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The Integrated Use of Enterprise and System Dynamics Modelling Techniques in Manufacturing Enterprises

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Abstract

Enterprise modelling (EM) techniques support manufacturing process (re) engineering by capturing 'as-is' processes and based on perceived outputs, support the design of 'to-be' process models capable of meeting manufacturing systems requirements. On the other hand, system dynamics (SD) modelling tools are used extensively for policy analysis and modelling aspects of dynamics which impact on businesses. In this paper, the use of EM and SD modelling techniques has been integrated to facilitate qualitative and quantitative reasoning about the structures and behaviours of processes and resource systems used by a Manufacturing Enterprise (ME) during the production of composite bearings

Keywords: Manufacturing Enterprises (MEs); Enterprise Modelling (EM); System Dynamic modelling (SD)

1. Introduction

A body of literature related to current trends in MEs has explained the enormous complexities and dynamics associated with the design and realisation of manufacturing processes [1-7]. Although MEs are inherently complex, traditional methods for solving problems in MEs have not fully accommodated complexities and causal relationships associated with processes in MEs [8, 9]. Research in the modelling and management of complexities in dynamic systems has resulted in the derivation and application of a number of system dynamics modelling tools and techniques. Notable among these are: Fuzzy Logics (FLs) [10-14], Neural Networks (NNs), Bayesian Networks (BNs), Petri Nets (PNs), Causal Loops (CLs) and Stock and Flow models [1].

Previous research by the first author has reviewed a number of EM and SD tools and has noted that the CL modelling technique is suitable for representing, qualitatively, the cause and effects evident in dynamic systems [6]. Other researchers have mentioned that CLs are useful for creating dynamic models of businesses for alternative policy verification.

Despite the advantages associated with the use of the CL technique, the authors have noted that CL models generate qualitative results and the cause and effects often inherent in manufacturing systems cannot be simulated using CLs alone. Thus on its own, CL cannot facilitate quantitative prediction of outcomes. Because of this limitation, the authors are of the view that for full benefits of CL modelling in support of manufacturing process analysis:

- There is the need to provide a structure around the modelling technique. This implies providing a means of specifying actual factors which influence situations in their context of application.
- The useful models derived from the use of CLs should be transformed into equivalent dynamic simulation models so that alternative process scenarios and 'what-if' experiments can be conducted.
- There is the need to develop a methodology which addresses the requirements specified in 1) and 2).

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To help overcome the limitations observed in the use of CLs, the authors have developed and tested an integrated EM-SD methodology comprising the systematic use of CIMOSA, CLs and a continuous simulation modelling tool called iThink. The application of the proposed methodology was tested in a rapidly growing bearing manufacturing company called ACAM Ltd to better understand:

- The effect of variations in customer demand on actual value generation by ACAM manufacturing processes
- The effect of constant sale orders on material supply
- The effect of company operations on payments or revenue generation.re introduce the paper, and put a nomenclature if necessary, in a box with the same font size as the rest of the paper. The paragraphs continue from here and are only separated by headings, subheadings, images and formulae. The section headings are arranged by numbers, bold and 10 pt. Here follows further instructions for authors.

2. The integrated EM-SD modelling methodology

To help address the limitations associated with the CL modelling methodology as described in section 1, an EM tool which helps to capture processes and their associated resources and flows is introduced. Although many EM modelling tools exist, previous publications by the authors and their colleagues in enterprise modelling show that the CIMOSA modelling constructs and representational formalisms are capable of decomposing complex systems into sub systems that can be analysed independently [5]. Further work by the authors and their colleagues has shown how processes can be classified as Enterprise Domains (DMs) and decomposed into their respective Domain Processes (DPs), Business Processes (BPs) and Elementary Activities (EAs) [2, 4, 5]. In essence, DMs represent functional areas of the enterprise which are decoupled from each other with clearly identified objectives which enable them to be composed of well defined processes for achieving the objectives defined for the domain. Based on the observed goals and associated processes, stand alone processes, called Domain Processes (DPs) are grouped to reflect the distinctions in goals and deliverables. In a graphical form, the achieved goal of a collection of DMs is modelled using suitable templates and this is termed as 'context diagram'. At the next stage of the process decomposition, interactions between respective domains in terms of information and material flow are modelled. The outcomes of this modelling stage are captured using a so called 'Top level Interaction diagram'. The interaction diagram therefore shows relationships that exist between the domain processes. Textual descriptions can be expressed but for the sake of simplicity a graphical representation of the interactive processes and their resultant elements of interaction are normally developed. At the next stage of modelling, DPs belonging to CIMOSA conformant DMs are further decomposed into lower-level processes called Business Processes (BPs). Relationships between BPs are described in sub-interaction diagrams.

