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ONE FOOT IN JAIL: MITIGATING THE INFLUENCE OF ERRORS ON THE OUTCOME OF DESIGN PROCESSES FOR INDUSTRIAL PLANT

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1. What is expected of us in the making of Engineering Decisions?

One foot in jail is a sentiment felt by engineering designers from the moment they sign their first design contract. The rest of their working life is spent keeping the other one out. Apart from the obvious origin of this sentiment in judicial systems, the situation has been aggravated by opposing demands from the market, such as increasing product complexity, increasing customer expectations, decreasing life cycles hence decreasing design times, and decreasing development budgets, as has previously been reported [Hubka 1991, and others]. These demands lead to the temptation to cut corners and make judgements and assumptions where good analysis could otherwise find better solutions.

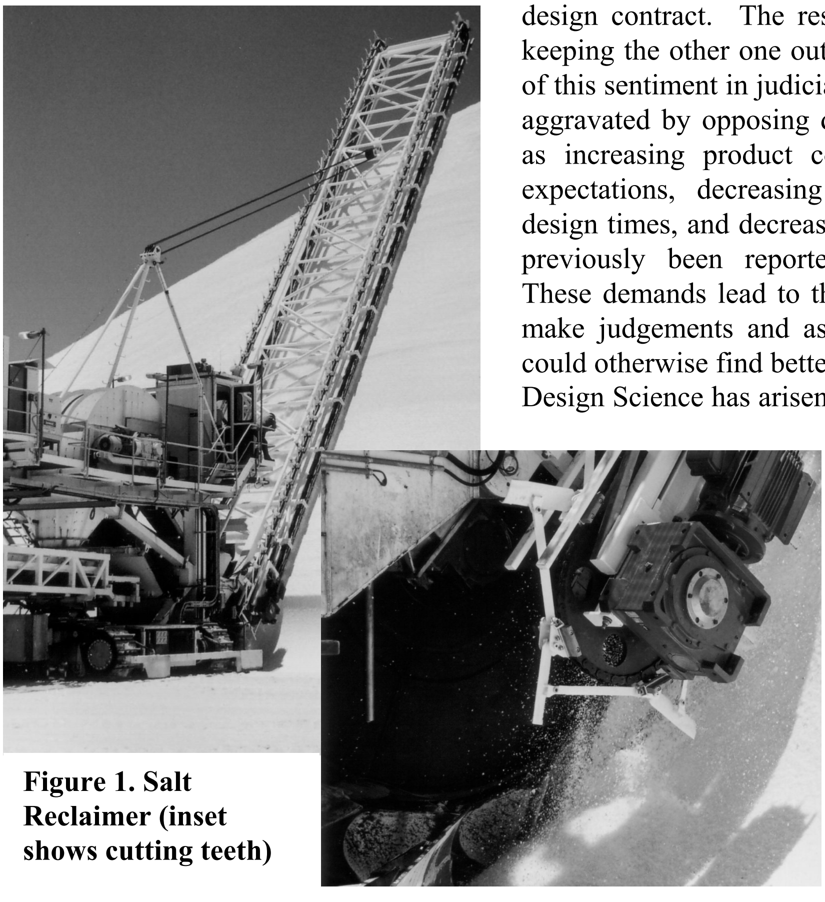


Figure 1. Salt Reclaimer (inset shows cutting teeth)

Design Science has arisen over the last few decades, either as a response to or as a line of defence against, the difficulties associated with these pressures.

That body of research aims to meet the challenge by understanding the way designers design and by developing methods and processes that allow the designers to improve their design performance and productivity.

As an ultimate goal for that research, Wallace proposed that an 'ideal' design process could be imagined, which is systematic, adaptable and flexible, and is performed by the 'perfect' team that results in the 'best' product.

> *"This ideal process would start by identifying a true market need. A perfectly balanced team would then undertake an effective and efficient design process using the most*

> *appropriate methods and tools, including ultra sophisticated and integrated VR simulation, supported by rapid prototyping. Prior experience, along with all the relevant process and product knowledge, would be instantly available in the right form through 'instant' communications. All decisions would be 'correct' and result in the best possible product definition and, eventually, completely satisfied customers."*
> *[Wallace 2000]*

Wallace's ideal of implementing all decisions correctly is of particular interest to the designer of cranes and of mobile machines for the continuous handling of bulk materials. This is a particularly onerous field since these designs are custom developed, each time to unique specifications, with tight monetary and time budgets and without the benefit of any prototypes. Thus, opportunities for detecting and correcting errors from the design process are extremely limited.

