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A Computer-aided Case Study to Enhance Manufacturing System Design Teaching*

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This paper presents a novel case study structure for teaching the process of manufacturing system design. The approach used for the case study removes many of the limitations of traditional methods of teaching the design process. It has been used successfully for a number of years and has proved to be both enjoyable and valuable to manufacturing engineering students. The approach used is to actively involve students in a design problem. The problem is defined using a modified industrial example and is open-ended in nature. The students must define the boundaries of the problem and seek the necessary information to be able to offer a solution. The use of software to support the activities of both tutor and student is central to the operation of the case study. The open-ended nature of the data gathering process in which students can ask questions of any member of the company management brings with it problems of consistency and response time. A flexible database system is used to support the tutor by providing a repository for responses to the queries generated by each student team. From the student viewpoint a key aspect is the requirement to assess the operation of the design through dynamic analysis since it is through this analysis that students, rather than the tutor, must decide whether the performance of the design is acceptable or not.

INTRODUCTION

UNDERSTANDING the process of designing and analysing a manufacturing system is an important part of any manufacturing engineering degree and must be regarded as a fundamental capability of any professional manufacturing engineer. Finding effective ways of developing this capability is therefore of critical importance. One of the problems associated with teaching manufacturing system design is how to enable the students to take theories and techniques from an academic environment and apply them in an industrial one. Lecture-based teaching normally concentrates on providing an understanding of the principles that underpin a given technique but pays little, if any, attention to creating an appreciation of how or when to apply it. The implicit assumption is that once the concepts are understood then applications judgements can be made from first principles. However, many experienced engineers would admit that their understanding of many fundamental principles improved immensely after they had gained extensive applications experience.

The desirability of providing applications knowledge as part of engineering courses has been recognized for a long time [1]. In most courses applications knowledge is gained through laboratory experiments, design projects and case studies. Laboratory experiments are normally and deliberately limited to the illustration of a particular principle and not intended to develop the student's understanding of the context in which the principles might be applied. For example, a student might develop model building skills during a simulation exercise but fail to gain any understanding of the circumstances in which such a model should be used in manufacturing system design. Case studies, particularly those based around a design task, are obviously better suited to providing an understanding of context and application. To be effective it is important that the design task be set in a context which is convincingly 'realistic' and that it be of sufficient complexity to challenge the students' analytical skills and avoid the rapid assumption of an obvious solution.

Providing an example that has sufficient complexity will expose students to a number of potential solutions which have to be analyzed and tested for acceptability. Such analysis will not only enable students to improve their understanding of the practical application of the techniques involved but also allow them to realize that selecting the 'best' design is not a trivial process. The selection of the best design requires a broader understanding of the contribution of manufacturing to the performance of the business.

This paper discusses these issues in the teaching of manufacturing systems design and describes the 'yoke flange' case study that has been developed to meet the extended requirements mentioned above. It explains that the creation of a more

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comprehensive, or 'rich', case context is dependent on the use of software tools to support the activities of both the students and the tutors. These software systems are discussed and future development options explored.

COMPLEXITY AND DYNAMICS IN MANUFACTURING SYSTEM DESIGN

In this section we seek to establish that potential exists to improve the more traditional approaches to teaching manufacturing system design by taking proper cognizance of the significance of complexity and dynamic behaviour in the design of manufacturing systems.

Complexity

Manufacturing systems are complex and thus the design process must reflect and consider that complexity. Demonstrating this point is important but is difficult to convey in a formal instructional environment without any form of active participation on the part of the students. Even with a hands-on practical case study deficiencies can still arise. Simple problems can be solved quickly, often by students using trial and error (or 'hacking' [2]) to search for a single, simplistic solution. The lack of complexity reduces the need for any formal or structured methodology to guide the design process and can make the whole problem appear trivial.

Another disadvantage of simple problems is the failure to present students with situations which require conflicting objectives to be settled and thus fail to reflect the necessary trade-offs demanded by 'real' industrial problems [3]. By introducing complexity the students will have to make decisions that they know will not provide ideal results.

Simple case studies also provide students with the security that there is a good solution to be found and that the tutor can be relied on to indicate when the solution has been reached and refinement of the design can stop.

Dynamic analysis

Judgement of the acceptability of a design adds to the fundamental understanding of the way the system will behave under normal, and less normal, operating conditions. By asking students to assess their own designs they are effectively being asked to develop a detailed understanding of both manufacturing systems principles and operations management.

Testing the robustness of a design is a common omission in reality as well as in case studies, when the solution will be based on the assumption of steady-state conditions. Whilst in an academic environment calculations are simplified, real manufacturing systems do not have the luxury to operate under stable, steady-state conditions. The impact of sources of uncertainty such as product life cycles, changes in customer orders, machine breakdowns, operator performance, scrap, etc. on the viability of the design are rarely considered. Requiring students to analyse and provide objective evidence of a design's robustness to cope with the conditions likely to be experienced in the real world will not only provide a better solution but also benefit the learning process.

