Integration of Reliability-Based Assessment Techniques into an Advanced BMS

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ABSTRACT

This paper outlines the 15-year bridge assessment programme which is currently being completed in the UK and highlights a number of problems which have been experienced. A continuous increase in vehicle weight, volume of traffic and deterioration of the bridge stock combined with a diminishing availability of funds for repair and maintenance has therefore resulted in an increased interest in bridge management.

A framework for an advanced bridge management system is presented. The framework has a modular format and includes components for dealing with inspection, data collection and storage, deterioration modelling, structural assessment, economic appraisal of maintenance, repair and rehabilitation (MR&R) actions through whole life costing, work programme optimisation methodologies and a number of reporting facilities.

Of primary importance in the bridge management process is the assessment of structural adequacy. A concept of bridge assessment at different levels, Levels 1–5, is introduced and it is explored how the proposed framework accommodates the two main types of assessment arising from this concept.

INTRODUCTION

In the UK there are some 9,500 bridges on the motorway and trunk road network and a further 100,000 bridges on local roads. The majority of bridges on the trunk road network were built between the mid-1950s and the late 1980s using, in eighty percent of cases, concrete as the main structural material. A large proportion of these bridges are now suffering from durability problems, many of which are a result of the generous use of de-icing salts in the past. Likewise, although the bridge stock on the local network is quite different in terms of both the age of the structures and the mix of material and construction types in that it includes a larger percentage of more traditional forms such as masonry brick arches and steel or wrought iron structures, it is the maintenance of these structures which poses the most significant problems faced by today's bridge engineers. What is required therefore is an approach to bridge management which is both flexible and versatile.

While in service all of these structures have experienced a constant increase in both vehicle weights and traffic density. The latest increase in vehicle weight was initiated when the European Council of Ministers adopted a directive in 1984 establishing a gross vehicle weight of 40 tonnes as opposed to what was then a limit of 38 tonnes and what had previously been 32.5 tonnes. The UK negotiated a derogation from this directive until 1 January 1999 and so, in order to ensure the adequacy of the trunk road network by this date, a 15-year assessment and strengthening programme was launched in 1987. During this period the intention was that all bridges on the trunk road network would be assessed against current standards so that any structures which failed to comply could be strengthened and upgraded as necessary.

Some years into the programme it became obvious that, due to continuously decreasing funds for bridge maintenance and repair and the large number of structures which were failing, either because they had been designed prior to the introduction of the standards which were being used or because of deterioration, it was going to be impossible to attend to all the deficiencies identified during the 15-year programme before the deadline. The decision as to which repairs to tackle within the given budgetary constraints was therefore both demanding and complex and in a desire to meet this challenge demand grew for a rational and consistent methodology which would enable bridge managers to prioritise works and allocate their scarce funds efficiently among a multitude of urgently needed tasks.

This paper describes the development of a bridge management framework which includes two different levels of structural assessment, deterministic and probabilistic. From the use of the respective assessment results more informed maintenance and management decisions are expected.

ASSESSMENT OF STRUCTURAL ADEQUACY

Current Assessment Practice

The assessment of structural adequacy is of crucial importance to the bridge management process. In the UK special assessment codes for concrete, steel and steel composite bridges have been developed (*1,2*) for this purpose. These assessment codes follow the respective design codes closely, although they do include some relaxations because it was felt that using the more rigorous design codes for assessment would lead to some bridges which have safely been in service for many years failing assessment unnecessarily.

The assessment of an existing bridge can be carried out in stages of varying sophistication. Given the large number of bridges that need to be assessed a simple, and therefore quick, check is the best approach in the first instance. If a bridge passes this check then there is no cause for concern, whereas in the case of failure a more precise approach is needed if the assessor is to be sure that the structure is really inadequate. The concept which is going to be adopted by the UK's Highways Agency is therefore to use 5 different levels of assessment, each level of which is more sophisticated than the preceding level, thereby, in theory, giving a higher level of precision. First proposed by Das (*3*), these 5 levels have subsequently been implemented into a departmental advice note (*4*) and can be defined as:

Level 1: In which simple analysis methods and code specified material properties are combined with the full values of partial factors given in the Standards;
Level 2: In which more refined analysis and better structural idealisation (e.g., grillage analysis, FE analysis) are used;

Level 3: In which the same analysis methods as in Level 2 are used but additionally structure specific material properties and loading can be included;
Level 4: In which modified partial safety factors are used to account for any additional safety characteristics specific to the structure being assessed;
Level 5: In which structural reliability analysis is used directly and, instead of partial safety factors, uncertainties in the design parameters are modelled probabilistically.

