The Development of a Design Method for Production Machinery Companies

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The Development of a Design Method for Production Machinery Companies

R. P. GOUVINHAS & J. CORBETT

SUMMARY This paper presents the development of a design method tailored to support designers within production machinery companies. The proposed approach was developed based on the perceived views from designers within these companies with regard to formal design methods proposed in the literature. The method is based upon a chart-based collection of appropriate design guidelines. A study which was undertaken on a new design of sub-assembly of a high-accuracy machine tool was used to test the method, and this is also presented.

1. Introduction

A research project carried out at Cranfield University has established the level of awareness and utilisation of 16 different formal design methods within production machinery companies [1]. The results suggest that few of these formal methods are used within these companies, and that designers rely mainly on their own knowledge and experience to develop products. Design review meetings and informal conversations were found to be the principal approaches used during this process. In addition, a number of roadblocks have been identified as being responsible for the low utilisation of formal design methods within these companies. In this paper, the term ‘formal design methods’ is used to refer to design methods which have been proposed previously in the literature.

However, it was observed that many designers were interested in learning more about formal design methods in order to establish whether they could apply them to good effect in their designs. Moreover, a demand was noted within production machinery companies for training in the implementation and development of new and/or existing formal design methods. Designers have suggested the development of simplified and/or computerised methods, which should be ‘tailored’ to meet each company’s own particular requirements [2].

It is considered that any new approach needs to be introduced gradually. Therefore, it is important to convince designers, initially using a relatively straightforward example, that formal design methods can be helpful. Designers can then be trained in the use of more complex formal design methods, which later can be integrated into the company’s design process.

The proposal was therefore to formalise the use of appropriate design guidelines,
i.e. ‘good design practice’ which have been empirically derived from years of design experience [3]. The main sources for obtaining the design guidelines were a literature survey, the experience of design practitioners and established design procedures within engineering firms [4].

Initial talks with a number of production machinery companies indicated that design guidelines were preferred because they are relatively straightforward and easy to understand. In addition, Stoll [5] stresses that if successfully followed, design guidelines can help designers to develop a high-quality, low-cost and manufacturing-friendly product.

The aim has been to help designers to understand the general principles of formal design methods and also demonstrate how they can improve their teamwork skills. The procedure will ideally be a first step towards a larger general acceptance of more sophisticated and more powerful methods. In addition, it should lead to an increased level of awareness regarding the use of formal design methods. However, it was important for the method not to be ‘oversimplified’, because this could lead to designers losing interest. In addition, the approach was developed to tackle aspects which were of real concern to the designers.

2. Background to Design Guidelines

It is recognised that many authors have claimed that the application of design guidelines is not a suitable way to help designers within the design process. For example, Ekman [6] stresses that design guidelines ‘do not help designers to work systematically’. In addition, Tichem [7] claims that ‘no direction is provided to the designer about which rule applies in a specific situation’. Moreover, Boothroyd [8] argues that design guidelines ‘can guide the designer to the wrong direction’. Boothroyd explains that this happens because, in general, the application of design guidelines puts too much emphasis on individual components and little attention is paid to the subsequent assembly process. Therefore, the use of design guidelines tends to produce increased overall product complexity.

However, many of the presented arguments depend on the way in which design guidelines are structured and how they are applied by the designers. If, for example, design guidelines are used only as a ‘list of recommendations’ without encouraging designers to consider their designs further, it is unlikely that the approach will be used successfully in practical terms. This is because designers may argue that they had already instinctively considered these recommendations when designing the product. On the other hand, if the design guidelines are organised in a systematic way, in which designers are encouraged to question their designs, it is believed that guidelines can bring major benefits to the design of new products.

One of the most substantial recent works on design guidelines has been undertaken at Cambridge University [9]. These researchers have developed a database which contains about 3500 design guidelines gathered from 75 engineering design textbooks.

The database was later updated, restructured and computerised and is referred to as the Designer’s Electronic Guidebook [4]. The Designer’s Electronic Guidebook has a hierarchical structure, with eight levels of data abstraction, i.e. machine design, mechanical design, design of machine elements, engineering design, design theory, theory of technical systems, design management and industrial design, which uniquely identifies the scope and application of each guideline.

Figure 1 shows the functional structure for using the database, which makes use of a glossary of design terminology [10]. The glossary is used to support a more effective
selection of guidelines for a particular design task. Nowack [11] has also developed an approach based on the design guidelines acquired by Aguirre Esponda and Wallace [9]. This approach aims to deliver information to designers in such a way that it can provide a means of linking design and manufacture during the product synthesis process in the early stages of design. It is centred on the collection, storage and delivery of the design guidelines.

