Signposting, a dynamic approach to design process management

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Abstract

This paper presents an overview of a dynamic guidance tool that has been developed to address a need for design support in the aerospace sector. The tool, called *signposting*, provides the means of directing activity by suggesting the next appropriate task in the design process. This suggestion, based on the presence of key parameters and their associated confidences, allows design to be a reactive process.

The underlying logic of the design process is captured using confidence mappings which determine when a task is possible, sensible or not achievable. The lack of a prescriptive process structure also allows new design tasks to be added at any time. The signposting technique is described with reference to a simple mechanical design process example.

1 Introduction

The design of complex products is a challenging task. This arises from the difficulty of coordinating large multi-disciplinary teams through complex design processes within the economic constraints of time and budget. Ideally, a project manager would wish to direct the team along the most effective design path to the defined design goals. However, in practice, project plans often consist more of optimistic expectation than practical reality and a more dynamic approach to project management is required. Such an approach should be able to accommodate the inevitable unexpected activities which arise in the design of complex products

One solution would be a dynamic planning tool that not only takes account of the design goals, but also considers the current state of the design. Such a tool, which uses expert knowledge of potential design tasks to identify possible design routes, has been developed. The tool acts as a dynamic signpost highlighting potential routes for the design process and also as a store of relevant design knowledge.

This paper describes the background to the research that has led to the development of a prototype *signposting* tool. The implementation of the tool is discussed, along with an example of its application to the design of a load carrying mechanical component.

2 Background

The original aim of this research was to investigate the means by which aerospace design processes, which typically are large and complex, could be captured. However, as a result of the initial research studies a number of more fundamental research questions were raised. These were:

(i) *Can a dynamic design process be constructed from knowledge of individual design tasks?*

(ii) *If so, what knowledge is required of the individual tasks?*

(iii) *How can such task knowledge be elicited?*

Section 3 of this paper describes the background to these questions, whilst Section 4 describes the development, implementation and evaluation of the *signposting* model which attempts provide answers to these questions.

3 Design Process Models

There are many different ways of modelling the design process ranging, for example, from the staged process models of Pahl and Beitz [1996] and Dym [1994], through activity models such as that proposed by Shigley and Mischke [1989] and Blessing [1994], to the task based approaches adopted by Steward [1981] and Eppinger et.al. [1994].

All these models have some common features. They all involve the execution of tasks, within some structure or process, to identify, evaluate and iteratively refine key design and performance parameters (Figure 1). In addition, they all aim to reduce the number of iterations required to generate a new design. It is the relative importance of the tasks, parameters and structure in defining the overall design process which characterises their different approaches.

3.1 A staged design process

A typical staged design process [Pahl and Beitz, 1996] includes four main phases: clarification of the task, conceptual design, embodiment design and detail design. These stages may be further subdivided to reveal a series of tasks that must be performed to transform the requirements for a new product into its manufacturing instructions.

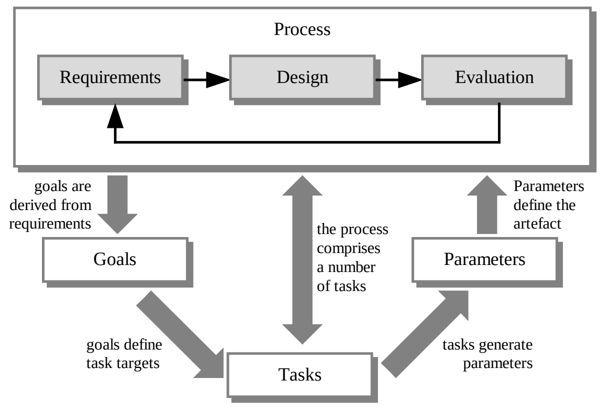

Figure 1 Relation of the basic concepts

In an ideal world, this sequence of tasks would be serial and defined in such a way that if the designer followed the tasks in order, a successful product design would result. However, such processes are static and exist only for some cases of variant design and lend themselves easily to automation. The simplicity of this process relies on the fact that the development of the parameters describing the product depends only on the correct execution of the prescribed tasks.

