A review of research into engineering change management: implications for product design

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This paper provides a review of key publications by industrial and academic researchers relating to the management of engineering change. The review, together with an analysis of currently funded EPSRC contracts, shows that engineering change is predominantly seen as a problem rather than an opportunity. The author concludes that, whilst this viewpoint is understandable, it fails to take into account the driving force that engineering changes provide for incremental product improvement. Further research is required to ascertain the business processes that are required to enable a company to maximize improvements in product design. © *1997 Elsevier Science Ltd.*

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There is a saying that design is 10% inspiration and 90% perspiration. No doubt the ratio of percentages depends upon the type of product being designed, the stage of the design process reached, and the viewpoint of the person voicing the statement. However, most engineering designers would agree that it represents a basic truth if the entire process of designing a novel product is considered. When the design activity is concerned with the addition of improvements to an existing product, the balance of effort must swing even further towards perspiration, especially when consideration is given to the 'knock-on' implications for production and inventory control, and manufacturing.

For the purpose of this paper, an engineering change (EC) is a modification to a component of a product, after that product has entered production. The problems that design modifications frequently present to manufacturing managers, and the considerable cost implications, have given rise to the observation that the resulting EC demands are an evil, foisted on the

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manufacturing function by design engineers who probably made a mistake in the first place.

1 Scope of the review

The author initially reviewed papers covering the period 1980–1995. These papers were identified through a search of the BIDS (Bath Information and Data Services) database. The search covered the Compendex, OCLC (Online Computer Library Centre, Inc.) FirstSearch, and ISI (The Institute for Scientific Information) sources. Over 200 abstracts were reviewed as a result of this first stage search. Of these, 58 papers were read in full, from which 15 core papers were included in this review. A second stage search was carried out by identifying key citations from the core papers. This resulted in the inclusion of a further eight papers.

The review of currently funded United Kingdom research was based upon information supplied by the Engineering and Physical Sciences Research Council (EPSRC). Key elements in this were the July 1995 annual volume of research projects from Design and Integrated Production, and the list of 'grants awarded' by the Innovative Manufacturing Initiative (IMI).

2 Topics for EC research

For the sake of clarity, this paper identifies two main categories in the body of EC related research. These topics are: firstly, 'tools' (almost entirely computer based) for the analysis of EC problems, or the synthesis of solutions to EC problems; and secondly, 'methods' to reduce the impact of ECs on manufacturing and inventory control. The paper is principally concerned with the second topic, though the first topic is included for completeness.

2.1 EC tools

In general, the review finds that EC tools are specific to particular industries and products, whilst methods and management strategies can frequently be described within generic frameworks. The normally specific nature of EC tools research is exemplified by the work of Lin *et al.*[1]. On the basis that specifications are frequently updated during the process of VLSI design, Lin and his co-workers developed a computer-based tool which automatically modifies an existing design to meet new requirements with a minimum of changes. The algorithm is divided into two steps. The first step identifies candidate signals, such that replacing them with a new function can rectify the difference between the old network and the new specification. The next step synthesizes these target functions by utilizing gates of the existing synthesized network. The authors reported that their approach is effective in reducing the number of expensive changes when

1 **Lin C C, Chang S C, Chen K C, Marek-Sadowska M and Cheng, K T** 'Logic synthesis for engineering change' *Proceedings of the 32nd Design Automation Conference*, Francisco, CA, USA 12–16 June 1995 pp 647–652

it is applied to combinational circuits. The work by Auch and Joosep[2] on an algorithm to compare a new discrete electronic circuit design with an older issue and identify factors that may adversely affect system timing, is a further example of a design aid to minimize EC effects. Because electronic systems are frequently easier to describe in terms of logical networks than mechanical systems, and because the input/output characteristics of discrete electronic components are easier to provide in library form, most of the work on EC related design tools is concerned with electronic systems. However, examples of work on mechanical and hybrid systems do exist. Conley[3] describes the problems in the provisioning and maintenance of US Naval vessels when ECs have been made during the vessels' working life. Ordnance and maintenance departments need to have access to up-to-date information on the status of equipment in all of the Navy's vessels so that mistakes are not made which could affect vessel efficiency and maintenance 'down-time'. Conley describes the development of a computer-based system which can provide the Navy and its contractors with a configuration status accounting (CSA) report on any US Naval vessel. Of course, the system can only work if it receives complete and accurate information on ECs.