Watson et al. propose an approach to help designers account for the possible trade-offs when dealing with different Design for X (DFX) guidelines [12]. These guidelines are classified according to the design phases expressed by Pahl and Beitz, i.e. conceptual, embodiment and detail design [13], and organised into a three-tier hierarchy, i.e. ‘DFX tools’, ‘design rules’ and ‘design strategies’. The design team selects and weights the guidelines and trade-offs for a particular project.

Even though these approaches are sound attempts at structuring the use of design guidelines, it is believed that they are relatively complex and are unlikely to be used in their present form, particularly by production machinery companies. This is because it has been observed that designers from the production machinery sector require simpler, less complex methods, tailored for their specific needs [2].

3. Development of the Initial Approach for the Production Machinery Companies

In general, production machinery companies use design review meetings when developing their products, and these reviews consider competitive factors such as functionality, ease of manufacture and assembly, and product cost reduction, etc. [2]. The proposed approach therefore aims to meet these demands by concentrating primarily on aspects which are thought to have the greatest impact on these competitive factors. This approach has been developed to be used during design review meetings as well as by designers while preparing their designs, which will be discussed later during the design review meetings. Figure 2 presents the methodology used for the development of the proposed design method and is divided into seven stages:

(i) A collection of design guidelines found in a large number of sources in the published literature. This included not only the guidelines produced by Aguirre Esponda and Wallace [9], but also many other sources including Bralla [14], Black [15], Trucks [16], Anderson [17], Lindbeck [18] and Moss [19], as well as inputs from designers from production machinery companies.

(ii) Selected guidelines were categorised for each different area of the product development process, such as assembly, maintenance, and manufacture, which was further sub-divided into areas such as machining, casting, etc.
(iii) The refinement, final selection and organisation of the design guidelines, to be included in the proposed method, took into consideration their potential impact on the presented competitive factors. However, alternative or additional guidelines may also be included to cater for specific company requirements. These guidelines can be obtained from existing or proposed company practice, or from the main database already mentioned.

(iv) The guidelines were organised in a checklist format, which allows those involved in the design review meetings to check whether each guideline has been considered.

(v) The selection of the most appropriate method for designers to assess the guidelines, for which a quantitative (i.e. weighting and rating) method and a qualitative method, which involves a subjective analysis, were considered. A qualitative approach was used in which the assessment is based on three levels:

(a) If it is decided that the design satisfies the guideline thoroughly, they should mark '✓' (i.e. okay).

(b) If it is decided that the design can be changed, but requires further discussion outside the meeting, e.g. function versus manufacturing, calculation or layout, etc., they should mark 'R' (i.e. review).

(c) If it is decided that the design does not satisfy the guidelines and should
be modified in accordance with a known recommended solution, they should mark ‘M’ (i.e. modify).

(vi) The presentation layout of the initial machining and assembly guidelines charts for consultation with designers from six production machinery companies.

(vii) Further refinement towards the final document, after considering the comments and suggestions made by designers in the six production machinery companies, which are discussed thoroughly in Section 4.

3.1 Features of the Proposed Method

The initial lay-out of the proposed method included an assessment column for evaluating the design under review as well as company information such as the project title, the date of the meeting, the division in which the meeting was carried out, the design review number, the member of staff who has issued the document and the actions, if any, to be taken/comments. This ensures that the relevant information can be stored in one single document, which subsequently makes it easier for the project team members to evaluate the progress of the project.

The use of a qualitative method of assessment was selected based on discussions carried out within the six companies visited (see Section 4): the principal reason being that the assessment would be more straightforward and easier to implement.

It is believed that the proposed method should be useful in three ways. It ensures a common agenda for aspects to be covered during the meetings, as well as enabling designers to analyse their designs individually before the meeting is held. Also, it ensures that objective decisions are taken, by assessing the design against relevant predetermined criteria and documenting these decisions. Finally, it establishes whether the previous design review actions have been carried out.

4. An Overall View from Companies Regarding the Proposed Method

Six production machinery companies were visited and designers interviewed in order to establish their views on the usefulness of the proposed method. This included whether they thought the important issues had been addressed by the method, and also gave them the opportunity to suggest other areas in which the method might be developed and/or ways it could be used more effectively.