A more realistic design process will involve iteration where the designer may have to repeat tasks to meet performance targets, and progression to later tasks may be dependent upon passing through design reviews where the confidence in key design parameters is assessed (see Figure 2). In addition, tasks often need to be initiated with incomplete information.

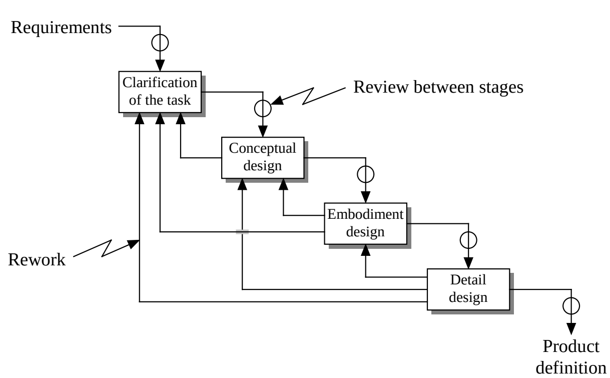

Figure 2 A process-driven design process

In a staged process the design process defines the task sequence. Hence, contextual task knowledge is not required and parameter confidence will only be important in an iterative design process.

3.2 A task driven design process

A design process may be task driven [Eppinger et.al., 1994]. For example, an apriori task execution sequence may be defined using the knowledge of task precedence captured within a Design Structure Matrix [Steward, 1981], where a task's context is recorded in terms of the tasks required to be completed before it may be started.

In a task driven design process the design process defines a specific task sequence based on the task contextual knowledge. For example, using Eppinger's approach, a task sequence utilising minimum iteration is derived from the knowledge of task precedence. Again, parameter attributes such as confidence will only be important in an iterative design process.

3.3 A parameter driven design process

A design process may also be parameter driven, where knowledge of the parameter requirements of each task, combined with a predefined task precedence network, allows a task to be executed when the required parameters are available (see Figure 3). For example, McMahon and Xianyi [1996] use petri-nets in this way to form a parameter driven process. However, such processes are static in nature and must be carefully defined for each new type of product. In addition, they are generally only suited to processes where the parameters are predominately numeric.

In a parameter driven process the design process defines task sequences which are executed in response to parameters being available. Contextual task knowledge is not required.

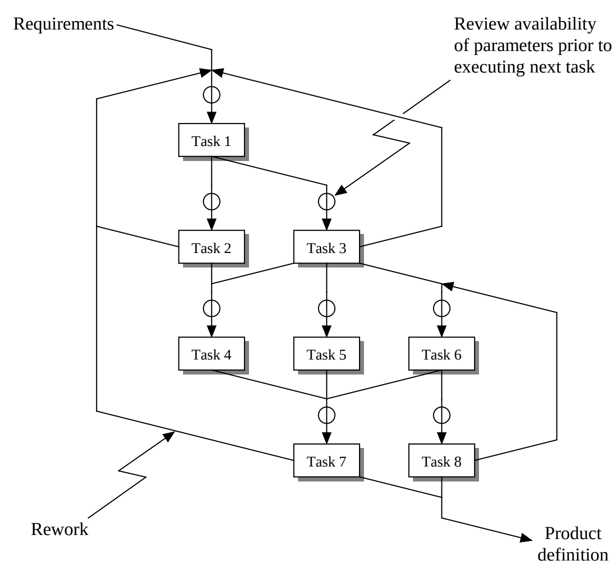

Figure 3 A task-driven design process

3.4 The signposting model

A further design process model has been developed which directs the designer to the next appropriate and available task, or tasks, at any point in the design process. This direction, or ‘signposting’, is derived from knowledge of possible design tasks and their associated contextual information [Clarkson and Hamilton, 1998].

The dynamic nature of signposting adds greater flexibility to the Design Structure Matrices [Steward, 1981] used by Eppinger and others and extends the potential of petri-nets to include the notion of parameter ‘confidence’ as a means to differentiate between similar tasks. In addition, signposting eliminates the need to capture the task precedence prior to constructing a model. The resulting process is truly dynamic reacting to the successes and failures of the emerging design.

The signposting model is a variant of the parameter driven approach, where it is not only the presence of a parameter that enables a task to be executed, but also its associated confidence.

