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DESIGN FOR RECONFIGURABLILITY: ACHIEVING FLEXIBILITY IN "LIGHT" MACHINES

Glen Mullineux[1], Tony Medland[1] and Jason Matthews[1]
(1) University of Bath, UK

ABSTRACT
Design for Reconfigurability is emerging as another important methodology of the "design for X". The important ideas behind the approach are discussed and their application is considered to the design of reconfigurable packaging machines for handling carton erection. It is found that typical motions required of such machines can be identified and generic mechanism modules to create these can be designed. It is shown that these modules can be combined to handle a range of different carton sizes and styles.

Keywords: Design for reconfigurability ,machine design, packaging machines, flexibility, cartons

1 INTRODUCTION
With the current manufacturing processes of individualizing products for each customer, there are requirements for companies to become more flexible in their practices and in the equipment they employ. Shi et al. [1] have defined that flexibility as the ability to hedge against the uncertainty that is an inevitable consequences of complexities generated by technological advancement. Williams [2] suggested that flexibility can be divided into two main streams, short term flexibility and long term flexibility usually referred as reconfigurability. Short term flexibility refers to the ability of a manufacturing system to process a number of different parts from a pre-defined group of parts. Manufacturing equipment is designed with an innate capability to handle such products this is initially achieved by simply providing tolerances to allow, for example, changes that occur in pack sizes to be accommodated, through user adjustments or complete sets of change parts. By the appropriate use of these approaches most normal variations in product setting can be handled. This has been colloquially known as Design with Adjustment (DWA) - where one does not know completely what one is doing (as one may not have modelled the product/assembly well), but hope to get the manufactured design to work, by including a lots of adjustments. Such designs produce lots of obsolesce in the design and substantially increase the costs. Another approach to offer the flexibility to manufacture a variety of products is that of reconfigurability, this presents the user with the required functionality and capacity that is needed, when it is needed [3,4]. Such an approach allows the addition and/or removal of sub-assembles that provide processing capability. This provides customized flexibility for a particular product family (open ended), so that it can be improved, upgraded, and reconfigured rather than replaced.

With the above in mind there is thus a requirement for a strategy/ framework to provide the ability to Design for Reconfigurability (DFR).The remainder of this paper discusses one such approach and its application to machine design. Section 2 presents the concepts of reconfigurability. Section 3 presents the domain where such an approach is specifically relevant. This involves the creation of a reconfigurable system for erecting carton for the packaging industry. This is a novel use in that much previous work on DFR has been in connection with machine tools and other "heavy" machines. By contrast, packaging machines and the reconfigurable system that has been created is much "lighter". This is because of the use of generic mechanism types to handle standard types of operation. The area is described in Section 3. Section 4 shows the approach in operation, discusses the generic modules, and shows how these can be combined. Finally some conclusions are drawn in section 5.

2 DESIGN FOR RECONFIGURABILITY

Traditional design methods are generic across disciplines, the basic principles and concepts apply across all branches of engineering. Although the underlying principles of design remain the same the approaches to design process, change. Design methods fall into two categories: prescriptive and descriptive [5]. Descriptive design describes current practice whereas prescriptive design describes how design should be done. An example of this being *the general design theory* developed by Yoshikawa [6]. This utilizes set theory to model the design knowledge and design process. The emphasis of this approach is based on the structuring of the design knowledge offering a greater understanding of the design process. Whereas prescriptive approaches are intended to encourage the designer to adopt improved ways of working, such as Pahl and Beitz [7] with their *systematic approach* to design and *the axiomatic approach of design* by Suh [8] which identifies general principles which govern good design solutions. These principles are formalized in terms axioms and theorems in an attempt to add design rules to the process: minimize information content and maintain functional independence while predicting some properties of designed objects These traditional design methodologies are *top-down*. They form the specification, then identify the functions and sub-functions, and split the design up into its component parts or sub-parts, sub-subparts, etc. (cf. figure 1).