The interviews also aimed to verify:

(a) If designers were comfortable with the lay-out of the proposed method and if it was compatible with the way they normally worked.

(b) If documentation of the design process was considered to be an important issue for the company and whether the lay-out of the method satisfied this requirement.

(c) If the proposed terminology used was clear enough, and if the terms used were understood.

(d) In which work environment, i.e. teamwork or individual, it was considered the proposed method could be used most effectively.

The various views with respect to the proposed design method are summarised as follows:

(i) Documentation of the design process was considered to be very important. In fact, some companies indicated that they had faced problems within
their product development process due to the lack of suitably structured documentation.

(ii) The method was considered to be more useful when applied in a teamwork environment.

This is probably because the method intends to highlight issues for discussion, and that most of the issues require a multi-disciplinary approach, which is appropriate for the design activity.

(iii) The method was generally considered to be easy to apply and to understand.

(iv) A qualitative assessment was considered to be more appropriate than a quantitative one.

(v) The terminology used was well understood, and a major reason for an overall acceptance of the proposed method was because of its structure and ease of application.

(vi) Some of the companies had already used a checklist approach, and several of the issues addressed in the proposed checklist were already being addressed within these companies. This resulted in some designers believing that the method was familiar, which also contributed to its acceptance.

(vii) In a few cases, there was a lack of understanding of a guideline and how it should be used. Any misinterpretation and/or misunderstanding of the proposed guidelines was taken into account later when compiling the final documentation.

(viii) Some designers believed that there were situations in which some of the design guidelines were impossible to follow and/or would inhibit the designer's creativity.

After further investigation, it was considered that these concerns were associated with a misinterpretation of how design guidelines should be used. For example, it was noted that some of the designers perceived the guidelines as being ‘rules that must be followed thoroughly’ in order to avoid a ‘poor design’. However, this was an incorrect interpretation. It is intended that the proposed design guidelines be considered as ‘issues for discussion’ to indicate factors that should be taken into account during the design stage.

(ix) One or two designers were concerned that they might end up with conflicting ideas by using the proposed method (e.g. If they design for ‘assembly’, are they making ‘machining’ use more difficult?).

These conflicts need to be resolved and are part of the design trade-off activity. In fact, it is hoped that the proposed method will help designers in dealing with these trade-offs by highlighting the important aspects for discussion.

(x) The method was considered to be useful for existing designs but not entirely appropriate for new concepts.

The belief that the method was not appropriate for new concepts was based on a misinterpretation as to how the proposed guidelines should be used. The method is intended to stimulate discussion and creativity, and as such, it is believed that it is also suitable for the development of new concepts.

(xi) Designers from two companies considered that the method required a certain level of design experience to use it effectively.
While accepting that designers’ experience and judgement are extremely important, the proposed method was also considered/intended to be a valuable tool for new inexperienced designers. This is because it can be used to stimulate a knowledge exchange between experienced and lesser experienced designers.

(xii) It was also considered that the proposed method should be tailored to meet specific company requirements.

The proposed method is intended to be flexible, and particular guidelines can be introduced to accommodate specific requirements of the company.

(xiii) Most of those interviewed proposed areas in which more design methods should be developed. These included, in particular, a method for materials selection integrated with the selection of an appropriate manufacturing process.

It is believed that companies have problems with materials and manufacturing process selection due to [2]:

(a) Relatively little attention being paid to the conceptual design stage. This is because production machinery companies operate on the basis of ‘adaptive design’ and they hardly know or use the formal design methods related to this stage.

(b) An inability of many companies to develop an appropriate teamwork strategy.

It was also noted that some of the companies visited had mentioned management problems when dealing with different departments. For example, one designer stressed that the product development in his company still adopted an ‘over the wall’ approach.

(xiv) Some considered that a few of the machining guidelines presented were not relevant because they were already using computer numerically controlled (CNC) machines and machining centres (e.g. can the number of set-ups be reduced?).

However, not all of the companies were using CNC equipment and the guidelines would therefore be useful to them. Furthermore, it is believed that, for example, the final guideline is appropriate for CNC machining and it is likely to reduce the number of different tools used, as well as reduce the number of manufacturing datum. Other specific guidelines could also be developed/tailored where appropriate.

In general, the proposed method was extremely well received, although it was found that some improvements were necessary in order to make it even more acceptable. The proposed method was therefore modified in line with the suggestions made by the designers, after which it was tested on a current project as one of the collaborative companies. Examples of the method are given in Fig. 3 (a machining guidelines chart) and Fig. 4 (an assembly guidelines chart).