LEARNING BY DOING HAS SIGNIFICANT ADVANTAGES

The approach of 'learning by doing' [4] has a number of significant advantages. These advantages do not just relate to making the process more interesting to students but also relate to student learning. The following highlights some key benefits:

- 'Learning by doing' makes activities, such as manufacturing system design, more memorable. The necessity to get involved with a detailed design task will result in design techniques and problems being more easily recalled than something read in a book or heard in a lecture. It will also allow students to build up a picture of a 'real' system to which they can relate existing and new theories [5].
- In becoming actively involved in a problem and seeking out possible solutions students will inevitably make mistakes in the application of a technique or concept. This is an important learning process that aids understanding.
- Within a lecture theatre or text it is difficult to convey some of the subtleties of a technique. Examples may include why a technique cannot be applied or why certain assumptions have to be made. Within a practical exercise this process is far easier.
- When applying a method or technique to solve a problem students will become more aware of why it exists and how it can be used. Students will achieve a better understanding of the fundamentals of a technique and the principles surrounding why it needs to be applied.
- 'Learning by doing' can also foster an understanding of value of particular solutions and how one solution can be superior to another. Forcing the students, not the tutors, to make such evaluations can only serve to strengthen their understanding of how to assess a solution.

PRINCIPLES FOR A PRACTICAL, HANDS-ON APPROACH

Ideally teaching manufacturing system design should be a combination of formal instruction and practical application. The application should be in a 'safe' environment and simultaneously provide an opportunity for learning and experimentation. This section introduces such an environment whilst the next section will describe a case study (called Yoke Flange) in which these ideas have been implemented and refined. Many of the concepts introduced here have been extracted from the way a manufacturing systems engineer would have to approach the problem in practice.

Definition of problem boundary

The process of designing any type of system requires a number of stages, starting with data collection, moving on to analysis, creating a number of design options and finally refining the selected design. Within an industrial environment the designer or design team must decide on what data and what type of analysis are required, and assess whether the final design solution is acceptable. In contrast, it has been suggested that, typically, academic problems tend to concentrate on familiarity with the mechanics of analysis techniques [6] rather than developing the other skills required by the design processes. Tutorial and simple design problems faced by students in an academic environment will normally define the problem boundaries and provide all the data needed for a successful analysis. Redundancy may be present in the information but the data will always be complete and accurate. Neither of these states are likely to be found in real applications. The student groups should be faced with problems that require them to experience all the stages between definition of the problem boundary and provision of a solution that is compatible with that boundary. This should ensure that students not only become comfortable with the mechanics of appropriate analytical techniques but also understand the circumstances which allow their confident application.

Experience shows that setting up a design exercise that is open-ended in nature creates apprehension amongst the students. The students tend to feel unsure about whether their approach is correct and whether the analysis is valuable or not [7]. Overcoming this apprehension can be helped by forcing the students to set their own objectives and project plan for the design. Assessed presentations of key proposals at several points throughout the exercise give an opportunity to provide feedback on progress.

By providing a minimal amount of information at the beginning of the design exercise the students are forced to develop their own project plan and determine appropriate performance objectives for the design. This in turn will drive their activities of data collection and analysis for the setting of such objectives requires a proper knowledge of the technical and business context of the work.

Factual information is requested by a student submitting written questions. The requirement for written rather than verbal questions has a number of benefits:

- the case tutor will deal with questions efficiently every 2–3 days;
- it forces students to be precise in their requests;
- the student must order their requests to reflect their investigation priorities;
- it makes a clear distinction between when students are asking for information or advice.

The process can be made more interesting by forcing the student groups to address their question, or 'memo', to one of a number of fictitious company managers. Each request can then be directed to the named manager (even if it is not the correct one) and the reply will reflect the outlook of the particular company department involved. Hence the same question can be posed to different personnel and receive different responses.

A simple way for the students to realize that they are at the 'end' of the data collection phase is to return an answer of 'not relevant' or 'no more information available'. However, it is more beneficial to force the students themselves to decide when to stop collecting data and therefore when to stop answering questions. If questions are asked on an irrelevant or previously unexplored area then an appropriate reply will be generated.

The students can be forced to make their own assumptions about parameter values by refusing to supply data on the grounds that company records do not exist or have been lost. The students must then make the appropriate judgements; for example, detailed data may not be available on the history of machine breakdowns.

Sufficient complexity

Simple design problems with little complexity allow a number of obvious solutions to be arrived at, allowing students to establish each one and select the best. Ideally the range of possible solutions should be so large the students do not have the time or, more importantly, the inclination to seek out each and every possible solution.