Task precedence knowledge is not captured explicitly, however, the grouping of related tasks assists in the identification of viable tasks. However, these tasks, with their associated task contextual knowledge, define a dynamic design process which changes as the design progresses. Here the contextual knowledge implies a task precedence which is dependent upon the current state of the design. Singposting is described further in Section 4.

3.5 The workflow model

Traditional workflow systems provide a framework for controlling business processes and are used to mediate the flow of responsibility in those processes from person to person and from task to task [Prasad et.al., 1998]. This matching of resource to need is suited to well behaved business processes where a standardisation of procedure can bring about increases in process efficiency.

However, the engineering design process is not a well behaved process and even in the case of variant design, where a new artefact is very similar to previously designed products, there can be considerable changes in the process that generates the design information [Dong and Goh, 1998].

Signposting provides an approach to manage such processes by enabling a situation driven guidance engine. The presence of certain key parameters activate the possibility of carrying out tasks. There is currently no ability to match a resource to the potential tasks, but work is being carried out that enhances the reactivity of the current signposting implementation by enabling the generation of task plans rather than the suggestion of just the next best task.

3.6 Summary

There are many different ways of modelling the design process. What distinguishes the different approaches is then the emphasis placed upon design process, tasks or parameters. In general, static design processes, suitable for variant design, are highly structured and dynamic processes, suitable for adaptive design, require greater knowledge of the design tasks.

4 The Signposting Model

The signposting model will now be described, starting with the assumptions upon which the model is based. This is followed by a description of the model representation, using as an example the case study which is developed further in Section 5.

4.1 Model assumptions

The signposting model is based upon the assumption that the design process may be thought of as a series of tasks concerned with the identification, estimation and iterative refinement of key design and performance parameters, until a sufficient level of confidence in those parameters is achieved.

In this context, design parameters are those that define the product’s physical structure, such as its geometry and the materials used. Performance parameters, for example stress distributions for given loading or drag characteristics, are then derived from design parameters and used to assess the performance of the design. These definitions are consistent with the terms *explicit attributes* (design parameters) and *implicit attributes* (performance parameters) used by McMahon and Xianyi [1995].

In the proposed task-based representation, a generic task is used as the primary building block of the process. To perform this role, the generic task representation must satisfy a number of criteria. In particular it must: be applicable at varying degrees of abstraction; be appropriate to represent all tasks; be linked to the knowledge required to perform the task; and represent the meta-knowledge specific to the task.

The representation must therefore couple the knowledge describing the specific method to be used to perform the task with meta-knowledge describing the context in which the task should be performed and the likely consequences of performing the task.

This is a similar approach to that adopted in the Hierarchical Object-Oriented Blackboard System (HOBS) [Carter and MacCalum, 1991]. In HOBS, knowledge sources (tasks) comprise of a *body* (knowledge required to perform the task) and a *shell* (meta-knowledge coupling the body to the system by defining the contents of the knowledge source and when and how it should be used.)

The task definition itself may take the form of a *translation* or a *test*. A translation involves the creation and/or modification of design or performance parameters, whilst a test is the evaluation of the results of such a translation. These definitions are consistent with the equivalent and non-equivalent transformations suggested by McMahon et.al. [1995].

There is a third class of tasks should be added, namely *identification*, concerned with identifying key design parameters. In the case study considered in this paper all the key design and performance parameters were identified prior to the actual process studied. However, this may not be the case in other studies. Indeed, it is unlikely to be so in truly creative and original design.

4.2 Task representation

In the initial stages of aerospace design, empirical formulae and rough calculations are used to establish estimates of key design parameters. Later, more exact predictions may be derived using complex computational tools and/or physical tests on prototypes. Due to the higher costs of these later analyses, they are usually only performed when the designer has sufficient *confidence* in the accuracy of key input parameters.

Confidence encompasses a number of meanings. To be confident in a parameter means that the parameter is detailed, accurate, robust, well understood, physically realistic and, in the case of a performance parameter, meets pre-defined performance requirements. The confidence in the output parameters is then a function of both the accuracy of the particular task and the confidence in the input parameters.