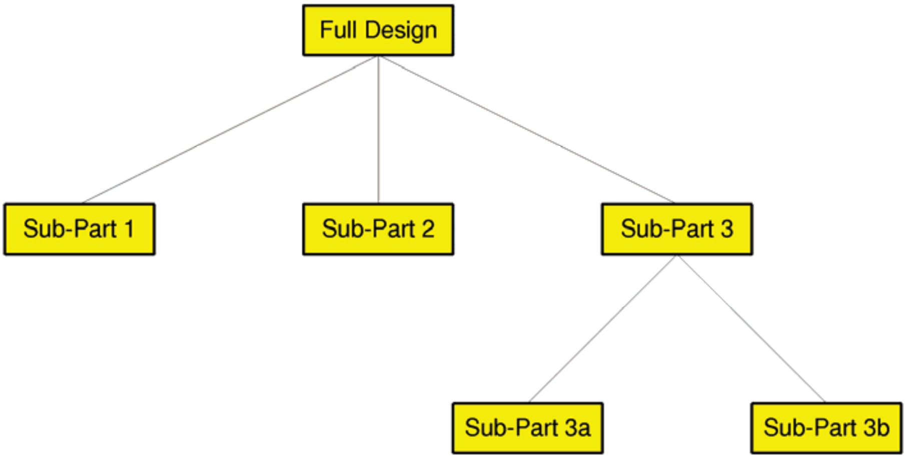

Figure 1. Top-down approach to design

2.1 Design for "X"

Design for X (DFX) is an umbrella term for many design philosophies and methodologies, which try to raise the designer's awareness of a certain product life-cycle value or characteristic represented by "X" [9] The need for such philosophies was identified as engineers became increasingly aware of a lack of appropriate detailed knowledge in important product life-cycle areas. Design for X methodologies can be seen as tools to analyze design proposals or existing designs for their suitability for certain life-cycle aspects. Manufacturability and assembly were among the first life-cycle values to have been considered since they were highly apparent cost reduction drivers [10]. In particular these tools bring designers and manufacturing experts together and address, typically because of education system shortcomings, lack of manufacturing expertise among designers [10]. The benefit of DFX tools, which also require the involvement of functional experts, is improved performance of products and related processes. DFX methodologies do not necessarily reduce the extent of design decisions, but they help to make them earlier. Substantial cost and development time savings can potentially be made as changes are easier to make the earlier they are provoked. But these approaches suggest that you know what you are doing and/or that you have a predefined market. The majority of the work in the reconfigurable design area has been focused on machine tools, in process inspection and assembly, the works of Mehrabi et al [3], Koren et al.[11], Katz and Koren [12], and Katz [13] by being examples. These works have presented six key characteristics which a reconfigurable design (normally) requires.

- *Modularity:* the compartmentalization of operational functions and requirements into units that can be manipulated between alternate machine configurations.
- *Integratability:* the ability to integrate modules rapidly and precisely by a set of mechanical, informational, and control interfaces that enable integration.
- *Customization:* the ability to adapt the customized (non-general) flexibility of production machines to meet new requirements within a family of similar products.
- *Scalability:* the ability to easily change production capacity by changing the production capacity of reconfigurable components in the machine.
- *Convertibility:* the ability to easily transform the functionality of existing machines, and controls to suit new production requirements.
- *Diagnosibility:* the ability to automatically read the current state of a machine and controls so as to detect and diagnose the root-cause of output product defects.

2.2 The Design for Reconfigurability approach

The DFR approach follows three distinct stages (cf. figure 2).