One means of permitting a wide variety of solutions to a problem is to make the case open-ended in nature. The case should have sufficient complexity that solutions cannot be worked out mentally but require a number of analysis stages to generate a manageable range of options. The most promising option would then be selected and refined.

Starting students off on a sufficiently complex design problem with an open brief is one means of delivering such an open-ended case (see Fig. 1). The case can be enhanced by providing a minimal amount of information to each of the groups. In order to arrive at a solution the students could request more information. This has two effects. Firstly different groups will end up with different perspectives on the same design problem. Secondly groups will have to tackle the problem of what data are needed to be able to tackle the design problem.

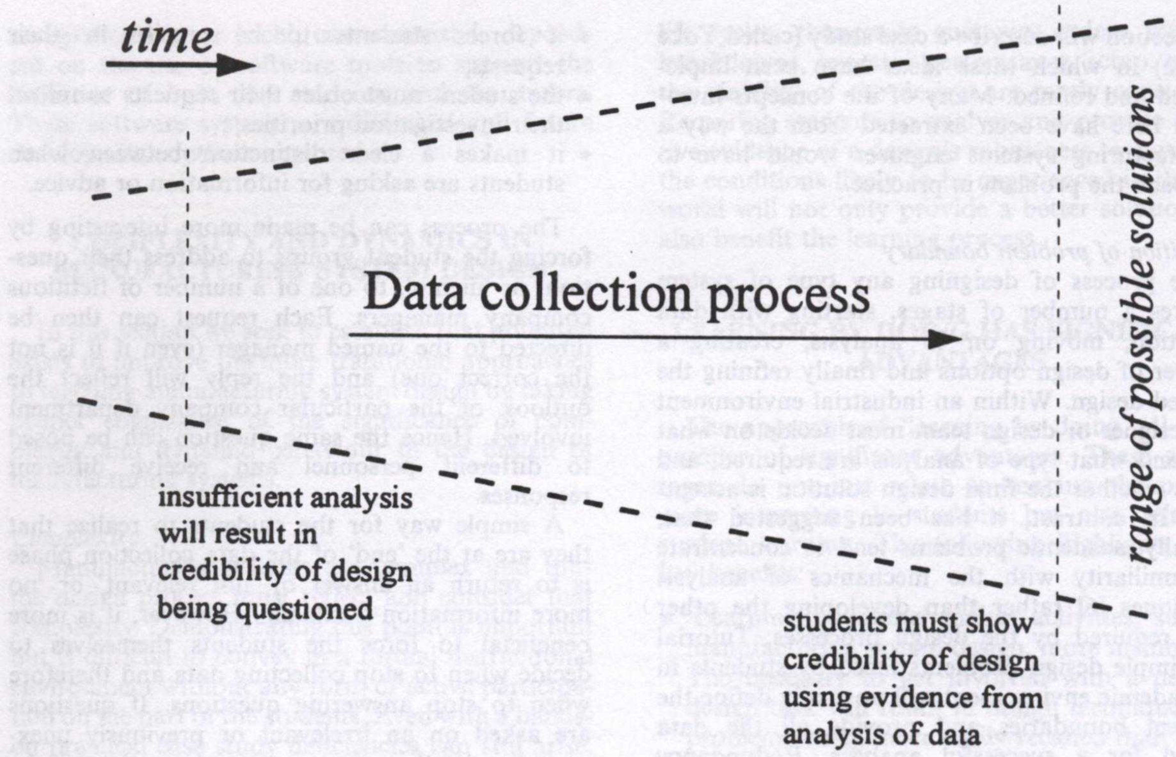


Fig. 1. Range of potential solutions increases over time.

Contact with tutor

The potential exists to minimize the amount of contact with the tutor and thereby provide a more cost-effective means of running the exercise. Although it weakens the tutor's control over the learning process, the students could be provided with a mass of information such that they would need to sort through it to identify useful and irrelevant information. A fundamental weakness of this approach is that the students would be aware that all the data required would be 'in there somewhere' and the extraction process required is inherently less demanding, and less realistic, than the investigation approach mentioned above.

Whilst the process of providing students with information could be handled relatively efficiently, it is undesirable for the student–tutor contact to be lost. It is valuable for student groups to informally discuss their design method and options with the case tutor. This approach gives students an opportunity to ask questions on the application of the methods and tools, and provide the tutor with an opportunity to intervene if serious misunderstandings or errors are evident.

A database should be placed at the heart of the case study. The tutor would use the database to hold all the case data, and it can be used to keep track of which students have asked for which information. The database is useful for ensuring that consistent information is supplied to the students whilst allowing the case information to be enhanced and updated each year. The availability of a consistent source of data also permits case management to be carried out by several tutors at once.