This definition of confidence is broadly consistent with the properties of parameters described by other authors: precision, uncertainty and accuracy [Chantler et.al. 1998]; randomness and fuzziness [Dym and Levitt, 1991]; approximate and probable [Wood et.al., 1990]; and uncertainty [Hykin and Laming, 1975]. It can be seen from the list of descriptions above there is little agreement with regard to terminology. However, the term *confidence* has been used since it was found to be better understood by designers. Further research continues to refine the definition of confidence and explore issues of terminology.

By introducing a confidence parameter into the procedural matrices proposed by Steward [1981], a modelling technique has been developed that represents the relationship between input and output parameters for a given task (Figure 4).

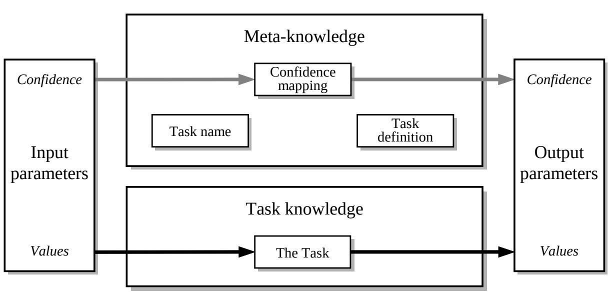

Figure 4 Task representation in the signposting model

In the model, confidence is represented using three discrete levels (Figure 5). These levels are assigned as:

Low - an initial un-proven design or performance estimate;

Medium - a feasible design or performance estimate;

High - a feasible design or performance estimate if the resultant product performance satisfies the design requirements.

More typically, representation techniques for confidence and uncertainty in the design process include: assigning numerical values [Ulman et.al., 1997]; using fuzzy variables and probabilistic distributions [Wood et.al, 1990]; and ranges of values [Duffy and MacCullum, 1989]. However, design experts were found to be uncomfortable in dealing with numeric representations of confidence. Indeed, individual experts responded much better to the use of discrete levels. Hence, the use of discrete levels in this model.

This approach is also adopted by Ullman et.al. [1997] who used a number of descriptive words to communicate levels of confidence between an individual and computer. A statistical survey was then used as the basis to map the descriptive words to numerical values [Herling et.al., 1995].

Three levels of confidence were chosen to demonstrate the concept of confidence mappings. However, in more advanced applications more levels may be desirable.

The confidence mapping may be represented by a table that relates the minimum confidence of the input parameters required to give a particular level of confidence in the output parameters for a given design task. This technique is illustrated in Figure 5 for the **Refine geometry** and **Finalise geometry** design tasks.

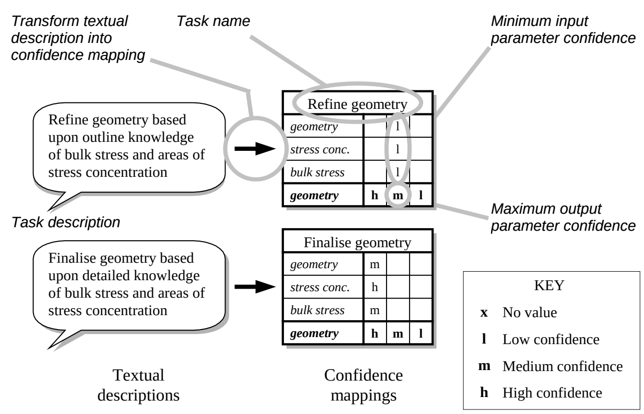

Figure 5 The use of confidence mappings

The confidence mappings are derived from the textual descriptions of the tasks and the expert's knowledge of its appropriate use. They describe the maximum benefit to be achieved by executing the task.

The **Refine geometry** task is used to increase the confidence in the *geometry* by ensuring that the estimate is physically feasible. The potential change in the confidence of the *geometry* is indicated by the confidence mapping. In this case, an estimate of the *geometry* may be considered to be a feasible estimate if the *stress concentration* and *bulk stress* are less than the limits prescribed (Figure 6).