Figure 1 and Figure 2 show examples of the type of machines that are designed by a design office owned by one of the authors (HM). The Salt Reclaimer (Figure 1) is a novel design used to scrape hardened salt from a stockpile at a rate of 2000 tonnes per hour (tph). The 26m long rake is fitted with 200 heavy duty teeth which are driven by a 2" chain in a fashion similar to a trench digger. The machine weighs around 110 tonnes and took approximately 1,400 hrs to design.


Figure 2. Coal Ship Loader (4000 tph)

The Coal Ship Loader (Figure 2) is more conventional, but was nevertheless designed to a unique specification. It has a mass of around 360 tonnes, consists of about 15,000 listed parts and took approximately 13,000 hours to design in detail. The joys, trials and trepidation seemingly inherent in the design processes conducted for the supply of these and other machines, are the source of ongoing reflection and have motivated this research.

The size and complexity of these machines, and the nature of the contracts used to supply them, mean that many thousands of decision have to be made rapidly. These decisions are made under a variety of decision environments, with a varying range of constraints arising from the set of preceding decisions, and require a varying degree of skill and creativity depending on the availability of existing designs for the particular design task at hand. This is yet a far cry from the ideals of Wallace.

Moreover, since the economics of such development processes do not permit prototyping, the final outcome of the design process is all the more dependent on the accuracy of decisions made. Any inaccuracies manifest themselves in reworking and redesigning costs during the fabrication and commissioning stages, but also extend into the life of the machine where they can potentially lead to catastrophic failures under unexpected circumstances. To ensure the most accurate possible outcome, design offices use a number of formal and informal methods, including CAD modelling, full checking processes (in contrast to estimating accuracy using statistics from partial checking), tight document control and auditing of the design by independent experts.

Despite these elaborate efforts, or because of tradeoffs with resource pressures, or both, errors continue to occur, resulting in corresponding rework together with the associated anxiety felt by designers due to the risks of consequences that are not just potentially costly, but also potentially tragic.

The present article describes the first part of a research effort being conducted by a group of practicing design engineers, and aims to address the effects of engineering decision errors, either by reducing the error rate itself, or the effects of error rate, through improved design processes, process planning and/or design method selection.

It is important to emphasise here that the focus of the research is not on any understanding of underlying principles of machine design, this understanding is assumed, but on the need to work through a mountain of engineering decisions in a time that is limited, and not altogether that large, and with a need to make these decisions with a surprisingly high degree of accuracy.

In considering methods to improve design accuracy, we need to understand why experts in the field continue to make errors at a rate that influences the outcome of their design processes, even when they have already designed similar machines in the past. After conducting a count of the number of decisions being made, it was found that when designing these machines to an appropriate Australian Standard (AS4324.1, similar to ISO5049.1) the designer makes approximately 34 independent groups of decisions per part [Mayer et al 2001]. Given that a typical ship loader may have as many as 15,000 parts, this constitutes an immense number of decisions that all have to be made during the design phase of the machine. After giving consideration to what may constitute an independent group of decisions, and applying statistical tools, it was estimated that, for a typical 5% development contingent to be adequate, the designers can afford an error rate in the order of 1 error per 300 decision groups.

Clearly, with such a perspective, it is no surprise that even the most knowledgeable and experienced machine designer must expect some impact of errors on the outcome of their design.

2. Present Literature

Reason (1990) describes insights by a vast body of research from cognitive psychology whose focus of study are Human Errors. Cognitive psychology divides (genuine) errors into basically two types, being **i)** slips and lapses and **ii)** mistakes. For practical purposes, slips and lapse are defined as errors leading to incorrect actions when correct actions were intended. These typically relate to human performance in clearly defined (hopefully), highly proceduralised and even well practiced processes. Mistakes, on the other hand, are errors resulting from judgements and assumptions that are made incorrectly, leading to actions that may execute as intended but carry a failure consequence as an outcome (pp 9). Mistake type errors are more subtle, more complex and less understood than slips and, as a result, represent a far greater danger. They are also more difficult to detect and tend to arise from management decisions and design processes, resulting in latent errors whose influence remains undetected for some time, perhaps years. The study of slips and lapses has significant implications for designers, and there is an opportunity to adapt insights from the man-machine interface to the designer-pencil interface in order to ensure a design environment with a minimal affordance for error. However, by definition, design is a process that is variable and undefined and therefore the bulk of error potential lies with the mistake type error. Cognitive psychology deals with this error as an undetected latent error in terms of its interaction with the performance of systems and the human operators when the influence of the error contributes to the precipitation of an accident. That is to say, while the efforts by cognitive psychology contribute significantly to the design of complex systems in an effort to design those systems for better compatibility with the human operator, there is little guidance, if any at all, for the designer of that system who has to avoid the making of mistakes while tackling the mountain of engineering decisions with limited time and resources.