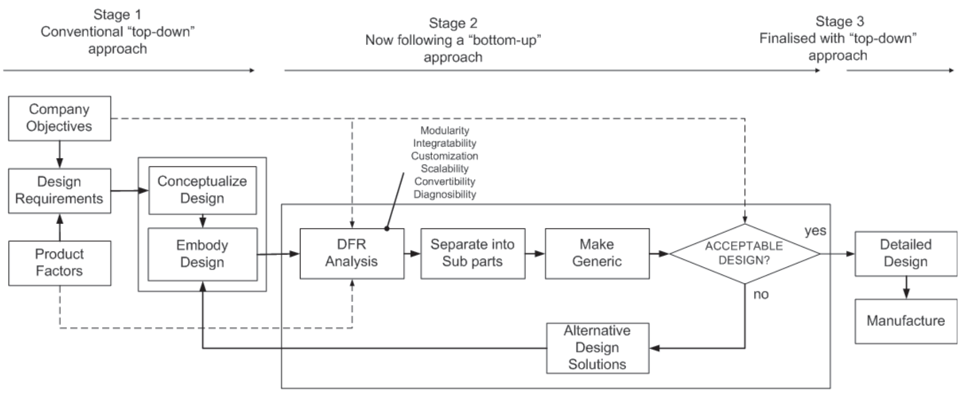

Figure 2. DFR methodology

- Stage 1: the approach follows the conventional *top-down* approach, until an embodied design has been achieved (as shown in figure 2). At this stage the six key characteristics noted earlier must be considered, but the prime objective is to deliver a system that can manufacture the product. Product factors (constraints) [14] need to be considered, as well as the requirements from the customer (end user of machine), key characteristic which the customer is likely to want considered are diagnostic and integratability).
- Stage 2: the approach then *abstracts* or *generalizes* the sub-parts (and sub-subparts). To be (slightly) more generic: this creates generic sub-modules (for specific tasks or types of tasks within the overall design). Each is reconfigurable (as far as possible) and they can be put together in different ways to achieve different resultants designs. The process is now working *bottom-up*, as suggested in figure 3 where the sub-parts can be used to create a larger variation in versions of the full design.
- Stage 3: once more the conventional *top-down* design approach is followed to finalize the design and its documentation.

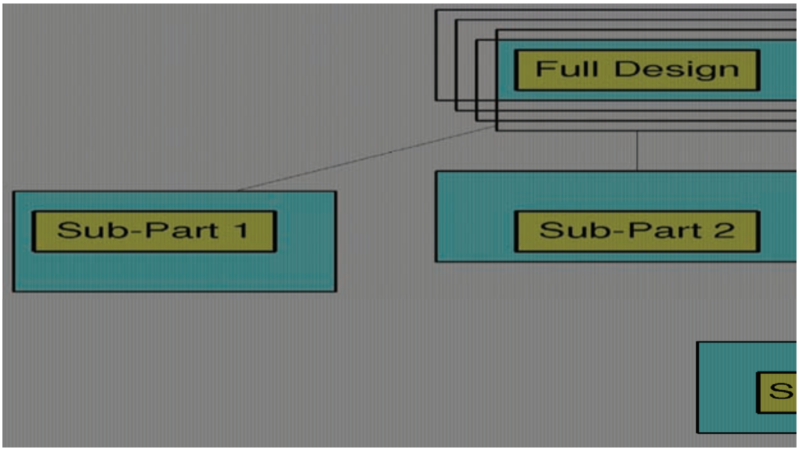

Figure 3. Bottom-up combination of generic parts

3 PACKER AND PACKAGING COMPANIES

Within the packaging industry they are two sets of companies: packaging machine suppliers (design and manufacture) and packers, end users who employ the machines to pack product. Currently, packaging machine supplier produce dedicated machines for specific cartons styles (possibly variable within tight bounds). If the packer companies have dedicated machines that will not pack the specials, then they do things manually. Whereas the packer companies (e.g. confectionary, cosmetics, pharmaceuticals) can be subject to pressures from supermarkets, marketing departments etc to produce special “gifting” packs for special occasions (Christmas, Easter, Valentine’s day), produce packs for short runs (e.g. hotels, airlines). Therefore there is an opportunity for packaging machine supplies to produce more flexible machines which could handle the specials. Due to the tight margins in the packaging industry, the packer companies are not going to purchase a machine with an endless innate flexibility, so reconfigurable machines present the best possible solution.

A visit to any shopping mall shows that cartons are presented in a wide variety of packaging materials and styles as figure 4 suggests. For the purpose of this paper the main interest is in packaging with carton board. Such cartons are normally supplied to a packer as flat nets. They need to be “erected” into their final shape. This can be done manually or, preferably, by mechanical means [15,16]. The blank as supplied has already been cut and its creases have been formed. The erection process mainly requires the formation of folds around these creases. The core function of the packaging is to protect the product in transit and while on display in the shops. The design of the packaging is also used to promote the product while on display. This along with environmental pressures to reduce the amount of packaging often leads to redesigns of the shape and size of the packaging.