One of the major problems frequently associated with EC, is that of ensuring that only current documentation is available to manufacturing areas. Lack of adequate control over documentation can mean that components and assemblies are manufactured to instructions that have become outdated due to a subsequent EC. At the same time, the design function will need ready access to a range of documentation issues including those that represent outdated and/or future designs. Records are required to be kept of when changes were made to items, what the changes were, and what products they are effective on. In a paper that deals with a method that provides such links, Krishnamurthy and Law[4] describe a hierarchical method of storing a design description. The original design is called the 'root' and, as changes are made, the descriptions develop into a fan (tree)-like structure with the latest entity descriptions at the branch tips. An engineer who wants to know when a particular change was made may ask the software to search back towards the root to identify the occurrence. The software will also compute the differences between two versions of a design, or provide a detailed description of any version. The authors do not give any evidence of the software being used in a working environment to assist the management of ECs; only a simple example is given of a change search being carried out on elements (beams) in a building.

It is frequently argued that any appropriate computer-aided design (CAD) tool is capable of decreasing the number of ECs by giving the engineer

2 Auch A G and Joosep H 'Automatic engineering change analysis for incremental timing analysis' *IBM Technical Disclosure Bulletin* Vol 26 No 10A (1984) 5127–5131

3 Conley D T 'Configuration status accounting made affordable' *Naval Engineers Journal* Vol 103 No 6 (1991) 63–70

4 Krishnamurthy K and Law K H 'Change management for collaborative engineering' *Computing in Civil Engineering* Vol 2 (1995) 1110–1117 increased opportunity for simulation and iteration prior to the launch of a new product or the modification of an existing one. On that basis, it might be argued that all CAD packages have an effect on EC. Regardless of this problem, there are some packages that are claimed to be particularly relevant to reducing the adverse effects of EC. Frequently, these focus on the interface between design and manufacture, and support a concurrent engineering approach. A good example of this type of development is that reported by Hayes and Sun[5]. Their work, which is built upon a foundation provided by Schmitz and Desa[6], involves a CAD package using a 'manufacturing planner' to generate and analyse a manufacturing constraint network. Hayes and Sun describe two bases for this type of system: (a) plan based, which is used when one subproblem cannot be separated from other subproblems; and (b) rule based, where the rules for the solution of the subproblem can be determined in isolation. Whilst other researchers have concentrated on providing the engineer with shape information, an important aspect of the work of Hayes and Sun is that it is based on the relationship between location tolerances and manufacturing cost. The authors claim that use of the tool will reduce the probability of ECs downstream, thereby reducing costs and lead times.

A useful review paper on the application of microcomputers to manufacturing is that provided by Marucheck and Peterson[7]. Although a little dated, the paper still accurately describes the various aspects of manufacturing that can be improved by computer implementation. Most of these aspects have direct influence on the control of ECs. The authors state that the effective revision of a parts list or bill of material (BoM) requires visibility and communication among all affected departments. The microcomputer can improve the management of an engineering change notice (ECN) in two ways. Firstly, spread sheets can assist in analysing the cost of ECs (i.e. scrap costs, rework costs, additional material costs, acquisition of new testing equipment, and training). Secondly, database management systems can ease the ECN monitoring function by better tracking of engineering change requests and change orders within the system. This work is also supported by a wider investigation by McClellan[8].