The making of engineering decisions is thus in the realm of decision theory and design methodology. Regarded as definitive authors on the state of the art in designing heavy mechanical equipment, Pahl and Beitz offer a thorough look at the methods and processes available to the modern designer and give guidance on how these can be applied in practice [Pahl and Beitz 1997].

Their design process is divided into four broadly defined phases: **i)** Planning and Problem Definition, **ii)** Conceptual Design, **iii)** Embodiment Design and **iv)** Detail Design, as described in Table 1. The terminology used there has been adopted throughout the remainder of this paper.

Table 1. Summary of the phases of design by Pahl and Beitz (1997)

Product Planning	Conceptual Design	Embodiment Design	Detail Design
Evaluate the environment; Define the problem and constraints; Generate and Select Product Ideas	Establish working principles and functionality; Generate and Select Solution Principles.	Engineer the form of the solution; Size and define all parts prior to detailing.	Detailed preparation of design documentation, including drawings and manuals

Pahl and Beitz propose the use of classic decision theory for the development of global solution principles to the problem at hand and endeavour to *proceduralise* the decision processes during the later phases as much as possible by offering catalogued solutions and checklists. Although many authors have lamented, and continue to lament, the lack of industry uptake of the methods proposed by design science [Frost 1999, Gouvinhas and Corbett 2001, Upton and Yates 2001, to name but a few], it is our experience that the methods and their application, as described by Pahl and Beitz, do broadly reflect the methods used by designers of bulk handling machinery. Possibly, this indicates a heritage in heavy industrial equipment design by those designers, which is also shared by Pahl and Beitz

However, neither this literature nor industrial practice adequately deals with the present problem, being the rapid making of many decisions particularly in the more highly constrained decision environments during the embodiment design phase. That is to say, the embodiment design phase is heavily constrained because global solution principles have been set, preceding design decisions and other technical constraints must be considered without error or omission, and time budgets and monetary budgets are set. It is also noted that existing methods do not adequately deal with this decision environment because they typically assume the availability of **i)** generous decision making resources, **ii)** appropriate tabulated solutions, and/or **iii)** prescribed calculation procedures. These are generally not so readily available and, as a result, novel and unique solutions must nevertheless frequently be found, and be found creatively.

At the same time, Pahl and Beitz do not offer, and do not purport to offer, a complete list of available methods. Some further, well known methods, which are described and discussed by design science include such methods as six-sigma, knowledge management, artificial intelligence, C-Quark and many others.

To conclude consideration of present theory, we have at our disposal insights from cognitive psychology that allow us to minimise in our design process, an affordance for error from slips and lapses, and we have numerous design methods and decision theory from design science to help with certain types of decision environments. However, these studies do not cover the variability in decision environments which are regularly encountered by the practicing designer, and there is a need to understand this variance and provide guidance on how engineering decisions may be adequately handled in the various environments.

3. Research Objectives and Methods

However much cognitive psychology has studied the making of errors and has contributed to the recognition of their reality and thus their ability to be managed, the practicing designer is faced with one sided expectations of design quality, and is therefore forced to deal with a notion of errors that sees them as being unforgivable lapses that should not occur. This further leads to them not being acknowledged for the design process, and so prevents their effective management in design processes. It also makes it difficult to devise effective treatment of the various decision environments with suitable methods.

Accordingly, the scientific method selected for this research in the long term is to

i) On the basis of experience and observations, re-conceptualise the design processes and decision environments within which engineers endeavour to manage their error outcomes.

ii) Describe planning and/or execution methods for the design process in a form in which they may be implemented in real design tasks, in order to provide a work environment which minimised unnecessary opportunities for both laps and slip type errors and mistake type errors.

iii) Treat these methods as hypotheses and test them through observations of real design tasks.

iv) Apply, if necessary, more rigorously controlled experimental conditions which may be required to answer specific questions, arising from the use of the method in the real design tasks.

This paper focuses on task **i)**, and proposes a conceptualisation of decision environments which more clearly describes the difficulties that need to be addressed by design methods. This conceptualisation is presented in a form that makes it suitable for the evaluation of the error risks associated with a particular design task. Design process planning can so be more efficient in identifying the type of design methods to be employed by the design team for the various design tasks. The characteristic map allows for consideration a method's capacity to deal with the potential error types arising from the tasks and so methods may be selected not just for their efficiency in generating design solutions, but also for their efficiency in helping the designer to affect that solution more accurately.

Integral to the overall study is a study of the types of errors that tend to be made in design processes for industrial machinery, as well as what their potential effects may be. A case study has been conducted for this purpose, and further studies are being conducted, the insights from which are being developed for publication elsewhere.