Figure 4. Typical cartons

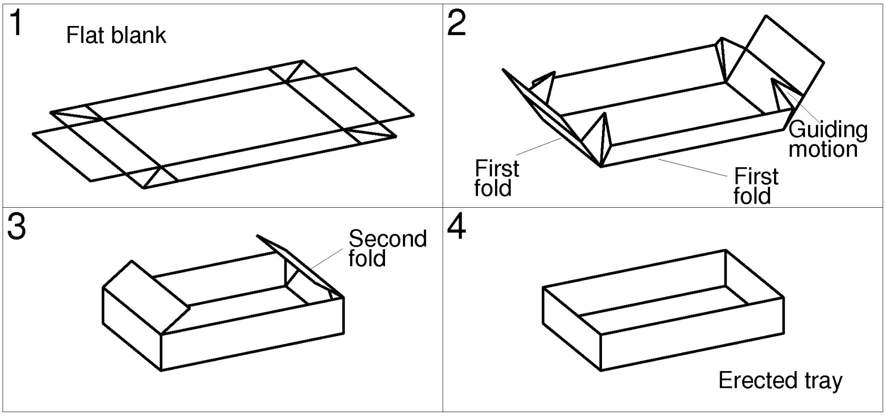

Figure 5. Stages in erection of a tray carton

4 DFR FOR PACKAGING MACHINERY

This section discusses the DFR approach applied to a machine design arising in the packaging industry. It represents the results of a research project undertaken to investigate reconfigurability of packaging equipment. A machine is required to "erect" cartons. This means that the carton is supplied as a flat net which is cut to the appropriate shape and has the creases defined and scored. What is needed is to fold the net along the creases so that the complete carton is obtained. It is normally necessary to fill the carton with product at some stage during the erection process. There are several ways in which the carton can be retained in its erected state and these include: tucking of flaps, gluing, and use of tape. Figure 5 shows a typical carton. This is a tray in which two of its sides are double walls; the formation of these serves to lock the carton in its erected form without the need for gluing. A second carton type is shown in figure 6. This is a "skillet" carton meaning that its basic shape is rectangular and this is provided to the packaging company with the long edges glued together and the carton then flattened. The erection process is firstly to open the skillet back out to a rectangle, and then to close the panels which form the base, and (after filling) the panel which form the sloping top, called the gable-end.

Taking the above as the basis of the design requirements, the top-down approach requires the typical packaging operations to be determined. An analysis of a range of typical cartons shows that the main operations are as follows.

- transport of blank to erection station
- holding the blank in place
- performing initial folding operations
- filling with product
- performing final folding operations
- releasing the hold
- transport to next operation

Passing to the next level, the typical folding operations are examined and the typical ones are found to be as follows.

- folding panels adjacent to the panel that is held fixed
- folding panels not adjacent to the fixed panel
- guiding operations (to ensure that related panels move correctly)
- tucking operations (to guide tabs into slots)

Figures 5 and 6 shows some folding and guiding operations that are required for the tray carton and figure 7 shows the relations between the various operations.