Based on the sub interaction diagrams, which represent aspects of flows among BPs, a top level causal structure can be created to clearly represent the direction of flows. The importance of the EMs is to provide a context for modelling and limit the tendency of modelling factors which are not directly related to the scope of analysis. The initially created EMs therefore helps to put a structure around CL models. Also key BPs and their associated relevant flows can be visualised and used as basis to identify important factors which impact on them.

At the next stage of modelling, based on the modelling objectives, questionnaires can be generated to derive the set of factors which are necessary for describing the problem initially identified. With these factors identified, sets of CL models can be created in context. Since the objective is to support decision making, it implies that initially created CL models have to be redefined and 'structured' to be able to provide useful contributions towards analytical decision making and quantification of CLs. Thinking about developing structured causal loop models (SCLMs), a set of rules are recommended to help reorganise the variables defined in the initial CLs. The starting point is to identify variables with measurable and operational meanings. Starting from this point enable other variables to be connected in such a way that estimation of 'operational variables' can be determined through the 'factual analyses' of the connecting variables. Whilst doing this, care is taken to ensure that the resultant SCLMs consist of variables which are causal, deterministic, time variant, directed and signed.

Although the resulting SCLMs are still qualitative, all parameters will have operational and measurable indicators so that at the next stage a 'stock and flow model' can be created by defining 'stocks, flows and converter' variables. A description of these modelling elements is shown in figure 1.

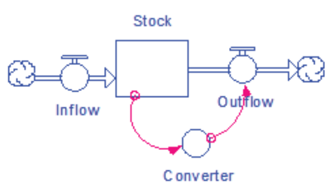

Fig. 1. Elements of stock and flow models

3. Case application of the EM-SD modelling methodology

3.1 Background of case company

ACAM Ltd is a small to medium sized bearing manufacturing company located in the United Kingdom. ACAM Ltd makes to order a range of advanced composites bearings. To help provide in-depth understanding about the processes involved in ACAM Ltd and also provide a context for the application of SD models, an Enterprise Model (EM) was created and used as the backbone for the creation of SD models. The EMs so created show how ACAM processes can be decomposed into elementary activities and used to support further business analysis.

3.2 Creation of the CIMOSA EM of ACAM Ltd

On resumption of the modelling exercise, a series of structured and unstructured interviews and shop floor visits were conducted to enable better understanding of ACAM Ltd processes. In addition to the data and information gathering exercises, company production data, human resource organization charts, sales and finance data were also examined. Based on these earlier understandings about process decomposition, a context diagram, as shown in figure 2, was created to represent all the DMs observed in the company. As can be seen from figure 2, six main domains were observed with three of them being considered to be Non-CIMOSA domains.

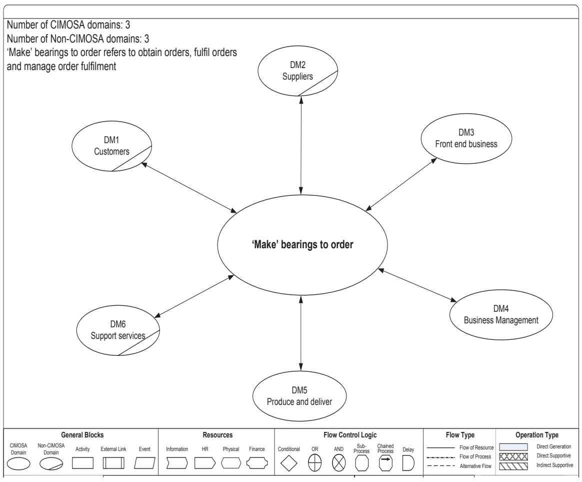

Fig. 2. Context diagram of ACAM Ltd

In correspondence with the main theme of the DMs, a high level interaction diagram was created to depict how respective domain processes interact (see figure 3).