Detailed guidance for carrying out Level 1 to 3 assessments is available in the form of standards and advice notes contained within the Design Manual for Roads and Bridges (*5*). However, no such guidance is available for Level 4 and 5 assessments as yet. Work is currently in hand to produce recommendations which will enable assessing engineers to undertake assessment to these advanced levels with limited help from experts. This paper will demonstrate in particular how these advanced assessment methods can be successfully used within a bridge management context.

Levels 1 and 2 are fully deterministic, which is to say that the loads are derived from worst possible traffic conditions and codified, nominal values are used for strength parameters. Level 3 aims to be more structure specific by allowing the use of 'worst credible' values for material strengths derived from samples obtained from the structure. The opportunity to derive bridge specific assessment live loading (BSALL) is also given in Level 3, which can, for example, be beneficial for long span bridges with low traffic flows.

To provide the necessary safety against failure, a single set of partial safety factors is applied to the nominal values of the design parameters, which guards against extreme variations of these parameters. In order not to over-complicate design and assessment rules for routine use, the values of the partial safety factors have been chosen such that they cover a wide range of failure modes, components and structure types. By implication these rules consequently tend to be conservative for the majority of bridges.

Adaptations Needed

Recent studies (*6,7*) have shown that, for a given bridge and/or component type relatively uniform levels of safety can be achieved by this approach. However, due to the wide variety of bridge types covered by the code the level of conservatism can vary significantly between bridge types, and, in some structures which are significantly different from the norm, levels of safety can be unduly high. This is acceptable at the design stage because it ensures that a certain minimum level of safety is met or exceeded in every new bridge. The additional cost which might be incurred due to some bridges being over-designed is negligible. However during assessment this over-conservatism can lead to bridges being unnecessarily strengthened at great expense.

The main responsibility of any bridge manager is to ensure public safety and survey results (*8*) suggest that there is indeed a strong desire to meet this obligation. What is sought is an efficient procedure for prioritising competing projects using safety considerations as the main criteria, while at the same time ensuring that the chosen remedial actions are economically feasible and deliver value for money.

FRAMEWORK FOR THE BRIDGE MANAGEMENT PROCESS

Faced with the challenge of how to manage a stock of ageing and deteriorating bridges efficiently under today's onerous traffic conditions and within the given budgetary constraints, a number of computerised systems have been proposed. These systems, collectively named Bridge Management Systems, have been developed with varying degrees of sophistication. Early systems were mainly databases which stored information collected during inspections together with inventory data such as the location of the bridge, road category and the construction date of each structure. Then, over time, more functions have been produced and systems have been developed which enable the user to undertake activities such as inspection planning, deterioration prediction, structural assessment and the economic evaluation of repairs.

A recent survey of bridge managers responsible for much of the English and Welsh road network, including both trunk roads and local roads (*8*), was aimed at identifying the real requirements of those involved in the day to day management of a bridge stock. When asked about the importance of a number of criteria to the prioritisation of maintenance, repair and rehabilitation (MR&R) works all respondents (100%!) purported to consider the safety of the structure when addressing this issue. This seems to be in sharp contrast to the approach taken by many BM Systems which base their recommendations as to the order in which to tackle competing projects mainly on the degree of deterioration of the structure. A condition index of some sort is assigned either to individual elements within the structure or to the structure as a whole during inspections and an algorithm is used, in most cases a Markov Chain process, to forecast future condition at given time intervals if no remedial work were done.