2.2 EC methods

By far the largest number of EC related papers are concerned with mechanisms for controlling ECs through manufacturing, and the minimization of detrimental effects of EC on the product. Martel[9] describes problems that can arise from implementing an engineering change order (ECO) on electronic circuit boards with surface mount technology. The description of boards with a mass of retrofitted jumper wires, and the resulting problems associated with decreased component reliability and rework describes EC

5 **Hayes C C and Sun H C** 'Using a manufacturing constraint network to identify cost-critical areas of design' *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* Vol 9 (1995) 73–87

6 **Schmitz J M and Desa S** 'Development and implementation of a design for producability method for precision planar stamped products' *Journal of Mechanical Design* Vol 16 (1994) 349–356

7 **Marucheck A S and Peterson D K** 'Microcomputer planning and control for the small manufacturer: Part II. execution and support functions' *Production and Inventory Management Journal* Vol 29 No 3 (1988) 1–5

8 **McClellan C** 'Five P & IC uses for a microcomputer' *Proceedings of the APICS 26th Annual International Conference* New Orleans, LA, USA, 1–4 November 1983 pp 142–145

9 **Martel M L** 'ECOs: Band-aid fix?' *Circuits Manufacturing* Vol 28 No 9 (1988) 57–60

in a manner that is repeated frequently in papers written by manufacturing engineers. The responsibility for these problems is usually placed squarely on the shoulders of the design engineer. This use of company-specific investigations to identify problems and define 'solutions' is a recurrent theme of many papers, particularly by EC consultants in the USA.

Frequently cited papers on EC methods include those by DiPrima[10,11]. These papers, together with a later linked paper by Reidelbach[12], establish the basic elements in an EC control system. Both authors see EC as a manufacturing issue. Like Martel[9], they see the EC process as predominantly correcting mistakes. Reidelbach recognizes that assessing the impact of a proposed EC on the company is an essential element of the control procedure. Nine impact related steps are defined. These are: (1) determination of gross requirements for each component; (2) initiation of new purchase or manufacturing order(s); (3) cancellation or modification of affected puchase order(s); (4) procurement of revised drawings/specifications; (5) submission of the EC notice for data entry and checking of revised BoM; (6) co-ordination of production control to accommodate the change; (7) assignment of new standard costs; (8) determination of the disposition (reuse, scrap) of parts made obsolete by the EC; (9) ensuring that all noncontractual requirements (e.g. updating technical manuals) are fulfilled. Like many other authors, Reidelbach stresses the importance of an EC control committee to assess, implement, and manage EC methods and procedures. The effect of ECs on the specification of bought out items, and ways of dealing with potential problems are described by McKnight and Jackson[13], who describe the need for care in assessing a vendor's capability to comply with an EC. A similar line is taken by Causey[14] who provides the EC control committee with a check list of requirements for vendors. Causey also provides a list of metrics which allow the impact of ECs on the shop floor to be assessed. This list is rather more pragmatic than that provided by Reidelbach.

An important observation by Reidelbach[12] is that ECs are potentially more damaging for companies that manufacture products with long lead times than those with short lead time products. The principal reason for this is that each change is more likely to have to be incorporated into products that are already on the shop floor, than is the case for short lead time products. A similar observation is made by Williams[15] in respect to jobbing shops, which frequently have a much higher number of ECs per product than in high-volume environments. A similar argument is presented by Heumann[16] who distinguishes between made-to-order and engineered-to-order. The former is a matter of combining standard parts where the maximum engineering effort might be the production of an assembly draw-