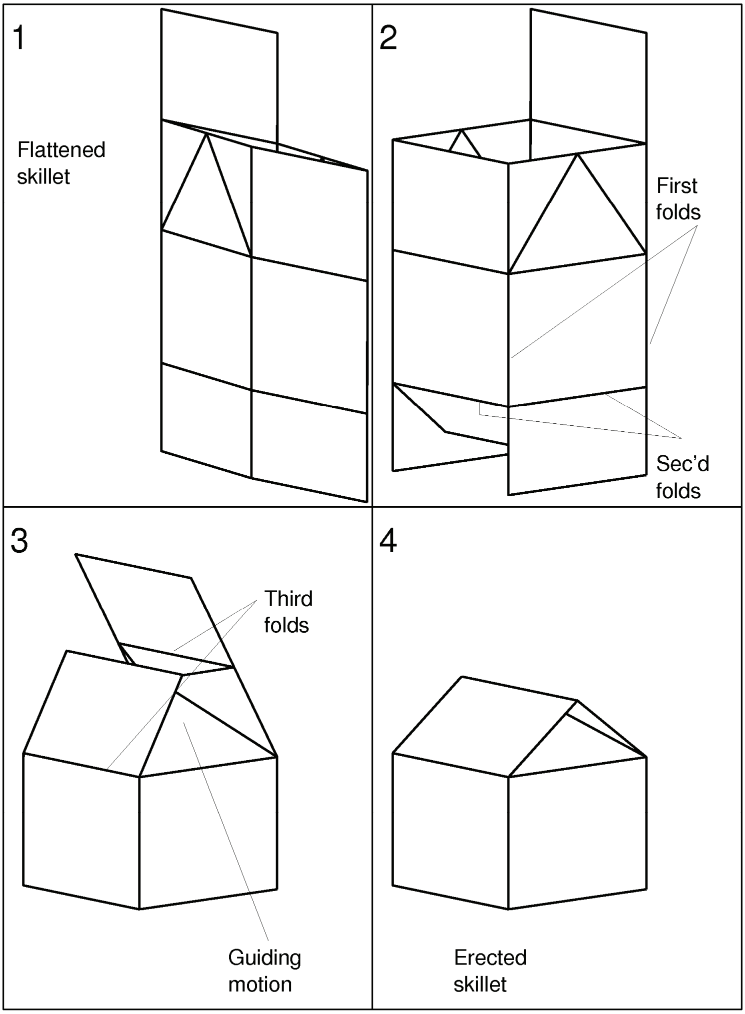

Figure 6. Stages in erection of a skillet carton

4.1 Folding units

Reconfigurable ways to deal with the folding and guiding operations are now considered. For the typical folding operation, a basic folder unit was designed and implemented. This is shown in parts 1 and 2 of figure 8. The operation is performed by the folding plate which rests against the panel to be rotated (about its pre-defined crease). The panel is rotated by the mechanism shown. The parallelogram arrangement of links allows the pale to rotate about a "virtual" axis so that inference between the carton and a physical hinge is avoided. The mechanism is driven using a small servo-motor whose motion can be driven by an external controller and arranged to work in collaboration with other operations.

The basic folder has some adjustability in its design in that the position of the plate in relation to the virtual hinge can be changed. Additionally the plate itself can be replaced by another as might be the case if a significantly larger carton needed to be erected. It is of course possible to use more than one of the folder unit placed along a long crease. The main aspect of reconfigurability for the folder unit comes in the ability to mount one folder on top of another. This is shown on the right in figure 8. The two folding plates now come together. This combination can be use, for example, to handle the double walls in the tray example of figure 5.