4. Differences between the Environments in which we need to make decisions

From the perspective of practicing engineering designers, the missing information in all of the present theory is the acknowledgement of the fact that a mountain of decisions has to be got through and that these decisions are to be made under many different working conditions, or decision environments. While the methods proposed and discussed in academic circles typically consider the need to apply a good, possibly rigorous, process to the way decisions are made under its regimen, they tend to consider the decisions one by one and make little differentiation, if any, between the circumstances imposing their influences on the designer. For example, the product planning and embodiment design phases are quite distinctly different in nature.

While considering, evaluating and selecting solution principles during the product planning phase, much effort is placed in the making of a few, globally important decisions. In this environment, there are few constraints placed on the decision, and those that are derive from the perceived market need or customer's specifications.

In contrast, further down the line during the embodiment design phase, many more decisions must be made. The bidding process is typically completed with the Concept Design phase (before the embodiment phase), at which time the supply budgets are all set, including those for the design process. The budget decisions will have been made on the basis of a heavily abbreviated and largely estimated decisions and assumptions. The decisions in the embodiment phase are then driven by numerous constraints arising from all decisions made before them, and they must be made rapidly, and now without error or omission. The reality is that a formal process of generating solution principles, evaluating alternatives and selecting the final solution for each single decision, (or group of decisions) will take much more time than is available, and will not necessarily lead to an optimised solution since a synthesis of solutions is called for rather than a sequence of rigorously executed individual solutions.

In other words, although decision theory provides systematic methods for the solution of problems, these methods are not necessarily practical to apply over the range of decision environments in which the designer has to work, who, on account of these differing decision environments, requires methods employing distinct treatments for the various categories of decisions made in the distinct environments.

5. What are these Decision Environments and how do they influence the decision process?

Although a knowledge of the differences between design phases may make the notion of distinct decision environments obvious, the design phases are by no means the only source of the distinctions. From a knowledge of how machine design is generally conducted, there are significant differences between the way certain decisions are made within each one of these phases. Moreover, these differences seem to be most strongly related to two particular characteristics that may be present at any one time. These are **i)** the level and type of constraints bearing on the decisions, which is closely related to the design phase and can therefore be expressed in terms of it, and **ii)** the level of skill and creativity needed to make the decision. From experience we hypothesise that these two characteristics are more or less independent of each other. Hence, we will represent these characteristics in two separate dimensions.

In this way we hope to express the decision characteristic of any one design task in terms of these two characteristic pressures on the decision environment on a two-dimensional chart. The objective is to identify the nature and extent of the associated difficulties we are likely to face in terms of financial and practical risks, and of risks for potential consequences from errors. Once so identified, we can then take steps to systematically manage these risks.

It would be possible to identify design phases in terms of the categories of Pahl and Beitz, but we have concluded from experience that their “embodiment design” phase contains within it two separate phases that are distinct from each other in terms of the thought processes and skills we use to conduct them, and this is due in part to differences in the constraints on the individual decisions or decision groups. We will use the categories of Pahl and Beitz but introduce this split when developing the chart described above and have called the two new phases “embodiment design of systems” and “embodiment design of features” for the reasons given as follows.

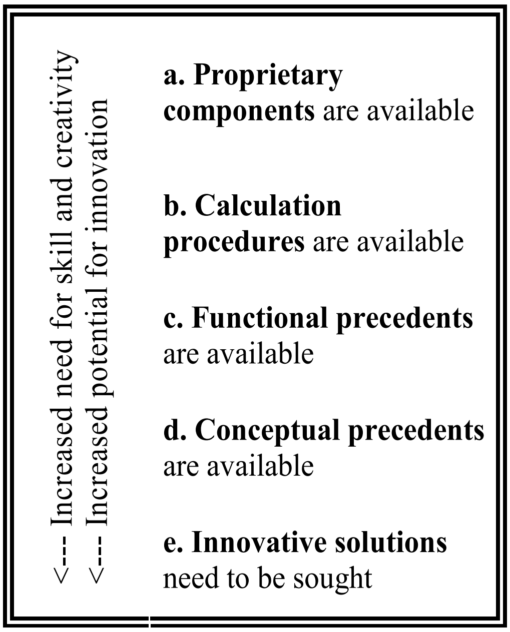


Figure 3. Relationship between Precedents

When designing during the embodiment phase, we generally embody the system first and engineer it, and subsequently embody the system’s features. So, for example, we may undertake the design of a structural system first, and then do the member connections and interfaces with other systems - the system’s features. For mechanical systems the work may be somewhat more integrated, but we nevertheless start with the design of the mechanical system and finish the phase with the decisions concerning localised features. The distinction arises because the constraints on the system are different from those on the localised features. In either of these two phases, as in any phase, we may be able to use standard calculation procedures to make decisions or be required to make decisions creatively in order to find appropriate solutions, and each combination of design phase and creativity leads to its own distinct characteristic decision making environment.