The database must be capable of on-line expansion so that as students ask new questions (relevant or irrelevant) new responses are recorded by the system. Ease of data reorganization is important to allow the database to be kept coherent even after considerable expansion. The database must also be organized to permit recording of conflicting 'replies' from different managers or company functions. Flexibility in format and indexing or retrieval mechanisms would be a vital attribute of the system.

Assessment of design performance

An important aspect of a case study is for students to test their own design. The test phase is useful for students to apply analysis tools and techniques in a protected learning environment, but this aspect is not the only benefit. By forcing students to test their design they are being asked to make a judgement as to whether their solution is an acceptable one. This part of the case study therefore allows students to develop an appreciation of when the analysis and development should stop. It also allows further development of the students' ability to discriminate between good and bad designs.

Commonly a spreadsheet-based capacity analysis is used for manufacturing system designs which can provide a steady-state analysis of the likely performance of the design. Often students do not appreciate the approximations that are implicit in the approach or consider whether the design can cope with the dynamics of real world operation. Thorough dynamic analysis of a design is important since it determines the operational robustness of the system. Simulation is used for this analysis since not only does it allow comprehensive examination of the performance of the initial design but also the process of building the model encourages students to clarify and refine their design proposals.

The design activities such as data collection, synthesis and analysis can be written up by each student in the form of a report. This process can be used to consolidate the student's understanding of the activities and techniques involved and should include a review of the quality of their design. Their analysis can feed into the design justification and thereby develop the student's understanding of the difference between good and bad designs.

Real world insight

The use of simulation offers a number of benefits when used for the design of manufacturing systems. Firstly, it can be used as a means of assessing the dynamic performance of a system. Secondly, it can be used to gain insight into a system and thus be used to both understand the system and make modifications to it. It is in the latter area that the use of simulation by students for design offers a number of very important benefits; it provides an understanding of the concept of dynamics and an environment in which the operation of systems can be observed.

Simple academic manufacturing system design problems ignore not only the complexity of real design problems but also the project planning element. By providing an in-depth problem students will have to plan their design activities over a number of weeks. The extended nature of this type of activity will allow students sufficient time to reflect on the work they are doing.

THE YOKE FLANGE CASE STUDY

Introduction to case study

The data used for this case study originated from an actual industrial problem. Over the years the case data have expanded considerably using the experience of those involved in the running of the exercise to introduce new compatible data as and when required. The case focuses on the need to move production of 'yoke flanges' (part of an automotive universal joint) to another, smaller area of the factory. The product is in the declining phase of its life cycle and thus any investment must be recovered within a few years. This scenario effectively limits the range of viable options to those which utilize existing plant rather than allowing radical changes to the manufacturing methods.

The product requires seven operations before being stored and then delivered to the main assembly line (see Fig. 2). The seven work centres contain a number of machines of varying states of capability (ability to machine to tolerance) and reliability. The production is predominantly semi-automatic and involves about 20 operators per shift.

The students are given a minimum amount of data describing their task and a routing sheet. Over a period of 10 weeks they must request a sufficient amount of data for their own analysis. The students collect the data and use this to pass through a number of design stages provided in the lecture material (see Fig. 3).

Design evaluation

The students' analysis should show the ability of the design to cope with fluctuations in demand, machine breakdowns, operator performance variations and scrap. A layout must be produced which takes into consideration the various height restrictions, obstructions and access requirements. Great emphasis is placed on the students providing the evidence that their design is robust.

Dynamics of case study and design option

All information required by the students comes through the case manager (see Fig. 4). The case manager can play the role of either the tutor (offering advice to the students) or one of the