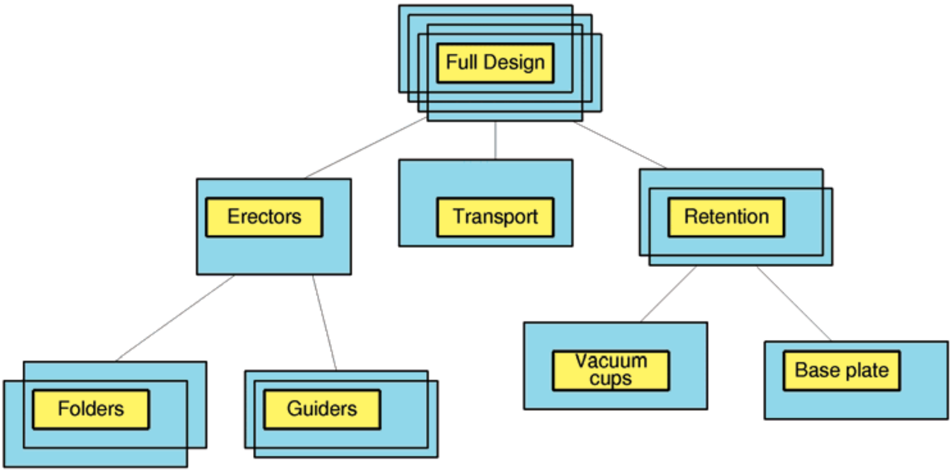

Figure 7. Various level of operation for carton erection

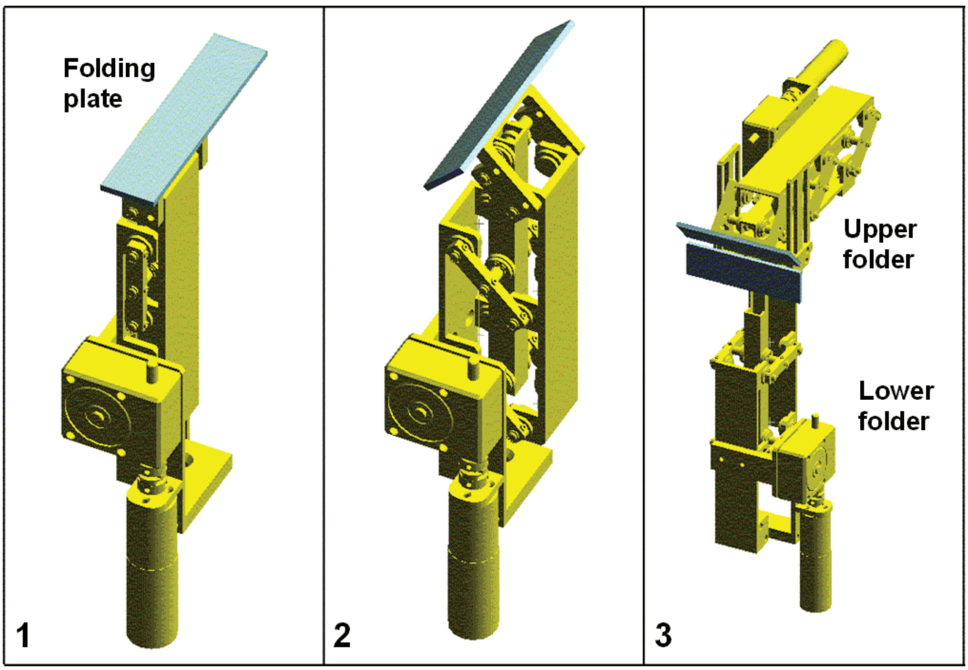

Figure 8. Folder and double-folder unit

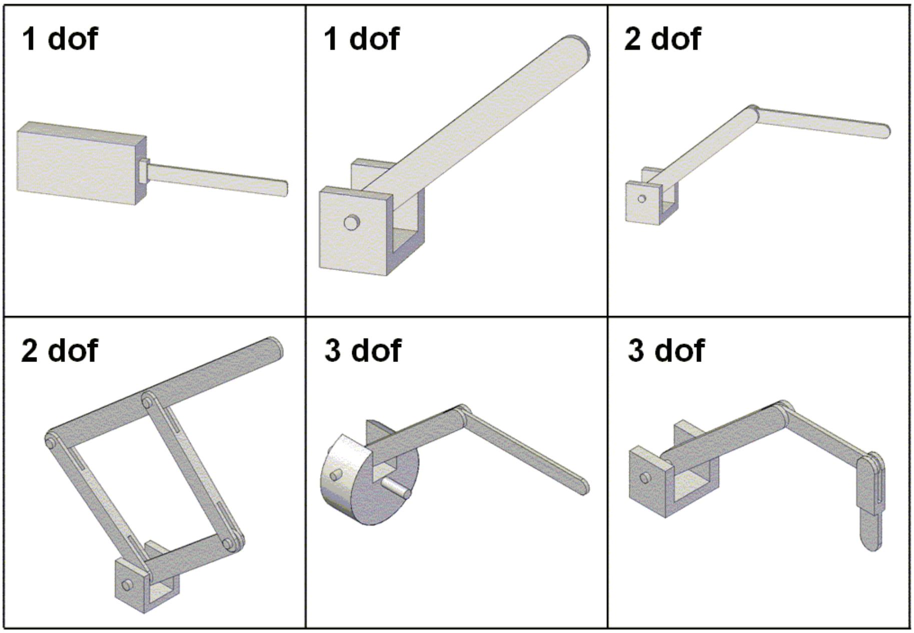

Figure 9. Styles of guider mechanisms with different numbers of degrees of freedoms

4.2 Guiding units

The requirements for a guiding motion are somewhat more intricate and several mechanism types can act as modules. In the simplest case, the guidance can be achieved by a motion with one degree of freedom (dof). The first two mechanisms given in stylised form in figure 9 are possibilities: one provides linear motion, the other angular. Often, the guidance arm needs to lie within the carton as it is erected. This means that it needs to be able to move to avoid interfering with panels moving around it. Additionally, there may be a need to avoid the guidance point moving its point of contact and so avoid damage to the surface of the carton. In these case a larger number of degrees of freedom are required (together with the appropriate control). Examples of such mechanisms are also shown in figure 9 (cf. also [17,18]). As with the basic folder mechanism, there is a not a great deal of reconfigurability within the individual guidance mechanisms. The reconfigurable arises in the possibility for choosing guiders to suit the particular application.