We now have the design phase axis of our chart articulated and we are left with a need to describe the skill and creativity called on to make particular decisions within each phase. Clearly, we will be entering a hornet’s nest if we endeavour to measure and express creativity for different design tasks. Nevertheless, a perspective is offered here, which may be clearer to those who know the German word *Konstruction*, and understand its distinction from it’s English counterpart – *Design*.

If we focus on the need to creatively decide how something will be done (more like *Konstruktion*), rather than what can be done (more like *Design*), then we can express the need for creativity in terms of what is available to the Designer within his design domain by way of *precedents* - being the information of which he may become aware, readily, during his design process. Different precedents have different types of relevance to the design task at hand and will require various levels of creative adaptation to apply to the design task. We can divide these into the following 5 categories of precedents, which quite aptly describe the type of adaptation that will be required, and are summarised in Figure 3. The figure describes the increasing requirements of skill and creativity the further the precedent becomes removed from the actual item being designed. Conversely, the closer the precedent, the better it is to rely on it. There is a strong trade off between the ease and rapidity of procedural calculation and the benefits available from innovative problem solving. It is prudent to decide at the beginning of the design task, which systems will be dealt with procedurally, and which, on the other hand, will enjoy the attention for innovative solution principles.
A more detailed description of the precedent levels can be as follows, described in terms of a platform travelling hoist drum as an example.

a. A **Proprietary component** which is adapted to the application by making a selection from a range of sizes and features using procedures defined and published by the supplier. The procedure can be quite succinct since it applies only to the particular product in question, and help may even be available from the supplier to make the selection. The engineer needs to have an understanding of the physical concepts driving the selection so that this selection is understood and peripheral decisions surrounding the part may be made appropriately. For example, if there is a platform travelling hoist to be designed, the engineer may choose to use a ready made hoist which is selected from such parameters as SWL, hook path, utilisation, and so on.
b. If an off the shelf hoist does not suit, then the engineer may refer to a number of standards which offer various **defined calculation procedures** that could be used to design hoist components. For example, when designing the drum shell, such a procedure is available to determine the shell thickness, the shape of grooves if these are used, and so on. Although the idea of having a defined procedure to make the decisions is the same as that for the proprietary item, these procedures are more general in application and are more specific to the features to which they apply. Hence, the engineer must have a sound understanding of the procedure and its parameters so that they are applied correctly within the hoisting system.
c. Because the defined procedure is general in application and more specific to the features to which it applies, having chosen to design their own hoist means our engineer will have many more decisions to make and, more importantly many for which the standards do not provide the desired procedures. When he comes to mount the drum shaft, he will find that he is on his own to decide about insertion strategy, hub dimensions, diaphragm shape, thickness and reinforcement, welding strategies and so on. To his delight, he finds in the office a drawing of a winch drum previously supplied by the company for a similar purpose. He now has a **functional precedent** to work with. The reasoning behind the features and assembly shown on the drawing is the same as for his own application. He is left with defining the load cases and verifying the adequacy of the precedent to his application before making appropriate modification, if this is necessary. It is now important to understand the reasoning behind the decisions represented on the precedent drawings and to ensure that intents and assumptions are retained through any modifications implemented. Thus, the required understanding and creativity is greater than for level b.
d. It may be that he discovered instead, while researching the precedent in his design domain, that the drawing was used to represent a conveyor belt pulley, rather than a hoist

drum. The idea is the same in that we have a drum rotating on bearings, using shell, diaphragm and hub to transmit loads between the shell and the bearing mounts. However, some of the basic parameters are different. The pulley rotates faster while the hoist applies its loads differently and may be utilised differently. Also, safety considerations and standardisation requirements are different. Nevertheless, load transmission, assembly and sealing strategies may be usefully transferred. The precedent is not quite functionally the same, but the concept may be used. It is a **conceptual precedent**. The engineer must fully understand the requirements surrounding hoist design and may transfer some of the ideas in the conceptual precedent for application to his hoist drum.

e. He may discover, however, that the design in the precedent used inadequate welds between the drum shell and diaphragm and used outdated shaft insertion methods understood on the basis that the company had difficulties previously with that design. If we say also that our engineer was unaware of the wisdom available from Pahl and Beitz (not to mention any of the other literature available on hoist design), then we do not even have a conceptual precedent and our engineer is required to find **innovative solution** principles. It is not only important to understand requirements, but he must now also be aware of engineering principles on a more fundamental level and must be able to assess the suitability of solution principles in his application, including the potential difficulties that may be experienced with the intended operating parameters, and any associated hazards.