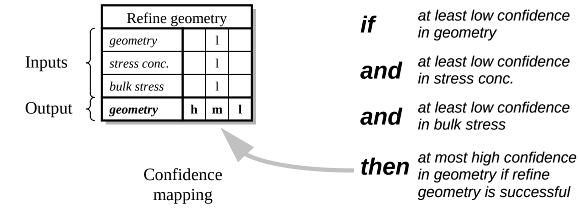

Figure 6 The confidence mapping

Given the parameters available and their associated levels of confidence, it is possible to estimate the effect of undertaking specific tasks from their associated confidence mappings. Consequently, given a request to calculate a specific parameter to a given level of confidence, the most appropriate task sequence may be identified. This is illustrated in Figure 7.

Given the low level of confidence in the *geometry*, it can be seen from the dynamic confidence mappings that it is initially inappropriate to use the **Finalise geometry** task. However, if confidence in the *geometry* is increased using the **Refine geometry** task, and higher levels of confidence are available for the *stress concentration* and *bulk stress*, it is then appropriate to use the **Finalise geometry** task to increase the confidence further. Hence, if the parameters for a given task are available, at the required minimum levels of confidence indicated by the task's confidence mapping, then that task is deemed to be possible. This process forms the basis of the dynamic task planning which is the core of the signposting technique.

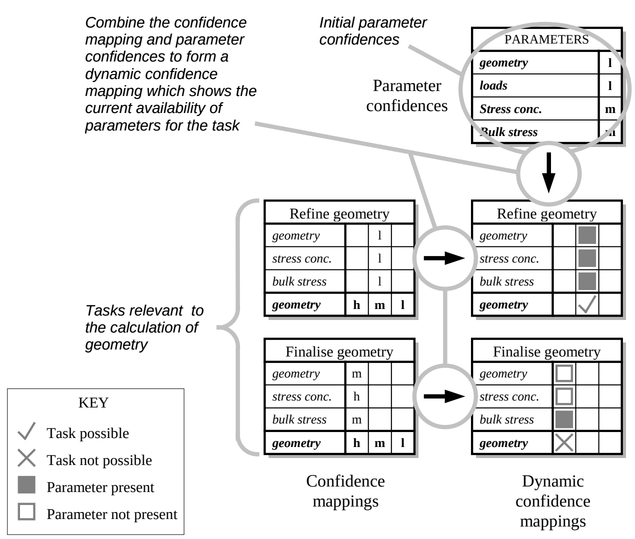

Figure 7 Task status derived from confidence mappings

4.3 Process representation

The structure of prior knowledge is of paramount importance in determining its effective use [Oxman, 1990]. Therefore, the means to simply categorise and sort design knowledge is a primary requirement of the proposed model.

The number of different design tasks that may be used in a particular design process is usually large. Therefore, it is sensible to limit the number of potential tasks presented to the designer at any given time. A method is needed to structure the tasks such that, given a particular design state, the tasks presented to the designer are restricted to only those likely to be relevant to the current situation.

Typically in design, a general strategy for tackling complex problems is to break the problem down into smaller, more manageable, problems and solve each problem in turn [Cross, 1994]. Therefore, one way to structure the tasks is to decompose the particular design process from the top down into its constituent tasks and sub-tasks. The hierarchical decomposition may then be used as a framework to categorise and structure the specific tasks elicited in the knowledge acquisition.

The proposed task-based decomposition is similar to the hybrid design model proposed by Eppinger et.al. [1994], who compares a task-level description of the design process (top-down) and a parameter-level description (bottom up). He then proposes a hybrid design model that contains both the task-level and parameter-level information. The hierarchical breakdown of design tasks is also adopted by the HOBS system [Carter and MacCallum, 1991].

Within a particular task cluster, it is possible to determine the next most appropriate task(s) to undertake by combining and reducing the dynamic confidence mappings (Figure 8). First, the output parameter confidences for each task in the cluster are combined into a single dynamic cluster mapping. Each row in the dynamic cluster mapping is then reduced to a single element in a dynamic guidance table, where a '✓' (task possible) takes precedence over an '○' (task not sensible) which takes precedence over an '✕' (task not possible).

This reduction process can be propagated upwards through the task hierarchy to provide guidance at any level in the model. A '✓', '○' or '✕' will then indicate the state of the tasks within a given cluster. This allows available tasks to be identified within a cluster of particular interest and in the hierarchy as a whole.

Traffic light colours have been used in the implementation of the model to represent the '✓', '○' or '✕' states, where green ('go') indicates a '✓', amber ('caution') an '○' and red ('stop') an '✕'.