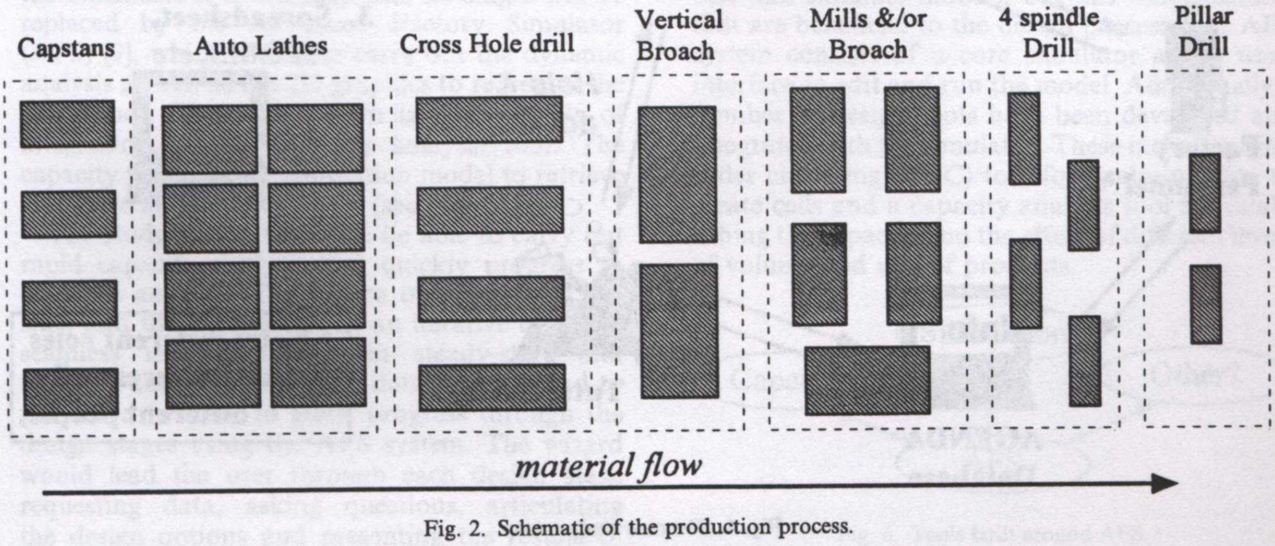


Fig. 2. Schematic of the production process.

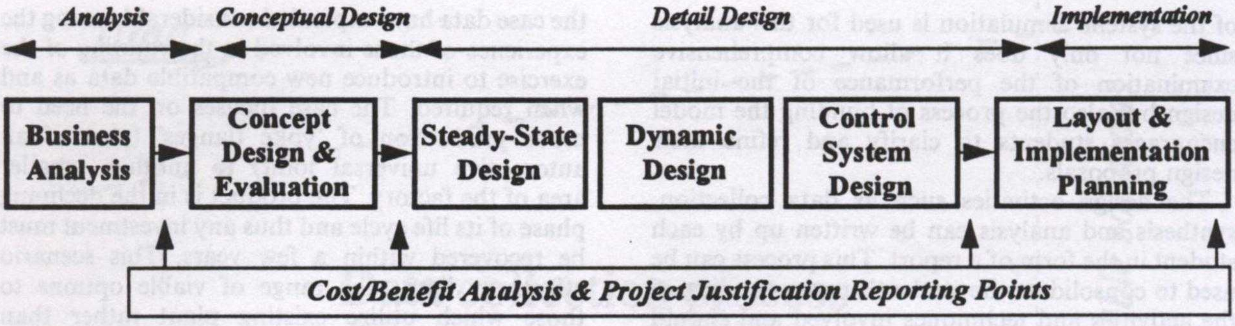


Fig. 3. The design methodology the students follow.

company employees. In the latter case the students must specify both the question and the employee to which it is directed, e.g. the production control manager or the company accountant. The student receives a reply which reflects both its nature and source. Note that different managers may give different responses to the same questions.

All information supplied to the students originates from the database, Agenda [8], used to support the case study. This is central to the case process and has proved an essential aid to ensuring the consistency of information supplied to different student groups and also to track the progress of each group as they request information.

The information is grouped according to departments in the form of questions and answers (see Fig. 5). On receiving a question the case manager would select the department and search for the information by looking for a similar question that has been asked in the past. Once a similar question has been found the students' group is noted and the answer (often grouped with other answers) is returned to the group.

If the information has not been requested before, after careful consideration of all other information held, a new answer is formulated and indexed (Agenda uses 'categories' rather than indexes). Once entered, the system automatically assigns the reply to as many categories as necessary after matching the text in the memo and its

