture product of dimensions 32mm in height and 83mm in length. A radial mechanism, indexes the location jaws into a set position. The position of the pivot points for the cam follower and 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 if fixed. For the purpose of this example we are not evaluating the cam profile to gain extra processing flexibility. This leaves the four links as the options to produce the configuration to process the new and old candy. The process described in section 2 is followed.

The parametric simulation model of the sub-mechanism is constructed in the constraint-based modelling environment and tested for functional requirements (Figure 6b). The next stage is to define the factors which stop the mechanism from functioning (failure mode constraints). The following failure modes constraints had been established for the ejection mechanism.

- Ejection arm movement is insufficient or incorrectly orientated to remove the confectionary from the jaws.
- There is a breakage in the mechanism
- The pushrod interacts with the frame of the machine
- The eject arm interacts with the pushrod of the mechanism
- The ejection arm rest position to far forward causing a clash with other mechanisms
- The ejection arm maximum position
- The ejection arm velocity too high

The respective detection methods for these failure mode constraints are applied, as described in section 2, and parametric variation is invoked and results analyse. From the results the visual representations can then be constructed and machine modification undertaken.

4.2 Extended product model

The previous section described the problem and the process performed, in investigating ability of the mechanism to process the variant product. This section describes how the information acquired through this process can be attached to the model and retained for future use. The figures below show the 3D model of the ejection mechanism within the NX3 environment, the user has highlighted the pushrod component.

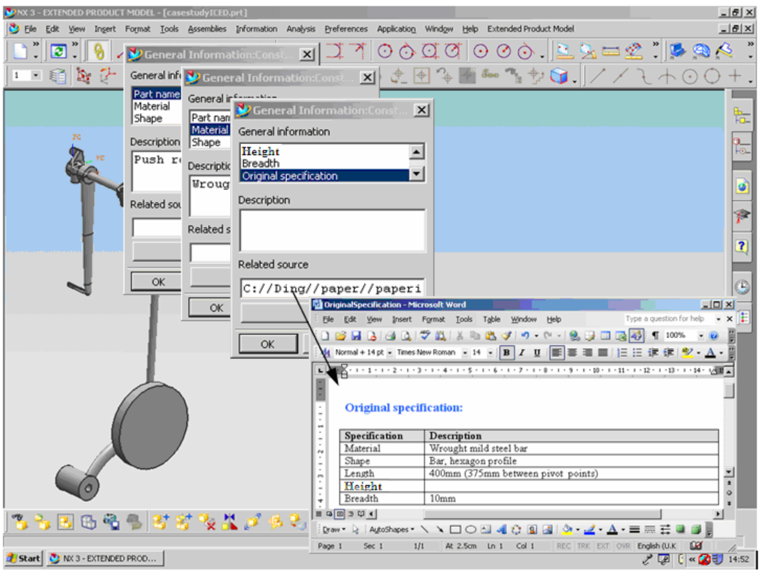

Figure 7 Product specification

In Figure 7, the system offers the user a general information window, from here the user can examine basic descriptions of product: name, material, shape, process by which it was manufactured and consumable parts fixed to this element i.e. wear plates and bearings. By selected these individual descriptions the model then offers the user more in depth information of the product, and links to other resources: text files, Jpegs and Mpegs. For example in Figure 7, according to the user requested, a text file showing the original configuration of the machine, before any of the modifications, has been opened automatically. The information that can be drawn from the example in Figure 7 is relevant to any redesign approach, but for a constraint-based approach, there are specific forms of product and redesign process information that are required. These relate to the forms of constraint and their respective variables. As noted in section 2, the constraints can represent relations between the design parameters which must be satisfied if the design is to be successful. Such constraints will represent the rudimentary relationships between the geometry of parts, and representations of performance and physical requirements of any design.