This system of categorisation provides a ready method of assessing the novelty of individual components of an overall design task. For example, when assessing the work required to design a ship loader, the design task is typically broken down system by system by sub-system by component, etc., until we have a list of individual design tasks, each of which can be assessed for the work that needs to be done for it. An excerpt of such a breakdown is shown in Figure 4. The resulting summary provides us with a description of the overall effort required for the supply of the design, which can be used in developing the two-dimensional chart.

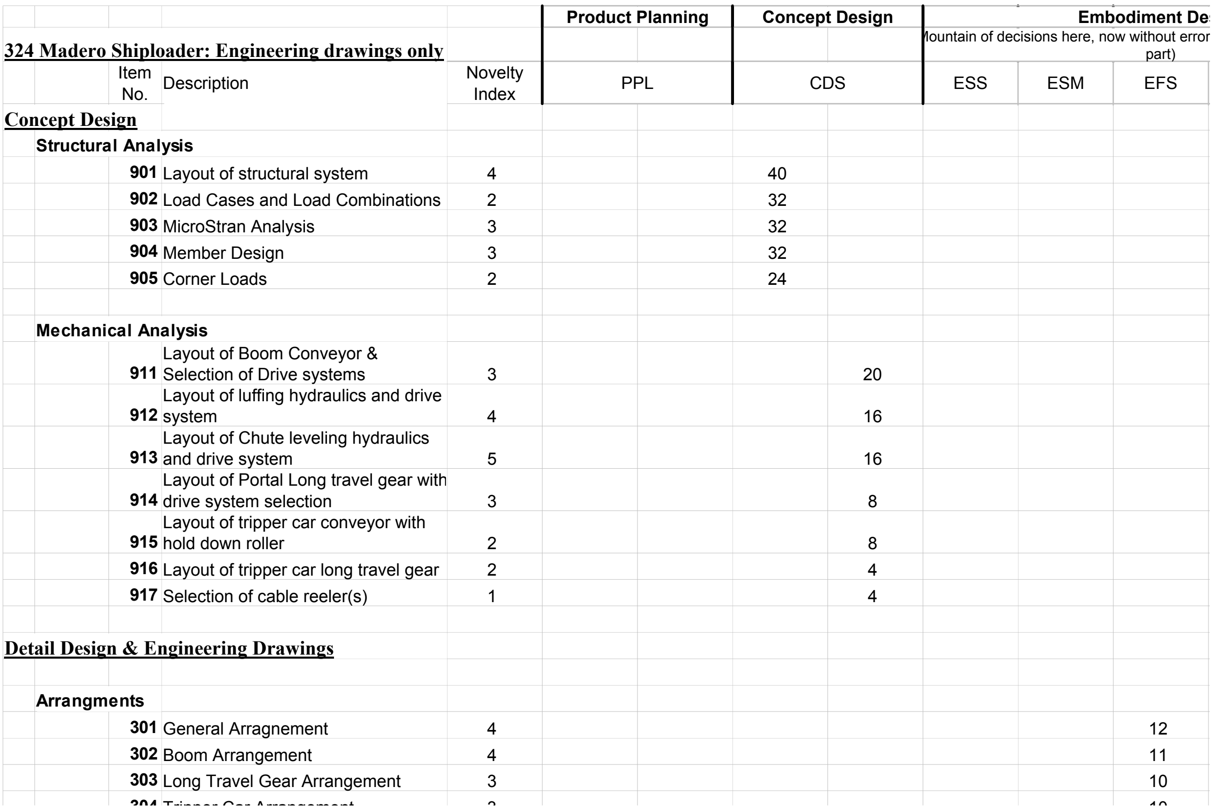
6. Application of the Decision Characteristic Map

We propose a two-dimensional map with design phase as one dimension and precedent available as the other. Figure 5 shows the proposed two-dimensional map. This map serves as the basis for representing the various components of the design Task.

On reviewing Figure 5 it may be noted that the level of constraint is represented by the Pahl and Beitz design phases on the left, with the additional distinction between systems and features embodiment. The level of skill and creativity is represented by the precedent categories across the top. For example, were we to consider the design of next year's Ford Falcon, generally a derivative of this years model, then the bulk of the design work would be conducted in decision environments represented from the top right of the map to the bottom right. In contrast, when the Mini Minor was being developed, several new concepts required development, including the constant velocity joint, which we now take for granted. This design work would, more probably, have been conducted about the left hand side of the chart. Where many components are being designed, a mix of old and new may result in a more even distribution over the chart. This chart gives an immediate impression of the nature of a given project.

When evaluating the resources required to conduct a design job, the first step is to assess the systems to be designed and the degree of novelty that will be present. Using the Characteristic decision map, we have an opportunity to represent this visually with immediate impact.

To begin the process, the design task is broken down into its components to a level that allows for easy evaluation of resource required, as is standard practice.