At the next stage of the enterprise modelling exercise of ACAM Ltd, a decision was taken to further understand the process interactions that existed between the sub business processes of DP3 and DP4.

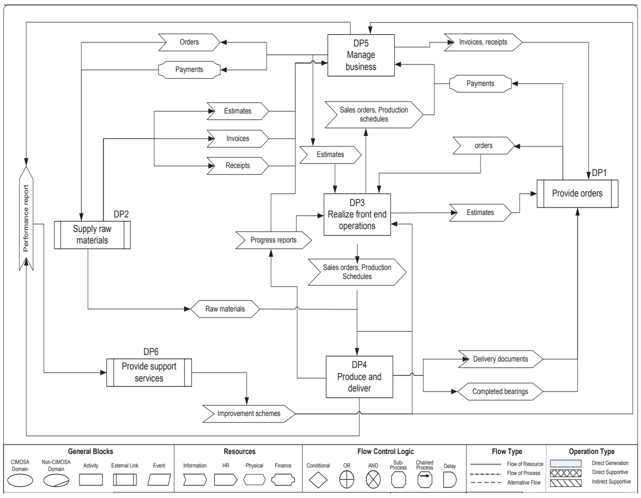

Fig.3.Top level interaction diagram

A sub interaction diagram showing how material and information flows between BP3.1, BP3.2 and BP3.3 is shown in figure 4. Instances of interaction of these BPs with external DPs such as DP1, DP2, DP4, DP5 and DP6 are also shown in the figure.

Many other interaction diagrams for the other DPs were created but not shown in this paper for the sake of convenience.

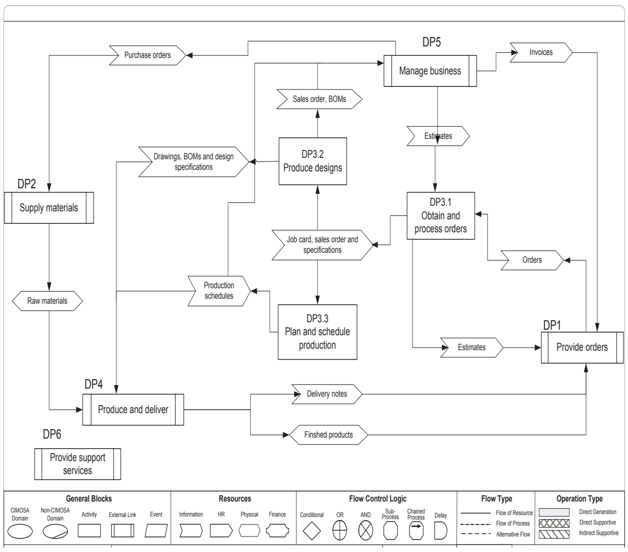

Fig. 4. Sub-interaction diagram for DP3

3.3 Creation of CL models of ACAM Ltd

A careful study of the top level interaction diagram (figure 3) reveals that there is no direct interaction between ‘provide orders’ (DP1) and ‘supply raw materials’ (DP2). Also there is a unidirectional interaction between ‘supply raw materials’ (DP2) and ‘produce and deliver bearings’ (DP4). Similarly, a unidirectional interaction exists between ‘produce and deliver bearings’ (DP4) and ‘provide orders’ (DP1). However bidirectional interactions exist between: ‘provide orders’ (DP1) and ‘realize front end operations’ (DP3); ‘provide orders’(DP1) and ‘manage business’ (DP5); ‘realize front end operations’ and ‘produce and deliver bearings’ (DP4); ‘produce and deliver bearings’ (DP4) and ‘manage business’ (DP5); ‘manage business’ (DP5) and ‘supply raw materials’ (DP2

An initial causal loop model describing how customer orders influence purchases and supply of raw materials is shown in figure 5. Customer demand is influenced by a number of factors but because these factors are external to the main business domains, investigations were not carried out to establish the actual variables influencing customer requests.