A study investigating the safety levels inherent in different types of bridges (*9*) demonstrated that similar bridges designed to the same standard end up with a range of initial safety levels because of variations in the materials used, the quality of workmanship and practical limitations such as the availability of only certain diameters of reinforcement. Hence some bridges have a greater reserve of strength than others and will, even after a certain amount of deterioration or increase in loading, still be safe, while others will become critical more quickly. It can also be perceived that bridges without any noticeable signs of distress might nevertheless be at risk, for example, due to the original material specifications or the initial design requirements being inadequate. Examples of this are the early (pre-1970) shear design rules for reinforced concrete elements, which have since been significantly improved and the use of ASR (alkali silica reaction) prone aggregate, which is now prohibited. Affected bridges might not have developed any signs of distress because they have not yet encountered their worst loading conditions. Nonetheless they are potentially at risk, a risk which needs to be assessed and which, if found to be unsatisfactory, demands that refurbishment and strengthening actions be considered. The implication therefore is that sound structure management needs to be based on safety requirements rather than observed or measured deterioration alone.

Traditionally bridge management procedures used to be based on deterioration and a purely deterministic assessment of strength. In the UK the Highways Agency recently reviewed the entire approach to bridge management key activities such as inspection, assessment and prioritisation and following this review a need was recognised to base MR&R decisions on the actual safety of a bridge rather than its load carrying capacity alone (*10*). A consistent yet flexible methodology is therefore needed which clearly identifies those bridges most at risk. And this process needs to be embedded in a comprehensive bridge management framework.

Based on this need a framework (Figure 1) which includes both deterministic and the newly developed probabilistic assessment methodologies is proposed and, in the next section, this paper will explore how the results of both types of assessment can be used to obtain a more rational and consistent prioritisation of MR&R works.

Bridge management is a dynamic and constantly changing process. Key parameters such as the available budget, repair and maintenance technology and the traffic pattern on certain routes are subject to constant change and political and environmental pressures shift priorities from time to time. In order to allow for this dynamic nature a modular basis was chosen for the framework which will help to make the bridge management process more flexible and open to new developments and changes in direction. Smith et al. (*11*) comment that many of the existing systems suffer from problems resulting from the lack of a unique framework for system development. Without a suitable framework in place the different parts of the system which are developed independently can generate serious difficulties when combined together and will most likely fail to produce the desired results.

The approach taken here was to develop the modular framework first and, based on the results of the user survey (*8*), core requirements were specified for each of the modules. The advantages of the modular format are a greater degree of simplicity and clarity in the design of the system. Each module performs a specialised function and, when combined, a number of modules cover the entire bridge management process starting with inspection planning and the collection and processing of the inspection results to the final decision of which projects to tackle and the design of actual work programmes. A clear advantage of this approach is that the implementation of the system can be done in stages. This accommodates the typical problem encountered by many authorities that a lack of staff and resources makes it difficult to find sufficient time for the initial entry of data or the transferral of data from previously used systems. Depending on the user's requirements it is also possible to use only some of the modules to assist with certain tasks without necessarily adopting the system as a whole. This again provides maximum flexibility.

In relation to the research and development which is constantly taking place into bridge management techniques, the modular design also lends itself to being easily updated. New developments in any of the areas can be introduced by simply replacing the existing module with a new one. In order for this approach to work smoothly, however, clear rules need to be established concerning the type of data which is being passed between the different modules, the data format, data storage and processing rules and the design of matching interfaces.

As can be seen in Figure 1, the system is composed primarily of five main parts: An inspection and inventory section, the central system manager, a structural and economical assessment section, an optimisation section and an outputs section.

The inventory and inspection section is intended to deal with the planning and scheduling of different types of inspection and the storage of inventory data. For example, depending on the type of inspection routines used these modules could present

