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Managing risks to structures

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Structural engineering has changed markedly over the last decades, creating new challenges and new opportunities. Consequently, structural engineers are widening their thinking from just technical issues to the effects of other matters on the risks to their structures. In particular there is a need to find better methods for integrating hard and soft risks. Hard systems are physical and technical matters traditionally dealt with by engineering science. Soft systems involve people and include matters traditionally dealt with by engineering management. In order to make improvements, engineers have to combine good-quality evidence from disparate sources, both technical and from wider issues. The current paper demonstrates how disparate evidence can be measured and combined using interval probabilities drawn as colourful 'Italian flag' indicators of risk. Process models are used to map the progress of projects. An Italian flag is associated with each process to indicate the level of dependability, based on all the information available at the time, that the process will be successful, which is to reach the stated objectives. A new method of pairwise combinations is described and used to calculate the flags through the entire process model. An example of the procurement of a building is used to illustrate the method.

1. INTRODUCTION

Structural engineering has changed markedly over the last decades. Not only are new powerful computational tools available, but there are different challenges such as terrorist attack and the impact of climate change. Consequently there is a much greater awareness of the need to deal explicitly with risk in all aspects of life. A key difficulty is how structural engineer decision makers integrate information from many disparate sources to manage the risks to structures; this is the central topic of this paper.

2. INTEGRATING HARD PHYSICAL RISKS WITH SOFT 'PEOPLE' RISKS

In many projects, accountants manage the known financial risks well, the engineers manage the known technological risks well, the safety specialists manage the known health and safety risks well, the quality managers manage the known processes well and so on. Major problems, however, even in successful companies, seem to arise in the gaps between these specialisms, resulting in unknown and unintended complications such as cost and time overruns and consequent quality problems. Even within specialisms, however, a range of techniques may be used to assess different aspects of risk which are difficult to integrate. The problem to be addressed in this paper is how to facilitate good balanced decisions to manage all of the risks and hence minimise unintended harmful consequences: in short to improve the ability to do 'joined up' thinking across a fragmented industry.

Hard systems are physical systems that are commonly said to be 'objective' in that they are supposed to be independent of the observer and hence the same for all of us. Hard systems are the topic of traditional engineering science. Soft systems are, as the name implies, systems that are difficult to define—the edges are unclear. Generally soft systems are governed by the behaviour of people, which can be complex. Soft systems are the topic of traditional engineering management. The emphasis in soft systems is not therefore on prediction, but rather on managing a process to achieve desired outcomes.

Processes are the way things behave in hard systems and what people do in soft systems. All designed hard systems have a function. For example a beam in a structure has the function of carrying the loads from the floor slab. A dam has the function of holding back the reservoir water. The steel and concrete of which the beam and the dam is made does not 'know' it has that function—it has no intentionality. The function is ascribed to a hard system by the people who own it, conceive it, design it, build it and use it. This function can therefore be perceived as a role in a process. Part of defining that role is to decide the criteria of failure. This is done by different people from different points of view and may be contentious. Clearly some functions are obvious; others are less clear and unintended. For example a bridge designed to carry road traffic was almost certainly not designed to be used as a shelter by homeless people. In one case the cost of repair to concrete damaged by the fires lit by homeless people to keep warm under a bridge was substantial.

In summary all designed hard system processes are embedded in one or more soft system processes.

3. PROCESS MODELS

A process model is used as the integrating structure on which everything else is built.[1] There are many views of what

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constitutes a process. Most people use the word to distinguish the form of the 'doing of an activity' from the content which is the output, for example a product. Here a new way of thinking about a process is applied, which does not separate form and content. This new concept of what constitutes a process is much richer than an input transformed into an output, a recipe, a Gantt Chart, a network or a flow chart, although it can be simplified down to each of these if required. In this methodology each process is seen as a holon, that is it is both a whole and a part at one and the same time. It also has emergent properties,[1] from systems theory, that arise out of the complex interaction of the parts. The relationships between processes are captured in a process map and then each process individual process is used as a 'peg' on which to attach all other data and information. The process map therefore sets out the basic structure of a project and all of the data associated with it. The traditional separation of process from product is lost because, by this view, a process can be the 'doing of an activity' or the 'performing of a physical system'—the structuring of the information is the same for both.

In order to use this idea the map of the interconnections has to show how processes relate to each other. This is the purpose of a 'project progress map' (PPM): it enables various data such as risk registers, structural calculations, project progress measures and so on to be integrated. As stated above, the processes in the PPM form a central spine or skeletal structure on which all data and attributes are attached.

A product is the output of a process. It is useful to keep these two ideas of product and process quite distinct because it is useful in defining what the clients perceive they are buying. It is important to understand that, because products do things and exist through time, products are also processes seen from this wider perspective.

The process holons are arranged hierarchically in layers. Initially the whole system is described as one process: the 'top' process and the top layer. Obviously to achieve success of this top process many sub-processes have to be successful and these are the second layer. For the sub-processes to be successful some sub-sub-processes must be successful and this continues down to a level of detail as appropriate for the particular system. It is important to realise that this is not reductionism because the many interactions between processes at the same layer are recognised and modelled as far as they are understood. For example time relationships can be included using a standard critical path network analysis.

Each process is monitored to keep it on a path to success. Success is defined by a set of precisely stated objectives. Every process should have a process owner, that is a person who is responsible for delivering success of that particular process. Parameters and performance indicators of the process are monitored to keep them within required bounds and to provide evidence of trends that need remedial action. In this way unintended consequences can be identified early. Thus at any given time during a process evidence is available from past and present performance and predictive analyses about the future can be used. The words 'who, what, where, when, why and how' are formally used to capture and record information for appropriate sharing with authorised other people. In this way each and every process is steered to success based on up to date integrated information.