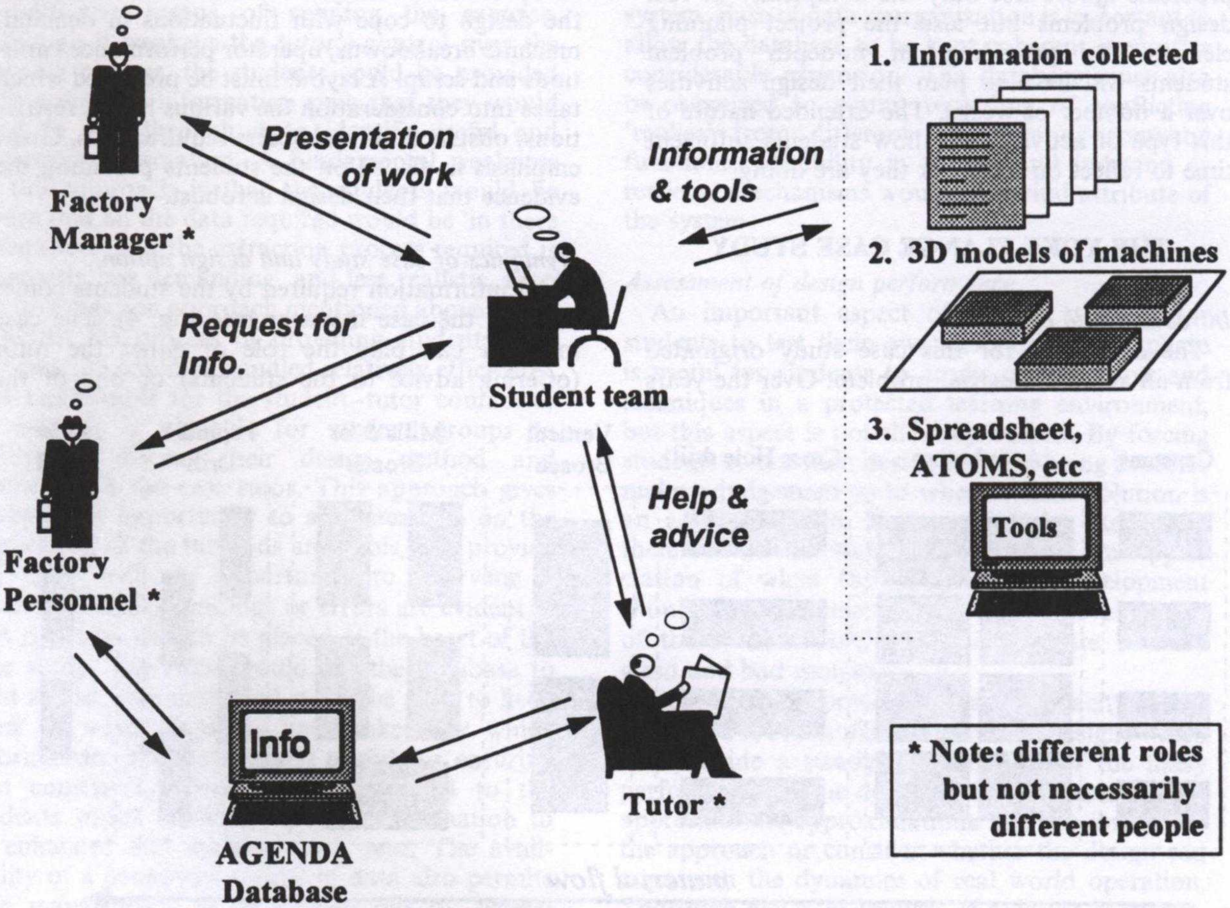
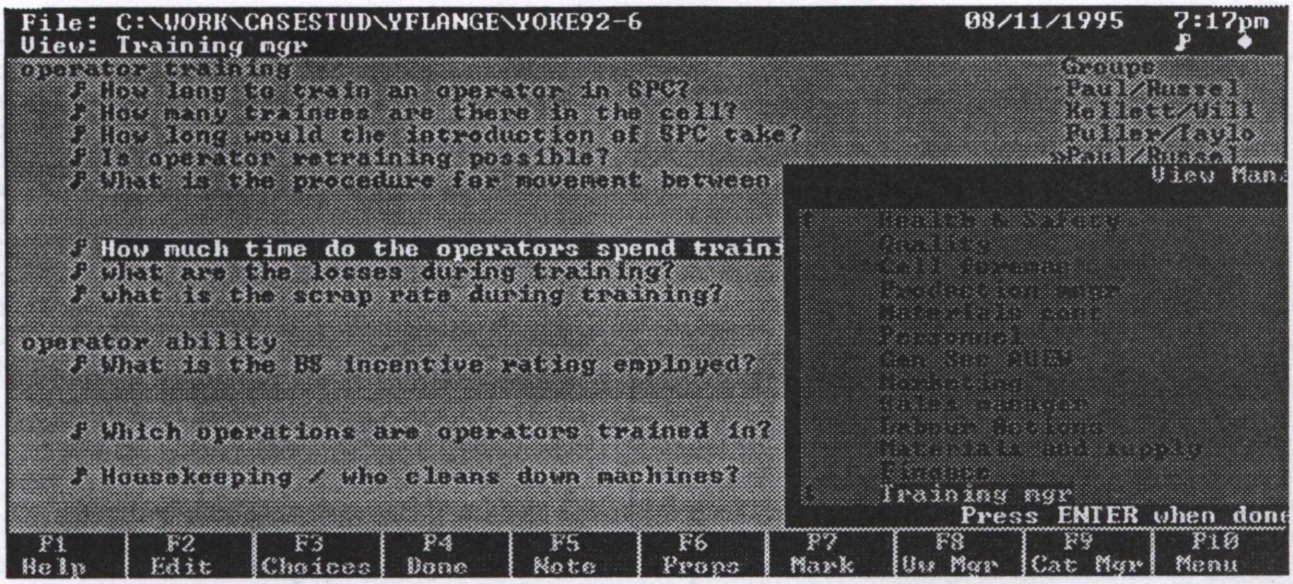


Fig. 4. The case study set up.