324 Madero Shiploader: Engineering drawings only

Item No.	Description	Novelty Index	Product Planning PPL		Concept Design CDS		Embodiment De lountain of decisions here, now without error part) ESS	ESM	EFS
Concept Design									
Structural Analysis									
901	Layout of structural system	4			40				
902	Load Cases and Load Combinations	2			32				
903	MicroStran Analysis	3			32				
904	Member Design	3			32				
905	Corner Loads	2			24				
Mechanical Analysis									
911	Layout of Boom Conveyor & Selection of Drive systems	3				20			
912	Layout of luffing hydraulics and drive system	4				16			
913	Layout of Chute leveling hydraulics and drive system	5				16			
914	Layout of Portal Long travel gear with drive system selection	3				8			
915	Layout of tripper car conveyor with hold down roller	2				8			
916	Layout of tripper car long travel gear	2				4			
917	Selection of cable reeler(s)	1				4			
Detail Design & Engineering Drawings									
Arrangments									
301	General Arragnement	4							12
302	Boom Arrangement	4							11
303	Long Travel Gear Arrangement	3							10

Figure 4. Excerpt from design resource estimation data

The ideas behind the characteristic map have evolved from ongoing reflection of our design experience and form the basis of an endeavour to address the issues associated with undetected errors. What the overall effect of this technique is on the outcome of the design process is yet to be determined.

However, it is clear from experience that, when methods are being developed, it is important to take account of the fact that decisions are being made by engineers in very different environments from day to day and that, therefore, the methods need to differentiate between those environments.

Figure 4 shows a brief excerpt from a design task estimation sheet. The design task is broken down into the various work steps that need to be taken and these are typically based on calculations and drawings. Level of skill and creativity likely to be required is identified within the column headed *Novelty Index*. This column is a number allocated to each of the precedents. Here, any work step for which a proprietary item is to be selected and purchased, is allocated a '1'. At the other extreme, any work step which required an innovative solution, or for which an innovative solution is sought, receives a '5' for the Novelty Index. By allocating a Novelty Index for each row, we have made the assessment of the level of novelty we will need to deal with for this overall design task.

We then estimate the number of hours needed for each design item in each design phase and write down this number in the appropriate field. The fields across the top (such as Product Planning, PPL) represent work codes allocated for each design phase. For clarity, not all fields are shown in the figure 5.