Where more than one task is possible, i.e. more than one green light, it may be necessary to advise the designer on the most appropriate next step in the design process. There are a number of ways in which this might be achieved based upon knowledge elicited from the expert designer or forward searches of available design routes. This is an area of further research.

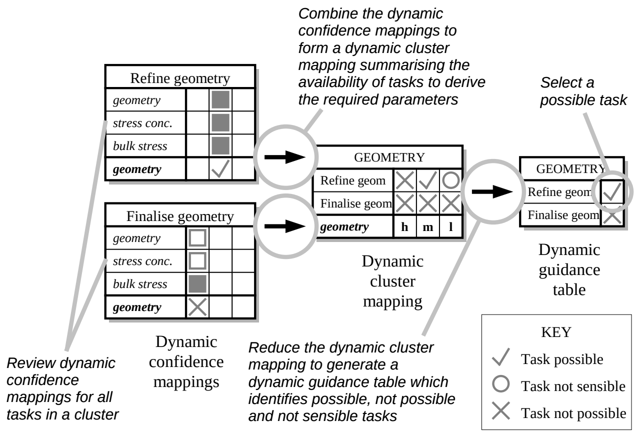

Figure 8 Signposting the next task

The tree structure adopted for a particular design process is not critical since clustering only serves to reduce the apparent complexity of the problem. Indeed, there may be many appropriate clusterings for a particular process.

This lack of formality in clustering has another benefit. When new tasks are added to the model, so long as they appear at least once in the model, they will be made available to the designer. This flexibility allows the designer, in principle, to add new tasks without needing to know their 'position' in the overall design process. Indeed, a new model could be created a task at a time using this approach.

5 A Case Study

The following case study serves to illustrate the application of signposting to a simple mechanical design task.

5.1 Introduction

Consider the design of a simple mechanical component, such as a spanner, which is subject to a number of external loads in use. The design of the component involves the definition of geometry such that the applied loads result in an acceptable level of stress.

Important design parameters are the geometry (G), the applied loads (L) and the level of stress. The later may be described by the bulk, or average, stress (B) and a stress concentration factor for geometric discontinuities (C). These parameters are interdependent, with the geometry dependent on the stress and the stress on the geometry.

This is illustrated by the parameter dependence matrix shown in Figure 9 which assumes that a single task exists to determine each parameter. Here each row identifies the parameters required to determine the parameter identified by the row label. For example, the geometry and loads are required to determine the bulk stress.

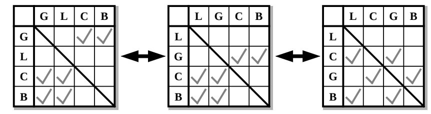

Figure 9 Parameter interdependence

The parameters cannot be reordered (see Figure 9) to break this interdependence, which is a common problem in design. However, if an additional parameter (G_1), and by implication an additional task, are introduced to represent an estimate of the final geometry (G_2), then the parameter dependence may be reordered to define a sequential design process. This is illustrated by the lower diagonal matrix in Figure 10.

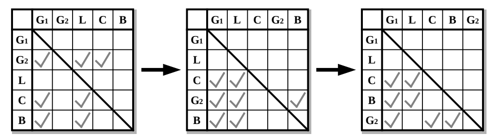

Figure 10 Parameter dependence

A lower diagonal matrix implies no task interdependence [Eppinger et.al. 1994], but only task dependence. Also, since the diagonal just below the leading diagonal is not fully populated, the design process will possess a number of alternate design routes (see Figure 11).

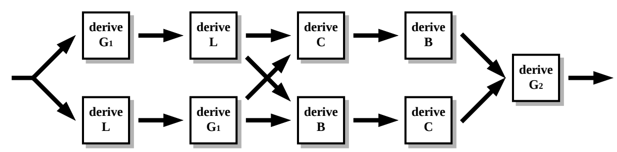

Figure 11 Parameter sequence

Signposting will only be successful if task dependence is characterised by a lower diagonal matrix. If this is not seen to be the case then more tasks will need to be defined.