10 DiPrima M R 'Engineering change control and implementation considerations' *Production and Inventory Management* Vol 23 No 1 (1982) 81–87
11 DiPrima M R 'Engineering change control: key element for improving productivity' *Proceedings of the 26th Annual International Conference of the American Production and Inventory Control Society*, Toronto, Canada, October 1983, pp 258–260
12 Reidelbach P E 'Engineering change management for long-lead-time production environments' *Production and Inventory Management Journal* Vol 32 No 2 (1991) 84–88
13 McKnight S W and Jackson J M 'Simultaneous engineering saves manufacturing lead time, cost and frustration' *Industrial Engineering* Vol 21 No 8 (1989) 25–27
14 Causey J W 'On the art/science of expediting' *Production and Inventory Management Journal* Vol 30 No 1 (1989) 73–75
15 Williams O J 'Change control in the job shop environment' *Proceedings of the 26th Annual International Conference of the American Production and Inventory Control Society*, Toronto, Canada, October 1983, pp 496–498
16 Heumann A K 'Master production planning and the engineered to order product' *Proceedings of the 26th Annual International Conference of the American Production and Inventory Control Society*, Toronto, Canada, October 1983, pp 293–296

ing, whilst the latter has a considerable amount of design input. In an engineered-to-order environment, each product is 'new' and carries the implication of a large number of ECs just as any new product would. In reality, the observations of Reidelbach, Williams, and Heumann are related to (and better explained by) the work of Sherwin[17] who looked at the particular problems for inventory control when introducing a new product. Sherwin emphasizes that there will be a large number of ECs during the period following the introduction of a new product, as design faults are identified and initial market responses become apparent. However, his proposals for an EC control system do not differ from those suggested by other authors who are considering the 'steady-state' condition some way down line from product introduction.

Wasilczyk[18] is one of the few authors who have taken a detailed look at the requirements for modifying part numbers following an EC. Wasilczyk argues that in cases where a company sells directly to customer order, it is important that the EC process within the organization is largely invisible to the customer. This is particularly true when the EC is concerned with rectifying a mistake. The marketing function needs stability with product model numbers, and these should change as little as possible in rsponse to changes to internal components. However, internal part numbers may have to change when ECs are implemented. The problem is to ensure that the company can identify which parts are incorporated in a particular unit. The author presents a strategy to alleviate this problem based upon a serial number to identify component revision details.

Useful additions to the body of EC papers are those that present case studies of problems and improvements in particular companies. Watts[19] has presented the results of an investigation into time delays caused by ECs at a company that manufactures computer products and components for end users and OEMs. The company had to respond quickly to the need for product changes to stay in business. The changes, which stemmed from new products and releases, totalled over 100 per month, and were mainly initiated by field engineers. Each change took (on average) 40 days to design and develop, 40 days for paperwork processing, and 40 days to implement the EC on the production line. It was decided to concentrate on reducing the time spent on paperwork. The resulting study reduced paperwork processing time to five days, and EC paperwork from 1.2 million sheets per year to 700 000 sheets per year.

A study by Harhalakis[20] at Ingersoll Rand found that over 98% of ECs related to BoM and contractual changes on their made-to-order production line. This author proposed a new system to handle these changes effec-

17 Sherwin R 'Managing the new product introduction process' *Proceedings of the 26th Annual International Conference of the American Production and Inventory Control Society*, Toronto, Canada, October 1983, pp 283–285

18 Wasilczyk T J 'Controlling the model number-part number interface' *Proceedings of the 26th Annual International Conference of the American Production and Inventory Control Society*, Toronto, Canada, October 1983, pp 300–303

19 Watts F 'Engineering changes: a case study' *Production and Inventory Management* Vol 2 No 4 (1984) 55–62

20 Harhalakis G 'Engineering changes for made-to-order products: how an MRP II system should handle them' *Engineering Management International* Vol 4 (1986) 19–36 tively, but did not report if the suggestions were implemented. Stalk[21] has identified product lead time as being an equally important measure of company management performance as product price. This point was picked up by Hegde *et al.*[22] who, in their case study at the Eastman Kodak Co., examined the links between company functional areas, and evaluated the detrimental effects on response if these links were strained. The authors found that a typical part spends nearly 22 days longer in the system for each ECO released, making ECOs by far the most influential factor regarding time delays. Like Forrester[23], Hegde did not make any judgement on how the situation regarding ECO related delays could be improved, and did not relate the work to other factors such as the complexity of the product, batch size, organizational structure, company systems or management strategies.