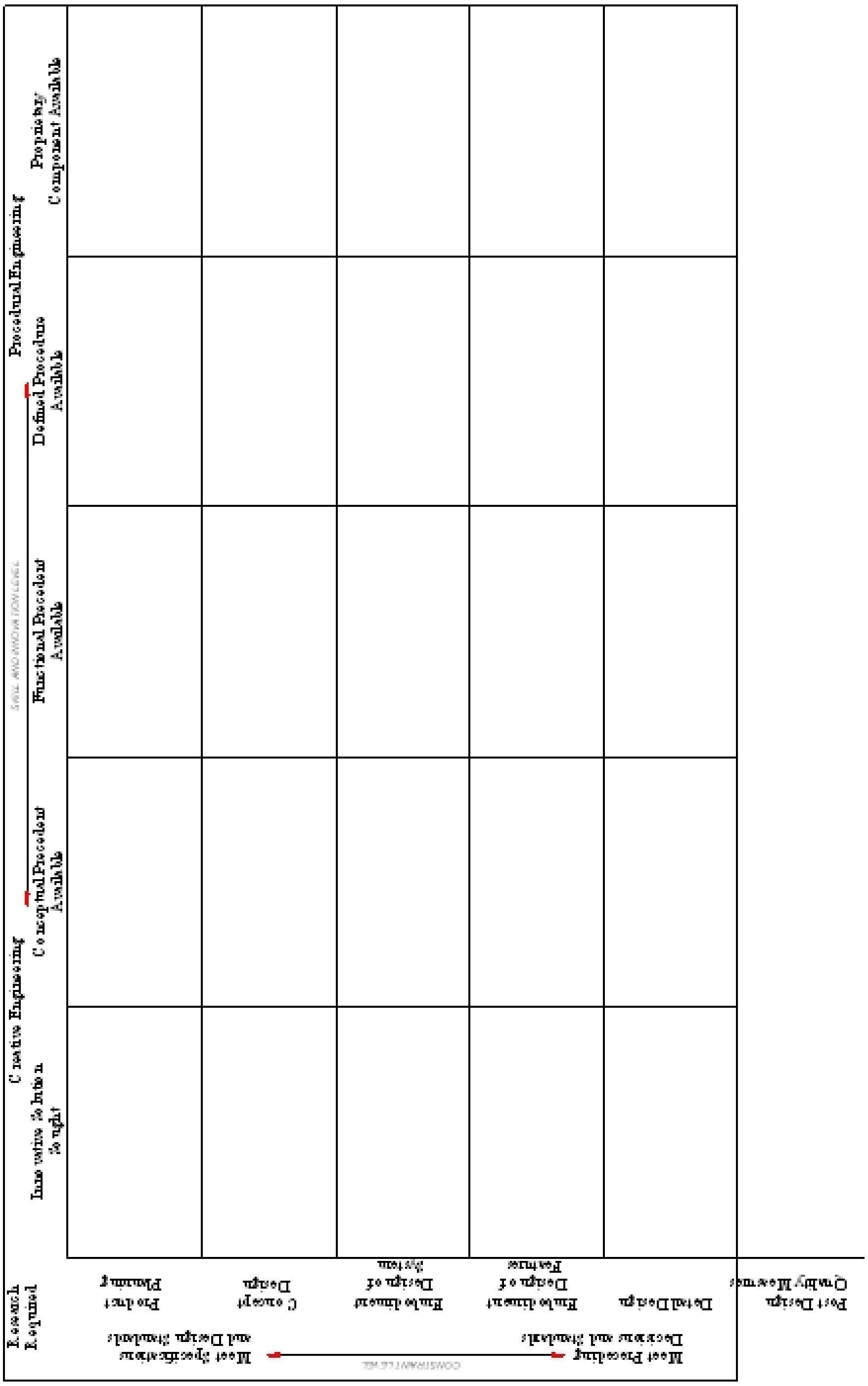


Figure 5. Template for the Characteristic Decision Map

In the process of estimating the number of hours required, we can already have regard to the fact that some design items require a high degree of novelty and it is therefore prudent to budget extra time to complete those tasks. It is prudent to multiply the number of hours originally estimated for any item which requires a novel solution, by a factor of at least π.

We can now map this information to a characteristic decision map by taking account of the novelty index and the number of hours estimated for each design phase for each design item. The resulting chart is a two-dimensional frequency distribution representing the number of hours estimated in each field of the map.

Various strategies can be used to make the representation, with the aim of achieving a quick visual understanding of the decision characteristic of the task at hand. Colour plots and colour contour plot, such as are used to represent the results of FEA stress analysis, give good results.

7. Discussion and further research

The plot as described above provides a visual representation of the type of decision environments in which the bulk of the work for the design task will be conducted. This information provides an important foundation for further assessment.

1. Most significantly, the information provides an overview of where the risks lie for the effects of errors which may remain undetected by the design process. For example, the type of errors that will be made during the detail design phase with defined procedures being available are very different from the type of potential errors while working during the concept design phase without a precedent
2. The map (Figure 5) clearly shows where the resources need to be allocated and what skills these resources need to have.
3. In the future, the aim is to select suitable design methods to meet the requirements of the various decision environments that may be prevalent on the characteristic map, thus avoiding the allocation of sparse resources where they are not needed.
4. By combining the above analysis with an understanding of the type of errors that need to be expected in each component of the design, an educated estimate can be made of the type and level of contingent which needs to be budgeted in the contract chain.

Again, various strategies are available to make the necessary representations for these assessments. One good method is to create overlay maps of the various risks to be assessed and to compare them with the job's characteristic data. Such assessment can then also be made numerically. The type of strategy to be used may depend somewhat on the design task, as well as the design office which uses it, and the particular industry it may be applied in.

To assess the effect of the characteristic map, such a map will be created and used in our design office at every opportunity in the next few years, and observations will be made in the office, on the work shop floor and on site. The data collected will include the number and type of errors being found, and the influence they actually had, and/or potentially could have had. Also, comparisons will be made between the hours estimated for a job and the hours actually logged, including the characteristic field in which they were logged.

The aim of collecting this information is primarily to improve techniques used to estimate resources for design tasks, which are, by their nature, difficult to predict. Secondly, by more accurately, and more specifically, estimating resource requirements, it should be possible to reduce the potential pressure on designers due to time overruns. It is not hard to hypothesise that such pressures contribute to rushed decisions that result in incorrect or ill considered decisions. It also provides a powerful basis from which to negotiate the need for contingents (allowance for rectification) with customers.

8. Conclusion

From the perspective of practicing engineering designers, the missing information in the present design theory is the acknowledgement of the fact that a mountain of decisions has to be got through, while minimising errors and omissions to a manageable level, and that these decisions are to be made under many different working conditions, or decision environments.

Our objective is to describe and implement a working environment which will enable design engineers to minimise errors. Given that making no errors in these circumstance would be miraculous, we are aiming to draw extraordinary performance from ordinary mortals, such as us.

The proposed characteristic decision map provides a tool with immediate visual impact, with which the risks of errors, and other difficulties, can be assessed on the basis of the decision environments in which the decisions are to be made, so that they can be managed.

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