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File: C:\WORK\CASESTUD\YFLANGE\YOKE92-6                08/11/1995   7:17pm
View: Training mgr
operator training                                              Groups
   How long to train an operator in SPC?                      Paul/Russel
   How many trainees are there in the cell?                   Kellett/Will
   How long would the introduction of SPC take?               Fuller/Taylo
   Is operator retraining possible?                           »Paul/Russel
   What is the procedure for movement between                      View Man

                                            Health & Safety
   How much time do the operators spend traini    Quality
   what are the losses during training?           Cell foreman
   what is the scrap rate during training?        Production mngr
                                                  Materials cont
operator ability                                  Personnel
   What is the BS incentive rating employed?      Gen Sec AUEW
                                                  Marketing
                                                  Sales manager
   Which operations are operators trained in?     Labour Actions
                                                  Materials and supply
   Housekeeping / who cleans down machines?       Finance
                                                  Training mgr
                                                      Press ENTER when done
 F1     F2      F3       F4     F5     F6     F7     F8      F9       F10
Help   Edit   Choices   Done   Note   Props  Mark  Vw Mgr  Cat Mgr   Menu
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Fig. 5. Example of the questions directed at the training manager.

heading with categories held in the database. Thus a reply concerning wages many be 'indexed' under categories such as costs, payment systems, personnel manager, foreman, incentives, morale and industrial relations. New categories can be added at any time. Over the years the database has grown considerably to reflect of the range of issues the students have raised—at present it occupies over 400 kbytes of storage. The students will always receive information to questions asked and rarely receive the reply 'ignore that, it's not within the boundaries of the problem'. This approach forces the students to consider carefully how much information they need and to decide at what point they should stop asking questions. The flexibility of the Agenda database allows new data to be readily accepted or regrouped as necessary.

Use of simulation tools

Currently the latter stages of the design process illustrated in Fig. 4 use a data-driven manufacturing simulator called ATOMS and 3D models of the machines. It is intended that all stages will be replaced by the Advanced Factory Simulator (AFS) [9], which is able to carry out the dynamic analysis as well as use 2D graphics to represent the shop floor. The AFS system is also capable of integrating with a capacity analysis tool. The capacity tool uses the simulation model to retrieve and store all the design data (see Fig. 6).

The students will therefore be able to carry out rapid capacity analysis and quickly progress to dynamic analysis. The nature of the interface is such that the process can be an iterative one with seamless movement between steady-state and dynamic analyses. At a later date it is intended to provide a 'wizard' to guide progress through the design stages using the AFS system. The wizard would lead the user through each design stage requesting data, asking questions, articulating the design options and presenting the results of analysis (static or dynamic) in a manner which supports the decision-making process.

USING TOOLS TO AID THE LEARNING PROCESS

To date the ATOMS [10] manufacturing simulator has been used by the students for dynamic analysis of the design. This provides an understanding both of the principles of dynamics and the performance of their design option. The ATOMS simulator is data driven and allows the user to build models using only data—no programming or any other form of model logic definition is required, thus the time and skill required to use it are relatively low. The simulator only allows evaluation of the design and does not guide the user through creating the model or interpreting the design performance.

The AFS is expected to replace ATOMS in this case study. The AFS provides the ability to create, edit and simulate models, but has other features that are beneficial to the design process. The AFS system consists of a core simulator and a user-interface to edit and run the model. Additionally a number of design tools have been developed and integrated with the simulator. These include a rank order clustering (ROC) tool for analysing data to create cells and a capacity analysis tool for establishing the capacity and the effect of different levels of volume and mix of products.

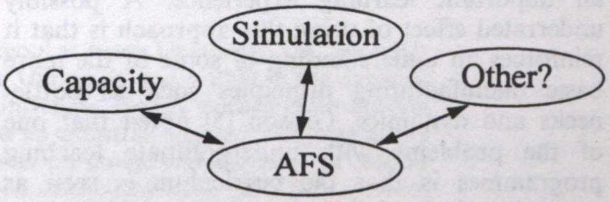

Fig. 6. Tools built around AFS.

Work has started on providing a methodological approach to building the simulation models. The user is guided through a process of data entry. During the data entry (via a 'wizard') the user is shown the results of static calculations that identify bottlenecks, maximum capacity, utilization levels, etc. This allows the user to modify the model prior to simulation and has the effect of reducing the model build and evaluation time. The rapid feedback and efficient user-interface encourages the student to explore more design options, thus leading to greater understanding of the influence of the various design parameters. So far a wizard has been created for 'U'-shaped cell design and evaluation. In due course this will be extended to support the design of a broader range of batch manufacturing systems. Such wizards help to clarify the design process for the student, but a careful balance has to be struck to avoid a situation in which the student simply provides the data and no inspiration.