Balcerak and Dale[24] carried out a valuable study of EC control at The European Truck Transmission Division of Eaton Corporation. They concluded that: people often confused the reasons for an EC with its purpose; organizations faced with many problematic ECs should investigate the adequacy of their design abilities and procedures; an EC classification scheme should be by both type (impact of the change within the organization) and grade (urgency of the grade); all but the simplest of ECs require more than one determinant to be considered when deciding the effectivity date; feedback is essential to the success of an EC procedure.

A worthwhile body of published research on incremental design can be found in journals and proceedings relating to economic analysis . Cohen[25] has given a good review of this activity. The conclusions of Cohen are particularly interesting because of the recognition that economic measures alone cannot be used to assess the effectiveness of either new or incremental design activity. The paper urges a more eclectic approach to design research incorporating input from technology and organizational management disciplines, as well as economists.

3 An EC research framework

The key EC related papers selected for this review suggest that the research undertaken over the past 15 years can be represented by the tree structure shown in Figure 1. Numbers provided in the lower level boxes of the tree identify relevant references in the text of this paper.

So far, the research effort has been predominantly directed towards computer tools and appropriate methods by which EC related decisions can be made, and the paperwork systems for expediting the decisions. The methods and paperwork systems that assist decision making are represented by 'elements of control' in Figure 1. Almost all of these publications are related to control

21 Stalk G 'Time – the next source of competitive advantage' *Harvard Business Review* Vol 66 No 4 (1988) 41–51

22 Hegde G G, Kekre S and Kekre, S 'Engineering changes and time delays: a field review' *International Journal of Production Economics* Vol 28 (1992) 341–352

23 Forrester J W 'Industrial dynamics: a major breakthrough for decision makers' *Harvard Business Review* Vol 36 No 4 (1958) 37–66

24 Balcerak K J and Dale B G 'Engineering change administration: the key issues' *Computer Integrated Manufacturing Systems* Vol 5 No 2 (1992) 125–132

25 Cohen W 'Empirical studies of innovative activity' in *Handbook of the economics of innovation and technological change* (**P Stoneman** (ed)) Blackwell, Oxford, UK (1995) pp 182–264

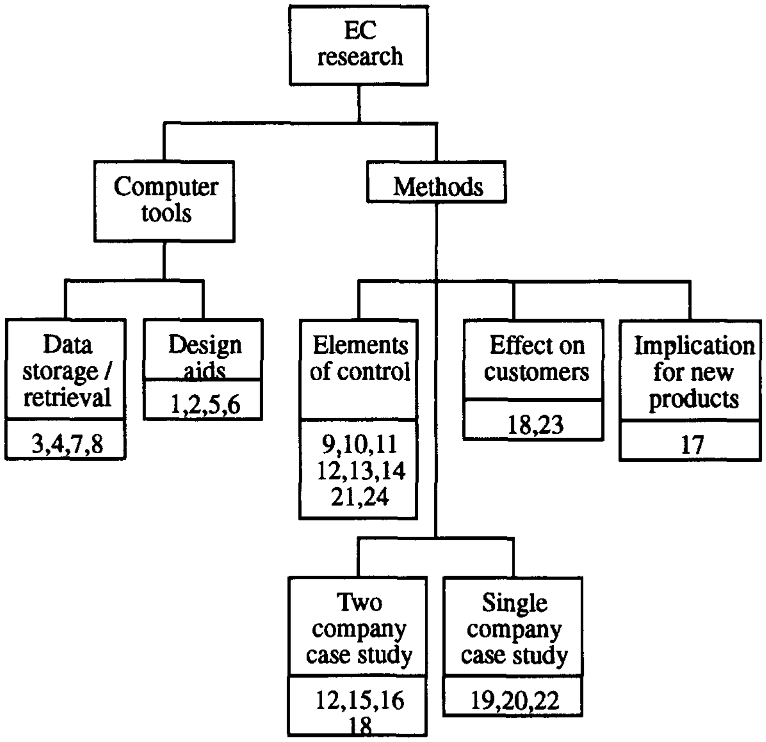

Figure 1 The structure of existing research in engineering change and incremental product design

of the manufacturing function. Case studies of either one or two companies are also good sources of comment on EC control mechanisms and systems. No publications were identified that dealt with EC from a business process point of view.