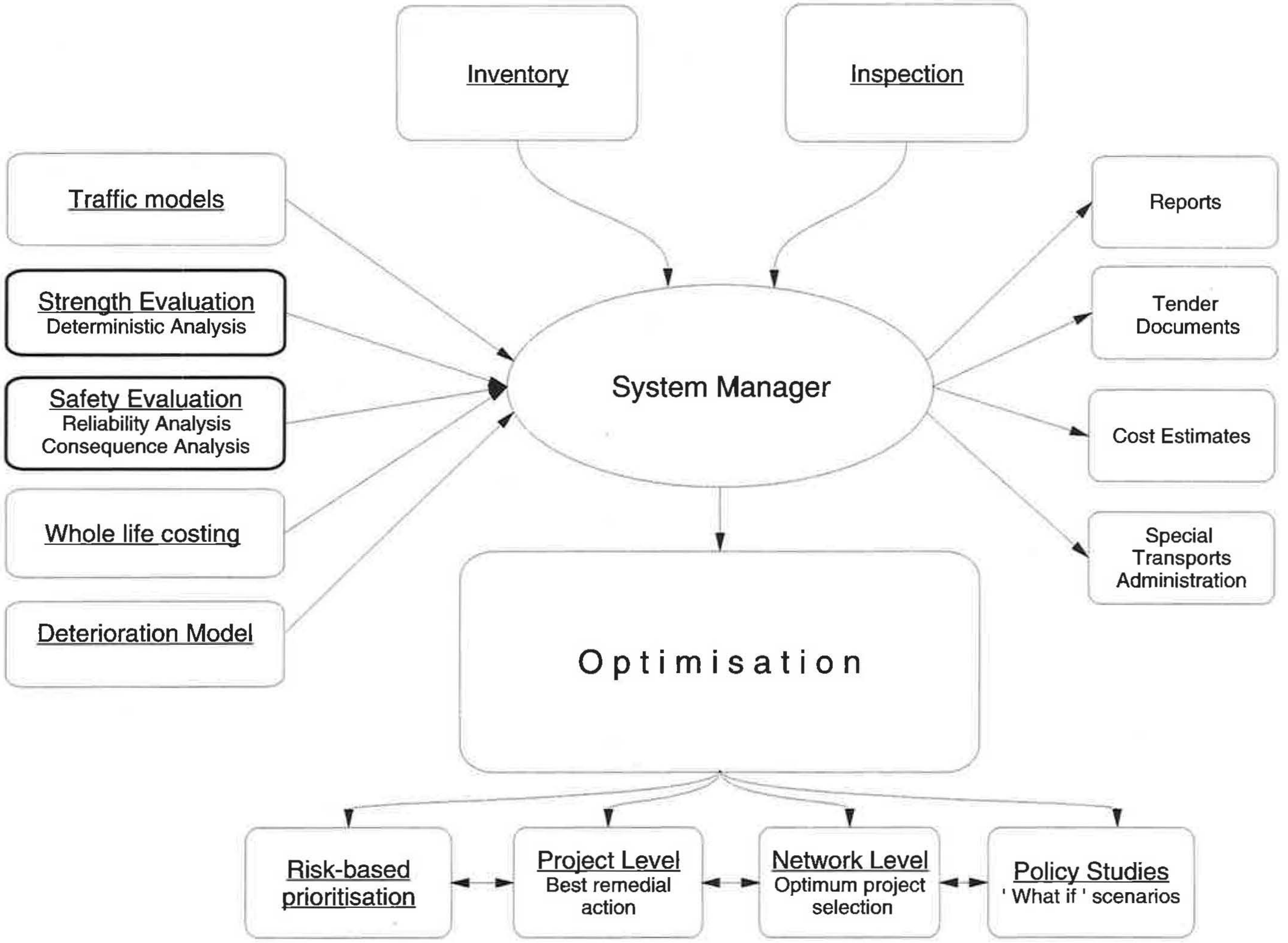

Figure 1: Conceptual framework of BMS.

inventory data in different formats such as text based information, photographs or drawings, retrieve data collected during inspections, calculate condition indices or monitor the development of defects over time.

The central 'system manager' will store and manage the systems data. It can be thought of as a type of database which will manage the data flow between the different modules. No actual calculations or any other form of data processing should take place inside the system manager and it should function purely as an intermediate step between the different modules by storing the results from one module and then, when required, providing it as input data for a second module.

It is also proposed that there should be a number of individual assessment modules dealing with aspects such as the identification of load carrying capacity, which will be explained in more detail later, the modelling of deterioration, whole life costing of different remedial options and bridge specific traffic modelling.

The optimisation section will contain a number of key modules which will use the output from other modules to produce a range of recommendations based on the decision criteria selected by the user. On the project level the optimum repair strategy for each bridge will be identified and if required these projects will be prioritised according to a set of criteria defined by the user, the most important of which is normally the available budget. Other criteria such as the importance of the bridge within the network, user delay costs and the cost benefit ratio of a repair can also be considered. Depending on the user and how much automation of the decision process is wanted different optimisation algorithms can be used. Possibilities range from somewhat simple cost-benefit ranking methods through multi-criteria decision algorithms to linear programming methods.