4.3 Examples of carton erection

With this range of folders and guiders, it is possible to create a system which can be reconfigured to deal with a number of different sizes and styles of carton. In the physical system created to demonstrate and test these ideas, each new carton blank is moved into place by a pick-and-place unit and is then held fixed by suction cups supported above a base frame. The folders and guiders are mounted on this frame, their positions and orientation being adjustable. The control unit then operates the mechanisms to erect the carton, and this is then removed by the same pick-and-place unit. Figure 10 shows three examples of erection of different carton style. In part 1, four folders and four guiders are used to erect a tray carton. In part 2, six of each of these units are used with a hexagonal tray. In part 3, two folders are shown erecting a skillet carton. Two guiders could also be used in addition here to ensure that the inner parts of the gable end fold in the correct direction.

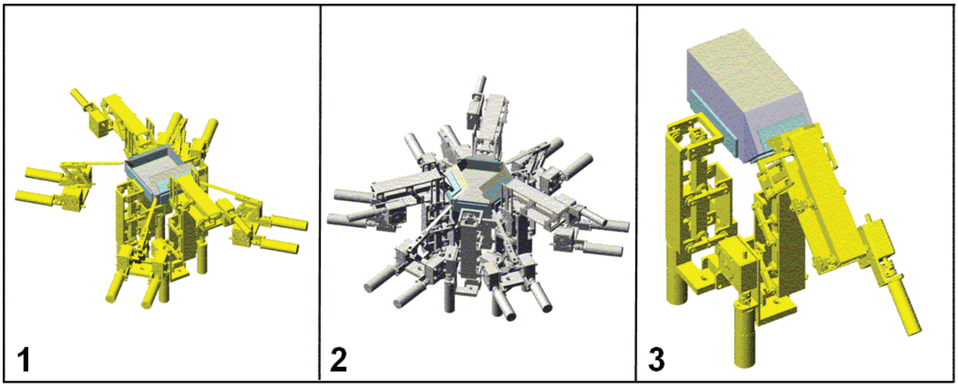

Figure 10. Reconfiguration for erection of different styles of carton

5 DISCUSSION

Section 2 identifies six key characteristics of a reconfigurable design. This section discusses the degree to which the reconfigurable machine satisfies these. Firstly the approach is certainly modular. The folder and guider units provide the basis of the modularity. They are designed to perform specific operations and they are combined in the previous examples with a vacuum system to hold the carton net fixed. The system is also integratable to a large extent in that the modules can be combined in different ways and motor controllers enable that integration. As described the modules are repositioned on a base and, in the tests undertaken, this was carried out manually, so the idea of performing the integration "rapidly" is not present. However such manual intervention is provided between runs and not during operation.

Customization is achieved since the aim has been to be able to reconfigure the system to deal with the erection of different styles and sizes of cartons. The issue of scalability has not been addressed. As previously discussed, this concept principally involves the idea of changing the production capacity. This is not included explicitly in the design of the modules, except that of course one could always try to achieve greater throughput by increasing the speed of the various motors. This may however lead to problems with the carton-board behaving in non-expected ways. It has however been found in testing the physical system, that the speed of erection is comparable with that of standard dedicated machines.

It is not clear how relevant convertibility is in the specific application. The basic functionality required is the ability to erect cartons and so this does not change. However, new production requirements can certainly be met when the change is a change in the carton form. The individual elements of the machine are visible and so its positional state can immediately be assessed at any time. The status of the motors can be obtained via the controllers. This provides the element of diagnosibility.

Thus the reconfigurable machine meets the six key characteristics. Some previous researchers have suggested that reconfigurability also needs to be present in the individual modules themselves. What has emerged here is that while some flexibility (via adjustment) is possible within the individual folder and guider modules, it is in the ability to combine these in different ways that provides the key to the reconfigurability of the overall system.

6 CONCLUSIONS

It has been seen that design for reconfigurability (DFR) is emerging as another important aspect of the "design for X" methodologies. A number of aspects for DFR have been identified as useful aids to designers. It has been proposed that one approach is to consider the design in the conventional top-down mode. Once the individual sub-parts have been identified, it is possible to consider more generic forms of each. These can then be combined to form new variants of the original design, and here one is working in a bottom-up fashion.

These ideas have been explored in relation to packaging machines for carton erection. This has been the subject of a recent research project in which a reconfigurable packaging system was designed and tested. In the initial part of the design process, the basic operations which need to be undertaken are identified. Generic modules for undertaking the basic driving and guiding motions have been created. It has been seen how it is possible to combine these in different ways to successfully erect a number of different carton styles and sizes.