5.2 Signposting example

A more complete investigation of the design of a simple mechanical component requires the identification of further design tasks. Table 1 shows a number of tasks related to the estimation and refinement of the component geometry, applied loads, bulk stress and stress concentration.

Table 1 Geometry definition tasks

	Task	Output
1	Sketch geometry	Component geometry
2	Refine geometry	
3	Finalise geometry	
4	Estimate loads	Applied loads
5	Analyse loads	
6	Simulate loads	
7	Visual check on stress	Stress concentration
8	St Venant's principle	
9	Initial FE analysis	
10	Initial check	Bulk stress
11	Stress analysis	
12	Final FE analysis	

Corresponding confidence mappings for these tasks are shown in Figure 12. The tasks are clustered according to the parameter they derive. Note the table layout is the same for all the mappings.

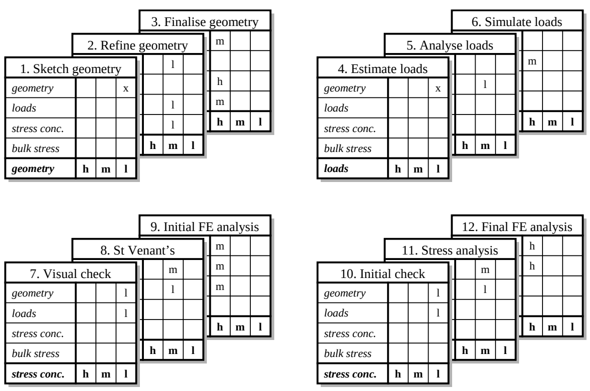

Figure 12 Confidence mappings

These tasks may also be viewed in terms of task precedence (see Figure 13), which is in essence a further development of Figure 10. A matrix, which initially suggests task interdependence, can in this case be reordered to show serial task dependence. However, as in the simpler example above, there may be many possible design routes (see Figure 14). In particular, there is significant flexibility in the evaluation of the loads.

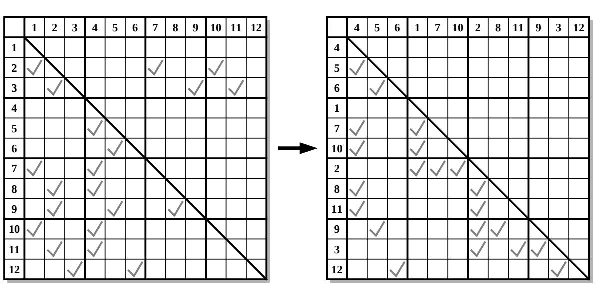

Figure 13 Task precedence

The specific design route chosen will depend on many factors, including: task cost, task duration, resource availability, process management, etc. The identification of an 'optimal' route is still the subject of further research.

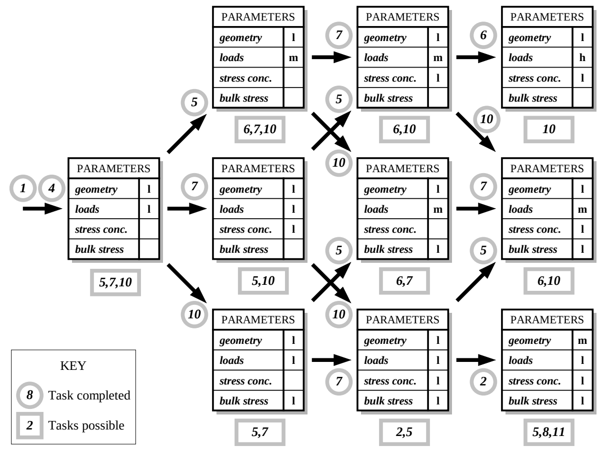

Figure 14 Examples of possible design routes

5.3 Guiding the designer

Signposting identifies possible tasks in a dynamic design process. A key factor in this identification is the communication of the resultant guidance to the designer. The traffic lights described in Section 4.3 provide a simple and intuitive interface based on a notional hierarchy of the design tasks.

Figure 15 illustrates the derivation of the traffic light colours from the current parametric state of the design. The process begins with the current parameter confidences. These are checked against the confidence mappings for each task to identify possible design tasks. The tasks are clustered by parameter, with Figure 15 showing only the geometry related tasks. For each cluster a dynamic guidance table is formed and these are finally reduced to a single guidance table for the whole process.