PROBABILISTIC ASSESSMENT

The safety of a structure depends on a multitude of uncertainties in load and resistance parameters as well as on other factors such as gross error, the occurrence of freak events, poor workmanship, etc. Structural reliability analysis offers a valuable tool by which these uncertainties can be modelled and a structure specific probability of failure calculated.

Structural reliability methods are now well established and readily available; however they have, so far, mainly been used in industries such as the off-shore and nuclear industries and their application to bridge engineering is relatively novel.

From previous applications of structural reliability analysis it is well known that the results, i.e., the computed probability of failure, are highly sensitive to both the input data and the chosen computational method. When probabilistically modelling the uncertain variables, the type of probability distribution and the distribution parameters such as mean values and standard deviations significantly influence the outcome of the analysis. A variation in the calculation procedures for load effects and element or structure resistance can also create different outcomes.

Bearing in mind what it is intended should be achieved from the use of these advanced assessment levels, namely the identification of those structures within a bridge stock which are most at risk and to allocate available funds in the most efficient manner, it is essential to generate results which allow the comparison of one structure with another. In the past it has been found that reliability assessments carried out by different engineers have not been consistent and the need to standardise the reliability analysis procedure for bridges has therefore been identified. On behalf of the Highways Agency such guidelines for Levels 4 and 5 are currently being developed.

In order to achieve consistent and comparable results it is desirable to have detailed guidance concerning the following aspects:

- For which type of structure and failure mode(s) benefits can be expected from the use of advanced assessment Levels 4 and 5;
- Probabilistic modelling of the basic variables;
- The formulation of limit states where the limit state describes the failure state of the structure, for example, bending failure or buckling of steel members;
- Methods for the calculation of load effects and element resistance;
- The calculation of system capacity;
- Computational methods for the calculation of probabilities of failure;
- Target reliabilities; and
- The interpretation of the results and their use for prioritisation purposes.

The last point is essential because at this stage most engineers have only a limited knowledge of structural reliability techniques, and in order to achieve the maximum benefit from the results it is important to interpret them correctly. It is, for example, important to stress that the calculated probability of failure (PoF) has no absolute meaning. A value of say 10^{-5} does not mean that one bridge in every 100,000 will ultimately fail. This is because firstly there are not 100,000 similar bridges in the stock and secondly, since PoFs only reflect the degree of confidence there is in the structure given a certain level of knowledge about the actual loads and the structure's resistance, they can only be considered to be notional numbers. However, providing a number of bridges have been analysed in a consistent way, it can be said that a bridge with a PoF of 10^{-5} has a higher likelihood of failure than one with a PoF of 10^{-7}. Therefore they can be used effectively to rank a number of bridges in terms of their safety. Should the bridge manager wish to do so, this ranking can be used directly to allocate funds to the bridges with the lowest level of safety. However, in most cases the final decision as to which bridges to attend to will be a result of a number of factors such as safety, cost and benefit of the repair. The next section suggests a prioritisation method which combines safety with cost to derive 'risk.'

RISK-BASED PRIORITISATION

Consider a bridge that has failed the deterministic assessment and has subsequently been assessed using the Level 5 method. It could well be that by modelling all the uncertainties related to the loads and the resistance of the structure it can be shown that the overall risk faced by the bridge is very low, in which case no strengthening work is required and the bridge can safely be left in service. If, however, the calculated level of safety is considered insufficient remedial action has to be taken. The problem which then arises is, if funds are limited and there is more than one structure with similarly low levels of safety, which should be upgraded first? If one is part of a heavily trafficked motorway while another is on a secondary route which carries less traffic, it may be anticipated that priority would be given to the former. This however may not be the most appropriate course of action.

The failure of any structure will have dramatic consequences including potential injury, loss of life, significant costs associated with rebuilding the bridge and, particularly in the case of the former, traffic disruption caused while the bridge is out of service. While, however, the failure of the bridge on the secondary road is less likely to cause injury or loss of life due to the limited number of users, it may cause significant disruption to a local community and vital emergency services may be forced to take large detours. The difficulties faced when trying to combine these different factors are immediately obvious. In order to make a rational decision in such cases a reasonable way of combining the likelihood of failure with the potential consequences is needed. To do this, the use of 'risk' as a measure is now widely accepted where risk can be defined as:

Risk = Probability of failure × Consequences

Consequences can be of different types and 4 main categories are normally distinguished:

- Human, i.e., personal injury or loss of life;
- Financial, i.e., the cost of rebuilding the bridge;
- Environmental, for example spillage of dangerous goods or pollution of rivers; and
- Economical, i.e., costs, such as traffic delay costs, incurred due to the loss of service of the bridge.