4 Current EPSRC research

None of the current Engineering and Physical Sciences Research Council (EPSRC) grants are explicitly directed towards a better understanding of the requirement for good EC management. However, a small number of contracts are concerned with studies in related areas. Grant GR/J97878 (New product introduction process in SMEs: audit, analysis and improvement – Professor M J Gregory, Engineering Department, University of Cambridge) is seeking to develop a new product introduction (NPI) auditing method by which companies might assess their performance. As already noted, the period immediately after the NPI stage can be expected to produce a relatively high proportion of ECs, and although this research does not have EC monitoring as one of its stated objectives, it would be useful to use EC numbers as a metric in the measure of NPI effectiveness.

Grants GR/K21726 and GR/K31756 (Complex product systems: a key technology management challenge for the 1990s – Mr H Rush, CENTRIM, University of Brighton) are concerned with effective product innovation in companies that produce engineering intensive, highly customized subsystems and components. Such 'products' have been identified as those that incur a large number of ECs at a high cost. Although, under these circumstances, ECs may be seen as something to be avoided, there is little doubt that they also provide an engine for product improvement and enhanced market performance.

5 *Requirements for EC related research*

From the manufacturing perspective, ECs are an evil that have a potential to disrupt the smooth operation of product production. From an inventory control viewpoint, ECs are potentially costly in terms of scrap stock or stock that requires rework, and bought out items that may require resourcing. From a production control perspective, ECs have the potential to confuse an already finely balanced loading on manufacturing resources. These are the functions that most of the authors of research reported in this review associate with, and attempt to find solutions for. However, to the marketing function, ECs are usually seen as the process by which the company stays effective in a competitive environment, whilst design is the company function through which these marketing objectives are implemented. Of course, in the long term, incremental improvements to products frequently lead to innovative 'leaps'.

It seems apparent that there is a lack of understanding of how ECs drive the incremental and stepwise development of product design in various types of company, the process of EC itself, and the way in which the EC process impinges on other business processes. Considering the important role of EC in all companies (but especially those producing long lead time and engineered-to-order products) it seems that this is an important omission. In particular, it is proposed that research into the following questions may lead to a significant positive effect upon engineering product design effectiveness.

- How do the reasons for, and purposes of, EC vary in different industrial environments?
- Can companies take market effectiveness into account when assessing the benefits of a proposed EC? What appropriate metrics can be determined to assess this criteria?
- How can the marketing and design functions estimate the downstream costs of a proposed EC, rather than leaving this assessment to an EC management committee?
- Is there a correlation between the number or type of ECs processed by a company and the market competitiveness of its products?
- What are the characteristics of activities and communication channels in

an effective EC management control system?

- To what extent does EC effectiveness influence design performance?
- What does the EC process map look like from the marketing and design function point of view?
- How does this map vary from that perceived from the manufacturing, production and inventory viewpoints, and how might these variations be accommodated?
- What are effective and efficient EC processes, and can these be defined on type specific and generic bases?

6 Conclusions

Historically EC research has been carried out from a manufacturing perspective, which ignores its capacity to provide the engine for product improvement. This omission is unfortunate, because it turns an opportunity for improvement into a matter for concern. The processes by which this engine works are not generally understood, nor the effect upon the process by different organizational structures, manufacturing and market environments, technology content and management strategies. These matters should be of concern to all companies that design and manufacture products.

A number of coordinated research programmes are required to establish the ground rules for maximizing the product design benefits from EC activity.