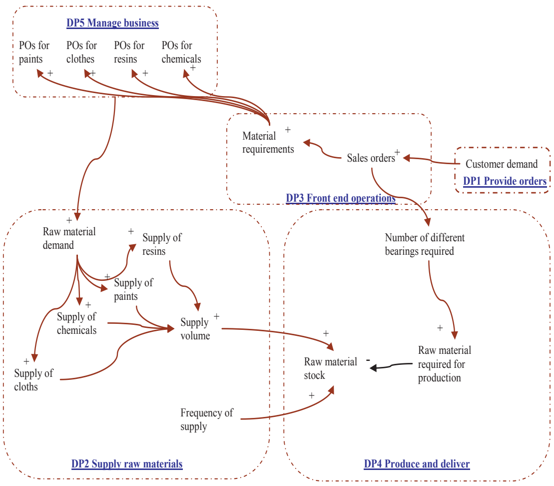

Fig.5. Initial CLM illustrating factors affecting raw material stock

A more detailed description of the causal influences of BP4.1 is shown in figure 6. A study of the sub-sub interaction diagram showing the process interactions of BP4.1 and BP4.2 shows that in the ‘produce and deliver’ domain process (DP4), raw materials are processed to meet the material requirements for producing flat products (BP4.1.2), strips (BP4.1.3) and round products (BP4.1.4). Therefore the total raw materials required will be equivalent to the sum of the total raw materials for flat, strips and round products, whose quantities are grossly influenced by the total number of bearings derived from the sales orders. As shown in figure 6, the total number of flat, strips and round products are dependent on the processing rates of the production shops in charge of producing these components. The processing rates of the three shops are themselves influenced by a number of factors such as: number of activities, resource requirements, resource capabilities and competence, material availability, machine availability, among others.

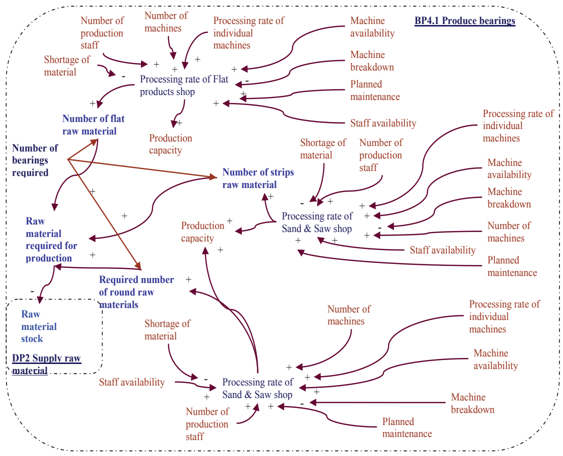

Fig.6. Initial CL model for bearings production (BP4.1)

3.3 Creation of structured causal loop models

The CL models shown in section 3.3 were helpful in describing qualitatively the causes of dynamics in selected key business processes of ACAM Ltd. With the view to achieving SCLMs of relevance to performance indicators such as cost and value, the initially created CLs (see figures 5 and 6) were revised based on the requirements described above. As shown in figure 9, to quantify customer needs, customer stock levels are taken into consideration. A negative polarity is indicated because as customer bearing stock level reduces, customer demand increases. Customer stock level is affected by a number of factors. Again, for the purpose of creating a structured causal loop model, the broad range of factors such as customer bearing failure rate, machine breakdowns, preventive maintenance schedules, customer stocking policies and other influencing factors are described simply as customer usage rate. In practice, ACAM Ltd operates directly with most of the engineering departments of their customers and is able to predict their maintenance cycles. Although ACAM Ltd is not in favour of stocking bearings, their historic patterns of sales are able to predict the bearing usage rate of their customers. In a more complex model, customers will have to be classified based on their usage rates, so that distinct analysis can be made for each customer. One critical thing derived from customer demand is the number of sales orders prepared by ACAM Ltd front end business (DP3) process. It was verified that about 92% of customer enquiries become sales orders; hence the number of sales orders generated within six months can be estimated. One other critical information from customer stock level is ‘payments received’ by ACAM Ltd. Although this link is not vivid, it is implied that since bearings are supplied before payments are made by customers, the quantity of bearings required to be paid by a customer is the difference between the ‘paid stock of bearings’ and the ‘unpaid received stock of bearings’. Most often there are some delays in payments. The actual value realised by ACAM Ltd is the total payments received from customers. But for budgeting purposes, ACAM Ltd estimates the total sales value from the number of different sales orders received. The estimated value of sales orders almost always exceeds the actual payments received from customers, so a ‘value deficit’ is created.