5. Testing the Proposed Method

The proposed method was used to analyse a toolslide assembly of a new turning machine. The development of the machine was very advanced and, therefore, unfortunately, the method could not be tested in a real design review situation. Nevertheless, individual parts included in the assembly were analysed by the authors.
<table>
<thead>
<tr>
<th>MACHINING GUIDELINES</th>
<th>PROPOSED ACTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce machining operations as much as possible.</td>
<td></td>
</tr>
<tr>
<td>Can one axis machining be used?</td>
<td></td>
</tr>
<tr>
<td>Can number of set-ups be reduced?</td>
<td></td>
</tr>
<tr>
<td>Can number of cutting tools be reduced?</td>
<td></td>
</tr>
<tr>
<td>Can standard cutting tools be used?</td>
<td></td>
</tr>
<tr>
<td>Can secondary machining operations be avoided?</td>
<td></td>
</tr>
<tr>
<td>Can machining be avoided?</td>
<td></td>
</tr>
<tr>
<td>Standardise and simplify machining operations.</td>
<td></td>
</tr>
<tr>
<td>Can machining of unnecessary areas be eliminated?</td>
<td></td>
</tr>
<tr>
<td>Can parts be machined on standard equipment?</td>
<td></td>
</tr>
<tr>
<td>Standardise materials use.</td>
<td></td>
</tr>
<tr>
<td>Can standard materials be used?</td>
<td></td>
</tr>
<tr>
<td>Can a cheaper material be used?</td>
<td></td>
</tr>
<tr>
<td>Standardise and simplify parts at maximum extent.</td>
<td></td>
</tr>
<tr>
<td>Can standard parts be used?</td>
<td></td>
</tr>
<tr>
<td>Can design features be standardised?</td>
<td></td>
</tr>
<tr>
<td>Can left and right hand parts be made identical?</td>
<td></td>
</tr>
<tr>
<td>Can shapes be simplified? (particularly internal)</td>
<td></td>
</tr>
<tr>
<td>Can parts be simplified?</td>
<td></td>
</tr>
<tr>
<td>Can all cylindrical surfaces be made concentric?</td>
<td></td>
</tr>
<tr>
<td>Parts should be easily fixtured and handled.</td>
<td></td>
</tr>
<tr>
<td>Can a base be provided as a reference?</td>
<td></td>
</tr>
<tr>
<td>Can part be fixtured and handled?</td>
<td></td>
</tr>
<tr>
<td>Be aware of cutting forces.</td>
<td></td>
</tr>
<tr>
<td>Can part withstand cutting forces?</td>
<td></td>
</tr>
<tr>
<td>Can long and extremely thin part be avoided?</td>
<td></td>
</tr>
<tr>
<td>Can internal features be avoided in long parts?</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 3.** The machining guidelines chart.
### ASSEMBLY GUIDELINES

<table>
<thead>
<tr>
<th>PROJECT TITLE:</th>
<th>DATE:</th>
<th>✓ - OK</th>
<th>DIVISION:</th>
<th>✔ - Review</th>
<th>M - Modify</th>
<th>DESIGN REVIEW NUMBER:</th>
<th>ISSUED by:</th>
<th>DUE by:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tbody>
</table>

#### Minimise the number of parts by eliminating or combining parts
- Can any part be eliminated? (see hints at the bottom)
- Can any part be combined with another?

#### Design parts for ease of handling
- Can all parts be easily assembled/disassembled?
- Can parts most likely to fail be easily accessed?
- Can parts be assembled single handedly?
- Can all parts be assembled from above?
- Can all parts be assembled from one direction?
- Can parts be installed incorrectly?
- Can parts be assembled without final adjustments?
- Can parts be self located?
- Can parts be self aligned?
- Can parts be designed symmetrically?
- Can any slight asymmetry be exaggerated?
- Can all tools reach functional area?

#### Minimise the number of separate fasteners within the assembly
- Can the number of fixings/fasteners be reduced?
- Can the variety of fixings/fasteners be reduced?
- Can push or snap on fasteners be used?

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**Hints:**
- Check if parts can be eliminated or combined by asking:
  - Does one part move relative to another?
  - Must parts be of different material?
  - Must the part be separate to make the assembly/disassembly process possible?
  - Does combining parts complicate its manufacturing or inhibit the assembling of other parts?