For each of these categories methods are available by which the appropriate costs can be estimated (*12,13*) although it has to be acknowledged that some costs, for example, those due to environmental damage, are difficult to quantify.

Using the definition above, a risk score can be calculated for each bridge and a number of bridges can then be ranked in terms of their respective scores. For a calculated probability of failure of, for example, 10^{-5} for two bridges with consequences of £1,000,000 and £250,000, respectively, where for simplicity it is assumed that these figures include only the reconstruction and traffic management costs, relative risk scores of 10 and 2.5 can be calculated. This demonstrates how relative priorities can be established in a rational way by accounting for both the safety of the bridge and the various consequences of failure. The order of projects from such a ranking reflects the relative importance of one project over another and can be directly adopted by the bridge manager to allocate funds to projects with high risk scores. Alternatively such an approach can be used to validate a suggested list of priorities which has been derived through another form of optimisation.

As opposed to most existing BM systems where the user is given a 'ready-to-use' list of prioritised projects which is the result of some form of economical optimisation, the framework which is proposed here will allow the user to generate a number of such lists, each depending on different criteria. In addition to a list based on risk scores the user could, for example, have a list which only uses the probability of failure and which in turn, to include the necessary economic aspects, could be complemented by another list which is based on the cost/benefit ratio of possible repairs. Existing systems have often been criticised for leaving no room for engineering judgement and many members of the bridge management community have felt strongly about the fact that a computerised system could not replace the human bridge manager with all his experience and knowledge of his bridge stock.

The proposed framework is different from most existing systems insofar that it offers a number of different ways in which structures can be assessed and subsequently prioritised for maintenance work. The traditional deterministic assessment methods, Level 1–3, can be used and the calculated load carrying capacities which are normally expressed via the live load capacity factor k can be fed into existing prioritisation or optimisation programmes. If however, the safety of the structure and the associated risk of failure are considered more important, the advanced assessment methods of Levels 4 and 5 can be applied and the calculated probabilities of failure used to derive the risk of failure. Ranking of structures for maintenance can then alternatively be done in terms of safety only, i.e., through the probability of failure, or in terms of risk, which additionally includes the consequences of failure.

The proposed system offers a great degree of flexibility in which the bridge manager can decide whether to follow a standard method, for example, where an optimisation algorithm is used, or can choose a number of different criteria such as safety, risk or a cost/benefit ratio and rank all structures in terms of these criteria. Based on these various rankings it can then be seen how a particular bridge performs in relation to different criteria which should encourage well-informed maintenance decisions.

CONCLUSIONS AND RECOMMENDATIONS

These days bridge managers have to deal with an increasingly deteriorating bridge stock on one hand and a shortage of funds for maintenance on the other. Faced with the complex decision of which MR&R projects to tackle within the given budgetary constraints there has been a strong demand for a rational and consistent, yet flexible and versatile, approach. This paper addresses two key issues in the bridge management process, the assessment of structural adequacy and the prioritisation of competing MR&R projects. The main conclusions are:

- A bridge management framework is presented which allows the new reliability-based assessment techniques which are currently under development to be included in the bridge management process.
- The proposed framework enables either traditional deterministic assessment techniques together with existing ranking methods or advanced assessment techniques to be used, allowing a prioritised list of structures requiring refurbishment to be derived based on a set of user defined criteria.
- Risk is identified as a useful criteria for ranking purposes because it combines the safety of the structure and the consequences of failure.
- The system is highly flexible and a central system manager is proposed to store data which can be used by a number of modules.

- Engineering judgement, which is still considered important by many practising engineers, can be used to compile priorities based on a number of lists each of which ranks projects according to different criteria.
- The proposed framework encourages informed decisions thanks to its ability to use a number of prioritisation criteria chosen by the user.

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