From the number of sales orders received, useful production and supply information can be deduced. This is reflective in the information presented on job cards and production schedules. On the production schedule the expected number of strips, round and flat products are indicated. The difference between the expected number of products and the actual manufactured products is the backlog ACAM Ltd needs to deal with. The actual production volume is affected by real production variables such as processing rates of the production shops, materials available, human resource, machine availabilities and bearing type. Based on the number of sales orders, the designers estimate the quantity of materials required. These quantities are compared with existing stock levels of materials to enable specific material orders to be raised. Historic data exist for number of material orders raised over the six months period. In some cases, the actual materials supplied did not match exactly with the quantity of materials ordered. Reasons provided by the Production Managers included the unavailability of materials in the suppliers’ domain, counting errors and wrong deliveries, among others.

The total material cost is estimated by the cost of the total materials supplied. There is also a difference in actual cost of materials and material cost paid by ACAM Ltd. This is due to the payment arrangements and delays between ACAM Ltd and some of their suppliers. In the ‘produce bearings’ domain, the factors specified in figure 7 were simplified and reorganized to provide a background for quantitative analysis of the production requirements in the shops. The key factors influencing the production rate of the shops was observed to be the number of activities required to fulfil specific orders. Taking into consideration the operation time of these activities, the number of bearings produced over time can be estimated. The operation time is a historic data which takes into account human resource and machine availabilities, breakdowns and all necessary adjustments in the shops.

The labour, machine, material and storage cost influence the total production cost. If these cost components are expressed in units related to number of products realised then production cost can be deduced from the production volume. In the ‘pack and despatch’ business process, it was also understood that packaging technology, availability of packaging materials were factors which affected the packaging rate.

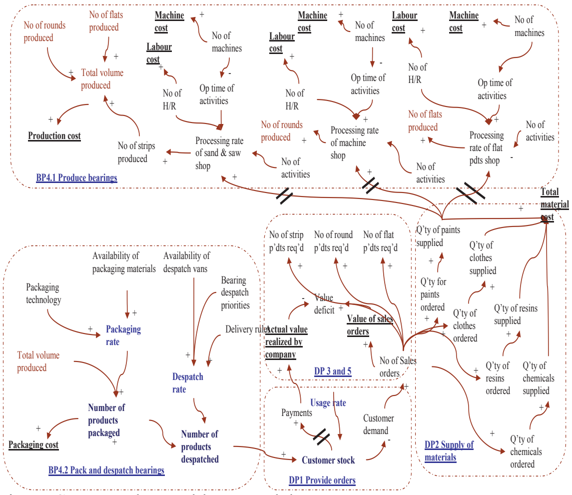

Fig. 7. Structured causal loop model

In the same way delivery rules, despatch priorities and availability of despatch vans affected the despatch rate. Packaging cost can be estimated by deriving the unit cost per product packaged from the resources and materials required for packaging. Finally, the increase in the number of products despatched increase the customer stock.

To gradually transform the qualitative model into a quantitative model, at the next stage of modelling, the variables specified by the SCLM were classified into stocks, flows and converters and modeled with the iThink simulation tool.

3.5 Simulation results and business analysis

After verifying and validating the results, several experiments were conducted to help understand the behaviour of the manufacturing system under varying conditions. An example results showing graphically the relationship between customer demand, value generated and material cost is shown in figure 8. A study of figure 8 shows that in ACAM Ltd, customer demand fell gradually from the beginning of the accounting year. The fall in demand had significant impact on actual value realised. Because of the random nature of payments received from customers, actual value realised is largely different from ‘expected value’ which is essentially dependent on number of sale orders for a given month. As shown on the graph, there is a gradual rise in value which means more payments are received at the beginning of the year with the peak of 'actual value realised' being in the fifth month. As customer demand reduces, there is a sharp fall of 'value realised' until it reaches its lowest level in the seventh month. Another set of results not published here showed the effect of constant 'sales orders' on 'volumes of strip, paints and chemicals supplied' as well as 'total storage cost'. Also realised are results related to total manufactured products, dispatched volumes, process cost, material storage cost and packaging cost.