**If you answer ‘NO’ to the above questions, part is candidate for combining or eliminating**
- For combined parts consideration should be given to other manufacturing processes (e.g. casting/moulding).

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**FIG. 4.** The assembly guidelines chart.
5.1 Description of the Machine Under Study

The machine subjected to the investigation was designed specifically for the high-volume turning of high-precision components. The machine will perform turning operations to a precision of ±1 μm for workpieces up to a diameter of 40 mm and a maximum length of 50 mm. Figure 5 illustrates the machine tool/workpiece zone.

Externally-pressurised oil hydrostatic linear bearings are used for the linear axes in the machine which position the cutting tools relative to the workpiece. These bearings provide the optimum combination of low friction, high static and dynamic stiffness combined with smoothness of motion. They also withstand the high acceleration forces generated by rapid tool re-positioning.

The tool/workpiece positional relationships are sensed and maintained in a manner unique to this machine, thus eliminating most inherent machine errors. The machine structure is extremely stiff with good damping characteristics and is housed within a single enclosure together with the control electronics, services and tool/workpiece coolant system. Two examples of the many suggestions for improvements of the design obtained by using the proposed method are discussed in the following section. The proposed modifications are presented in sketch form to emphasise the salient features of the parts. This is because it is how the method would be typically used in an actual design review meeting.

5.2 Proposed Design Modifications

5.2.1 Upper and lower rails. The upper and lower rails are long cylindrical parts which form the guideway of the hydrostatic linear bearing system (Fig. 6(a) and 6(b)). The diameter of these rails is 80 mm and their length is approximately 600 mm. These rails
also require a set of four and six 15-mm diameter holes, respectively, throughout their length in order to provide constant pressurised oil flow. The proposal was to replace these long small diameter holes by a single central hole, as illustrated in Fig. 6(c).

One of the main advantages of this modification is the simplification of the machining operations required to avoid machining relatively small internal diameter holes in very long parts. These features are very difficult to machine and set-up, and consequently would be very costly to manufacture. In addition, this type of machining would require
special cutting tools which would make the operation even more costly and subject to potential tool damage. The proposed modification could also make use of standard hollow-tube stock. Subsequent discussions with a designer of the collaborative company indicated that this particular design had been adopted to enable the hydraulic oil pressure to be measured at the end of the tube in the event of a blocked oil feed restrictor. It is, however, believed that the company have produced an over cautious design and it is probable that this is due to previous bad experiences with pressurised hydrostatic bearings, but which can now be overcome with the use of modern filter systems.

It was argued that it is also much easier to maintain the upper and lower rails with the existing design. However, this maintenance is very unlikely to be required if the oil filters ensure that clean oil is pumped through the restrictors to the hydrostatic guideway surfaces.

5.2.2 Swivel spindle and trunnion bearing. The swivel spindle (Fig. 7(a)) is a cylindrical component having a maximum diameter of 45 mm and a length of 75 mm. The swivel spindle accommodates a trunnion bearing (Fig. 8(a)) which, in the present design, takes the form of a split part to enable it to be mounted onto the swivel spindle, which is currently retained by the small shoulder at the extreme left-hand end. The proposed modification of the swivel spindle will enable the trunnion bearing part to be manufactured as a single part, and the swivel spindle is then retained by means of a thrust washer and a circlip. These proposed modifications are illustrated in Figs. 7(b) and 8(b).

Subsequent discussions with the designer of the collaborative company revealed that the trunnion bearing requires both lateral and rotational adjustment during assembly. Therefore, it was argued that this function could be achieved even more easily by means of a single-part trunnion bearing and a locking screw. This modification would further simplify the manufacture of the swivel spindle because the circlip and thrust washer would no longer be required.

6. Conclusions

The presented analysis indicates clear examples of the trade-off discussions which will occur during the application of the proposed method, and ensures that the designer understands the reasons and justification for the final design.
During the design exercise, it became evident to the authors that the designers’ experience and a well-managed teamwork environment are extremely important for the successful utilisation of the proposed method. In addition, it was observed that most of the modifications proposed were concentrated on improvements based more on the analysis carried out with the support of the machining guidelines chart rather than the Assembly Guidelines Chart. It is considered that the assembly guideline chart could have been used to a greater extent if the designers of the machine had been present during the review, because the function of each assembled part would then have been explained and understood in detail.

Despite these difficulties, this design exercise has indicated the potential benefits that the proposed method can provide to improvements of the design process, through the provocation of critical discussion among those who are involved within the design and product development process.

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REFERENCES