STUDENT REACTION

The case study requires the students to develop a systematic approach to data collection, analysis and design. The supporting lecture material tends to concentrate on key manufacturing system design principles and the core design methodology, leaving considerable scope for self-directed investigation, learning and application in areas such as plant layout or health and safety. The students must decide when approximations are justified and can test their assumptions in a safe environment. The extra organization required and the open-ended nature of the investigation can lead to some students spending an excessive amount of time on the exercise. This risk is minimized by tutor review at the reporting points indicated in Fig. 3. Whilst the case represents an additional burden compared with conventional tutorials, students report a clearer understanding of the principles of manufacturing system design, and experience suggests that this is reflected in improved examination performance.

The need to apply particular techniques forces the students to realize the advantages and disadvantages of using them. The students quickly gain an appreciation of the difficulties and time scales of using tools such as simulation. More importantly, insight into the whole of the manufacturing system design process is gained; the necessity to work effectively as a team provides an important learning experience. A possibly underrated effect of using this approach is that it reinforces an understanding of some of the more basic manufacturing principles such as bottlenecks and dynamics. Gibson [5] noted that one of the problems with undergraduate teaching programmes is that the curriculum is seen as compartmentalized and as a result knowledge can be bundled separately. It has been noted that towards the end of this case study a greater appreciation of how many of the manufacturing principles (often taught separately in different lecture modules) interrelate is shown.

Student feedback has shown that participation in the case study is worthwhile and enjoyable, both in terms of designing a manufacturing system and also of the element of competition that arises between different design teams.

The open-ended nature of the case study and the origin of the case data provide a good preparation for students to tackle real industrial problems. During the process of design they will have gained a good appreciation of the difficulties of obtaining data and the (often vague) format it is supplied in. They will have practiced the sequence of a number of design tasks and will have an understanding of the difficulties involved. The students will be knowledgeable on the means of testing their designs and the effects of the dynamics on the overall performance.

CASE STUDY POTENTIAL

The case study has been developed over a number of years. The information available to the students on the factory has grown and has necessitated the use of a flexible database to manage it. With the introduction of easier-to-use simulation tools the scope of the testing and refinement phase has been extended to consider the response of the system to sources of uncertainty such as absenteeism, scrap, rework, breakdowns, operator performance variability and demand fluctuation. Such developments have served to create more realism in the case study and provide students with a more effective preparation for real manufacturing system design work.

Recent developments include a requirement for students to present interim reports, written and oral, to the 'factory manager'. This results in the students committing themselves to design specifications or overall designs early on in the process and subsequently having to justify any changes they make. It also ensures the business and financial implications of the design activity are considered throughout the design process.

The construction of the AFS has been described briefly. One of the key properties of AFS is the underlying software architecture which was designed and implemented using object-oriented techniques. The use of object-oriented design and programming techniques has resulted in a simulator that can be gradually extended over time. Extensions have been demonstrated by the introduction of production planning and control functionality [11], and office modelling functionality [12]. The ability to extend the software functionality will allow the creation of case studies of greater scope and variety of context.

The ability to extend AFS is not confined to the development of modelling functionality and the menus and dialogs to create and edit it. The user-interface can be extended in novel ways. For example, work has been carried out on providing an ROC cell creation tool, a capacity analysis tool and a wizard for guiding the user through the design of 'U'-shaped cells. The ability to extend the AFS system in this way opens up opportunities to provide students with a richer set of design tools and a system which guides the student through the design stages, offering guidance and feedback in the process.

SUMMARY AND CONCLUSIONS

This paper discusses the problems of traditional methods of teaching manufacturing system design. It argues that whilst 'learning by doing' has a number of significant advantages, it is important to consider the complexity of the task being undertaken. It is concluded that a case-based approach of considerable depth would be most appropriate. This would allow students to develop not just knowledge of how to apply techniques but also give students valuable experience of working in an environment with conflicting requirements and no obvious solution.

The paper introduces the 'Yoke Flange' case study. The case is based on a real industrial problem and has been expanded significantly over the years to provide even greater realism. Software tools are essential for running such exercises. Tools are required for handling the vast and ever-changing body of information on the factory and for students to analyse their design effectively. The use of simulation forms a key part of the case study, in part to give the students greater insight into the case and general manufacturing principles and in part to enable students to assess the value of their design.

The case study has proved valuable in teaching manufacturing system design; the student feedback is favourable and exam results show an improved understanding of manufacturing principles. Experience has shown that the use of a case study with such depth and complexity is beneficial and that management and operation of the case study could not be easily achieved without the database and analysis tools employed.

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