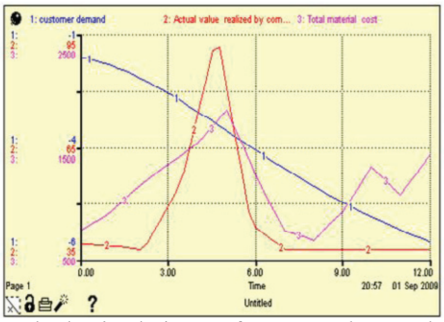

Fig. 8. Results showing the impact of customer orders on value realisation

4. Observations about the application of the modelling methodology in ACAM Ltd

The Managers of ACAM Ltd confirmed that the integrated modelling approach enabled understanding about their business; especially how resources and information flow from one unit to the other. This was helpful for them to understand the implication of activities in one department on the other. More critically, it was a good way of illustrating the factors which could be controlled and monitored to reduce cost and improve value. It was observed that the integrated method served as a strong modelling tool for capturing most of the salient factors in the company related to its 'architectural structures' and how these structures impact on (time based) 'organisational behaviours' . With a base model created for analysing the performance of ACAM Ltd, further experiments on process variables can be conducted to analyse optimal business performance in terms of process efficiencies, cost and values generated by the company, resource utilisation, among others. Essentially, the integrated models offer a means of:

- Replicating and understanding historic enterprise behaviour;
- Predicting future enterprise behaviours and impact on performance indicators and
- Experimenting alternative decisions before implementation, to save cost and minimise errors.

5. Conclusions

Dynamics impacting on business processes (BPs) have been modelled using an integrated EM and SD approach. Following the modelling approach, complex structure and dynamics impacting on aspects of the business, especially those influencing cost and value were captured.

Future research work will look at alternative means of simplifying the integration methodology so that non-expert system modellers can also populate data into enterprise models for in-depth business process analyses.

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References

[1] Sterman, J., *Business Dynamics: Systems thinking and modeling for a complex world*. 2000: McGraw Hill.
[2] Weston, R., *A model-driven, component-based approach to reconfiguring manufacturing software systems*. Int. J. of Operations and Production Management, Responsiveness in Manufacturing, 1999. 19(8): p. 834-855.
[3] Askin, R., *Modelling and analysis of manufacturing systems*. 1993: John Wiley & Sons.
[4] Bernus, P. and L. Nemes, *Enterprise integration-engineering tools for designing enterprises*. IFIP TC5 Working Conference on Models and Methodologies for Enterprise Integration. 1996, Australia: Chapman & Hall.
[5] Vernadat, F.B., *Enterprise modelling and integration; Principles and Applications*. First edition ed. 1996: Chapman & Hall, London.
[6] Agyapong-Kodua, K., *Multi-product cost and value stream modelling in support of business process analysis*, in *PhD Thesis, Wolfson School of Mechanical and Manufacturing Engineering*2009, Loughborough University: Loughborough. p. 437.
[7] Agyapong-Kodua, K. and R.H. Weston, *Systems approach to modelling cost and value dynamics in manufacturing enterprises.* International Journal of Production Research, 2010. First published on: 11 May 2010 (iFirst).
[8] Goldhar, J.D. and M. Jelinek, *Plan for economies of scope.* Harvard Business Review, November-December, 1983.
[9] Scholz-Reiter, B., M. Freitag, and A. Schmieder, *Modelling and control of production systems based on nonlinear dynamics theory.* Annals of CIRP, 2002. 51: p. 375-378.
[10] Wang, L., *Analysis and design of fuzzy systems.* USC-SIPI report, 1992. 206.
[11] Yester, J., J. Sun, and H. Wang, *Design and automatic tuning of fuzzy logic control for an active suspension system.* Proc. of the 12th IFAC World Conference, 1993.
[12] Batur, C., A. Srinivasan, and C. Chan, *Automated rule based model generation for uncertain complex dynamic systems.* Proc. of the 1991 int. symp. on intelligent control, 1991: p. 275-279.
[13] Srinoi, P., E. Shayan, and F. Ghotb, *A fuzzy logic modelling of dynamic scheduling in FMS.* International Journal of Production Research, 2006. 44(44): p. 2183-2203.
[14] Vinodh, S. and S.R. Balaji, *Fuzzy logic based leanness assessment and its decision support system.* International Journal of Production Research, 2010. First published on: 05 July 2010 (iFirst).