There is some flexibility (via adjustment) for each of the individual folder and guider modules. However, it is in the ability to form different combinations of these provides the reconfigurability of the overall system.

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REFERENCES

[1] Shi, D. and Daniels, R.L. A survey of manufacturing flexibility: implications for e-business flexibility. *IBM Systems Journal*, 2003, 42(3) 414-429.
[2] Williams, D.J. *Manufacturing Systems*, second edition, Kluwer Academic Publishers, Dordrecht, 1994.
[3] Mehrabi M.G., Ulsoy A.G. and Koren Y. Reconfigurable manufacturing systems: key to future manufacturing. *Journal of Intelligent Manufacturing*, 2000, 11(4):403-419.
[4] Bicheno, J. The New Lean Toolbox - Towards Fast, Flexible Flow, PICSIE Books, Buckingham, 2003.
[5] Cross, N. *Engineering Design Methods: Strategies for Product Design*, second edition, Wiley, Chichester, 1989.
[6] Yoshikawa, H. General design theory and a CAD system. In *Man-Machine Communication in CAD/CAM*, Sata, T. and Warman, E. (eds.), North-Holland, Amsterdam, 1981, 35-58.
[7] Pahl, G. and Beitz, W. *Engineering Design A Systematic Approach*, second edition, Wallace, K. (ed.), Springer-Verlag, 1996.
[8] Suh, N. P. *The Principles of Design*, Oxford University Press, 1990.
[9] Haung, G.K. *Design for X: Concurrent Engineering Imperatives*, Springer, London, 1996.
[10] Benhabib, B. *Manufacturing: Design, Production, Automation, and Integration*, Marcel Dekker, New York, 2003.
[11] Koren Y., Jovane F., Heizel U., Pritschow G., Ulsoy G. and VanBrussel H. (1999) Reconfigurable Manufacturing Systems. *Annals of the CIRP*, 1999, 48(2), 6-12.
[12] Katz, R and Koren, Y. Reconfigurable machines. In *Proceedings of ASME Conference on Engineering Systems Design and Analysis (ESDA08)*, Haifa, July 2008. 9 pages on conference CD.
[13] Katz, R. Design principles of reconfigurable machines. *International journal of Advanced Manufacturing*, 2007, 34(5-6), 430-439.
[14] Daniel J., Medland A.J. and Mullineux G. Use of parametric modelling to understand the functional requirements for a reconfigurable packaging system. In *International Conference on Engineering Design, ICED07*, Paris, 2007, 9 pages on conference CD.
[15] Hine, D. *Cartons and Cartoning*, Pira International, Leatherhead, 1999.
[16] Dai, J.S., Medland, A.J. and Mullineux, G. Carton erection using reconfigurable folder mechanisms. *Packaging Technology and Science*, to appear.

[17] Birglen, L. and Gosselin, C.M. Geometric design of three-phalanx underactuated fingers. *Journal of Mechanical Design*, 2006, 128, 356-364.
[18] Yao W. and Dai J.S. Dexterous manipulation of origami cartons with robotic fingers based on interactive configuration space. *Journal of Mechanical Design*, 2008, 130, 022303:1-8.

Contact: G. Mullineux
Innovative Design and Manufacturing Research Centre
Department of Mechanical Engineering
University of Bath
Bath, BA2 7AY
United Kingdom
Email: g.mullineux@bath.ac.uk

Glen Mullineux is a professor within the Department of Mechanical Engineering at the University of Bath. He is leader for the theme on Constraint-based Design and Optimisation in the Innovative Design and Manufacturing Research Centre. His interests lie in methods for constraint-based design, machine and mechanism design, geometric modelling and geometric algebra.

Tony Medland is professor of design engineering at the University of Bath. His interests are in design and problem solving and how these apply to the overall design process from initial concept through to manufacture, inspection, and beyond. Recent work involves the use of constraint-based techniques for human modelling with application to human-machine interaction and aids for the disabled.

Jason Matthews is a research officer in the Department of Mechanical Engineering at the University of Bath. He has considerable experience in the area of machine design and optimisation. He has been involved in numerous research project related to constraint-based machine design and the interaction of machines with product and packaging materials.