For the example shown two tasks are possible: refining the geometry and simulation of the loads. This is presented as available tasks related to geometry and loads.

Figure 16 shows the situation following the successful completion of geometric refinement. The confidence in the geometry has been increased. Two tasks are possible: simulation of the loads and stress analysis. Note that the designer sees only the guidance tables and is unaware of the internal workings of the signposting tool.

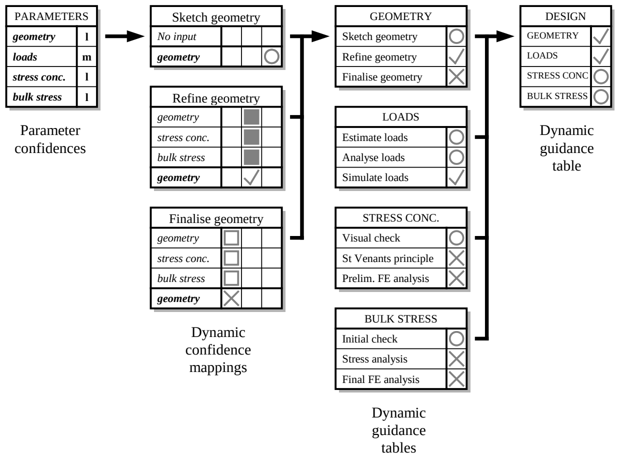

Figure 15 Example of signposting in action, I

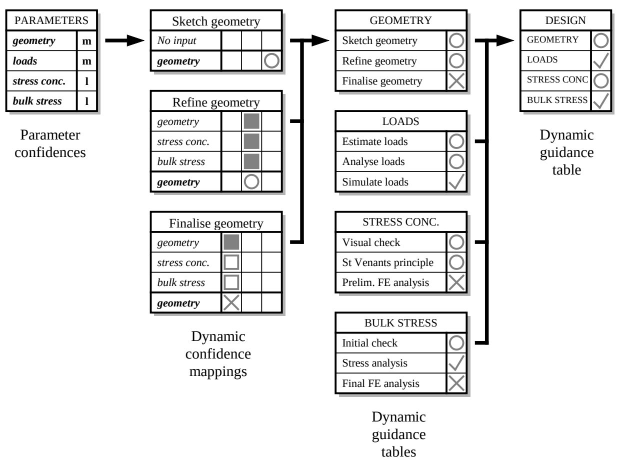

Figure 16 Example of signposting in action, II

Finally, it is interesting to note the difference approaches to using signposting where there are task choices to be made. Figure 17 shows three possible task sequences. The head of each arrow indicates the parameter, and its associated confidence, which has been generated by a particular task.

The first illustrates an incremental approach where all the parameters are progressively estimated and refined. This suits a simple process where most the activities are carried out by a single designer. Alternatively, a discipline driven approach may be used where a particular parameter is refined as far as possible at every opportunity. This suits a complex process where activities are distributed amongst a number of designers.

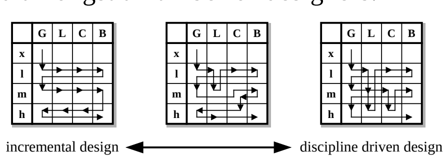

Figure 17 Task sequences

6 Conclusions

A signposting model has been described in which the confidence in key design and performance parameters is used as a basis for *signposting* the next task. The model is based on the assumption that the design process may be thought of as a series of tasks concerned with the identification, estimation and iterative refinement of key design and performance parameters, until a sufficient level of confidence in those parameters is achieved.

The use of a task-based model of the design process is not a novel idea. Eppinger, in particular, has applied Stewards' Design Structure Matrices to a number of design processes to great effect. However, such methods require a prior understanding of the precedence relationships existing between the tasks which is not easily elicited. This paper proposes that the introduction of a confidence parameter into such a technique allows a dynamic task-based model of a particular design process to be constructed without pre-prescribing the order in which the respective tasks should be performed.

The application of *signposting* to a simple design task illustrates its potential. Much further work is under way to improve the signposting approach and move towards a the dream of an 'optimum' design process.

Acknowledgements

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