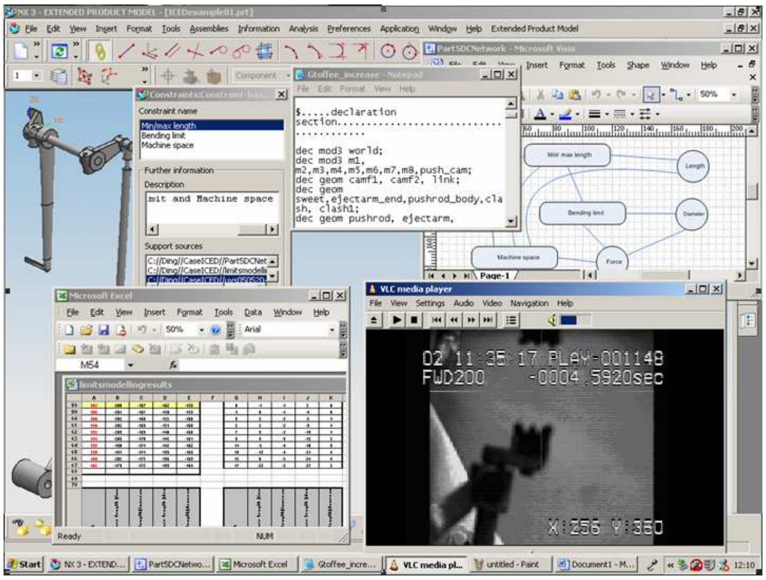

Figure 8 Constraint network

Figure 8 shows how the constraint information can also be retained within the extended product model. For continuity, as with Figure 7 the pushrod has been selected, this then offers the user the option to investigate related constraint information. It initially shows any related constraint and variables identified for the component. As with the general information windows, the user is given the option to open any files containing information related to the constraints. In figure 8, a text file showing the design constraint network for the component, the simulating model of the machine, an operation video and an Excel file recording the simulation results, have been opened or executed based on the requisitions directly through CAD model.

The model can also be linked to the constraint-based environment, so users can interrogate the constraint-based model operating. Prior research [16] has shown how general constraint can be implemented within a commercial CAD package (NX3). The extended product has taken advantage of this research, to give the user a simulation of the mechanism based on constraints. The process shown in figures 7 and 8 can be repeated for the other eight factors identified in section 3.2.2.

Possibly the most important factor for the designer is the retention of prior design solutions and the reasons why the design is no longer employed. Figure 9 shows the user interface fro this purpose. The interface re-presents any information that has been collated and recorded in previous designs and redesigns. The figure shows a redesign to the ejection arm. This has been performed by the manufacturer when a new ejection chute was required. The screen shot shows graphical, CAD representations of the design change and the present design solution, also presents a digital photo of the mechanism change. In addition to this supporting information that has been recorded by the design is presented, such as dates of change, actual modification, reason for design modification and reasoning why the design solution options was selected.

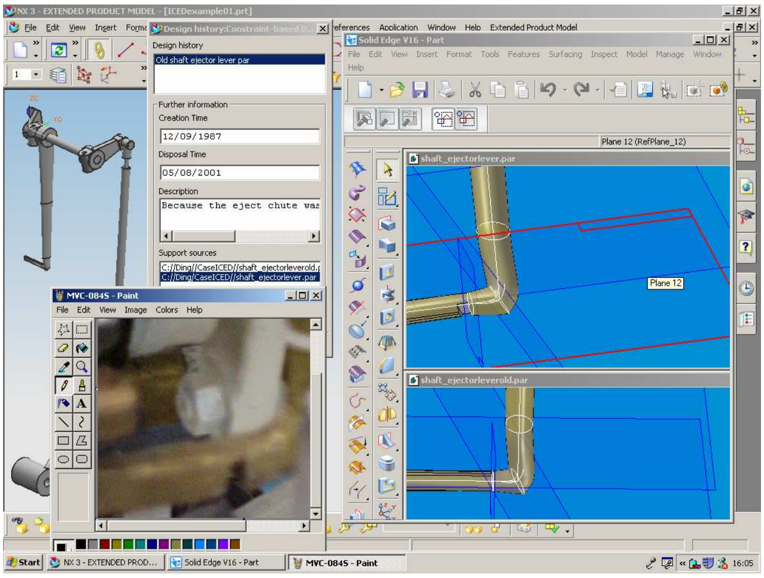

Figure 9 Design history

5 CONCLUSIONS

Existing product models provide good geometrical and topological information, but offer limited support information for the redesign process, specifically excluding factors such as performance capabilities, constraints, and the reasoning behind decisions. Although some text documents, e.g. design report, can provide some clues for experienced designers, the assistance is very limited, especially for a new designer.

The contribution of the research presented here is to encapsulate the information generated during the constraint-based redesign process within a new extended product model, so that it can be revisited and retrieved throughout the whole product life.

- The research extends the current CAD model beyond physical entities, including geometrical and topology information, performance limits, alternative concepts and solutions, and changed parts. As most of the concepts, solutions and change parts are linked/ referenced to the extended product model, the file size is kept to a reasonable size.
- It links the model elements with constraints, design activities, decisions-made and design rationale in redesign process, no matter what type of the document is used.
- It adopts hierarchical structure (e.g. from assembly to tolerances) so as to provide different levels of detail according to different specialist expertise and stages in the product lifecycle.

The initial implementation of this extended product model for constraint-based redesign has been employed in the investigations into the capability of food processing equipment to handle processed product variation. The case study has shown that the proposed product model is able to record the information generated in a constraint-based design, and provide a whole image of a redesign process so that it has the capability to:

- assist the designers to assimilate and digest constraint-based design;
- allow designers to revisit the design information directly via the CAD model;
- offer information management benefits for the machine redesign in the industry;
- support the whole machine lifecycle.

Future work will concentrate on the expanding the applications of the extended product model to other engineering design problems.

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