4. MEASURING EVIDENCE OF PERFORMANCE USING AN ITALIAN FLAG

A key idea of the methodology is to find evidence that any given process is moving towards success and there is no build up of difficulties that might bring about failure. Opportunities for improvement should also be located. The evidence will come from many sources of various types and there is a need to collect it, digest it, interpret it, learn from it and make decisions using it.

In order to have a measure of evidence that can be used in soft as well as hard problems it is necessary to assess, quite separately, the evidence in favour and the evidence against the proposition that a process is heading for success. This can be conceived of in several ways. One way is as a vote by a group. Another is as an individual responsible judgement—a kind of internal vote. A scale of [0, 1] is used as a measure of evidence in favour and evidence against. The degree of evidence that a process is heading for success is coloured in green, as shown in Fig 1.

Evidence against is also assessed on a scale [0, 1] and is coloured in red starting from 1 and working back to zero. The difference in the middle is white and represents incompleteness—the extent to which we do not know. The three colours together make the Italian flag.

An all-green flag means that there is complete evidence for and no evidence against (no red). An all-red flag means that there is complete evidence against and no evidence for (no green). An all-white flag means there is no green evidence for and no red evidence against and so we really 'do not know' or indeed have no view.

Figure 2 shows a simple model of a process with two sub-process holons, the successes of which are together necessary and sufficient for the success of the top process. The players who own each process associate an Italian flag with that process. The flag represents their view, based on evidence, that the process will be successful. Clearly there is something wrong in Fig. 2 since the flags are inconsistent in a rather blatant way for the purpose of the example. This means that when the process owners realise this inconsistency, they can discuss the reasons for it and decide on adjustments or on what needs to be done to improve the chances of success.

Until recently the flags were used entirely qualitatively as described in Ref. 1. Now a new algorithm developed for the purpose of propagating the flags mathematically is described. Certaiin constraints and assumptions need to be appreciated, however, before the method is used. The new algorithm is implemented in two 'sister' pieces of software called PERIMETA

Fig. 1. An Italian flag

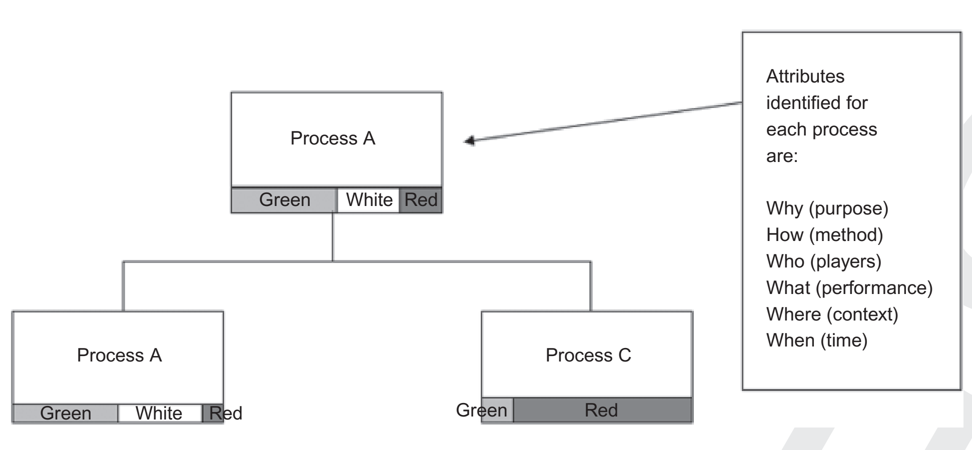

Fig. 2. A simple map of three processes. Note: The Italian flag of evidence for process C indicates that it is very likely to fail. Unfortunately the evidence available to the owner of process A indicates that it will be successful. If process C is necessary for process A then the two process owners need to sort out the reasons for their differing perceptions

(performance through intelligent management) and JUSTISE (joined up systems thinking for integrating synergy in engineering).

5. THE MATHEMATICS OF ITALIAN FLAGS

An Italian flag is defined mathematically as an interval probability—so the probability of an event or proposition E has a lower bound El and an upper bound Eu. So $p(E)$ is an interval number as follows

$$p(E) = [El, \; Eu] = [g, \; (1 - r)]$$

Here g represents the green part of the flag colouring an interval on the scale [0, 1] from *0* to g and r is the red part of the flag from $(1-r)$ to 1. The white part of the flag is therefore $w = 1-g-r$.

Now consideration is given to problem of calculating the Italian flag for a proposition H based on the flag for a single piece of evidence E. H is the proposition 'process H will be successful' and E is a sub-process of H at the next layer down in the PPM. The term $p(H)$ is therefore a measure of the dependability that the process H will be successful.

To calculate this, the total probability theorem is used

$$p(H) = \; p(H/E)\,p(E) + (1 - \; p(-H/-E))\,p(-E)$$

The values of $p(E)$ and $p(-E)$ are data from measurements, judgements or calculations. They may also be propagated from sub-processes. The values $p(H/E)$ and $p(-H/-E)$ are input by the user. The first measure $p(H/E)$ represents a warrant or justification for an action or a belief in the success of H if E is totally successful—it is the degree to which success in E, provides positive support (assurance, affirmation) for the success of H. In a similar way $p(-H/-E)$ represents a warrant or justification for an action or a belief in the failure of H if E totally fails: it is the degree to which the failure of E, provides negative support (testability and falsification) for the failure of H.

So $p(H/E)$ is called the positive support and $p(-H/-E)$ is called the negative support. They are judged by asking the following questions for each sub-process separately regardless of all other sub-processes.

(*a*) Positive support: if E succeeds what are the chances that H will succeed regardless of the evidence for other sub-processes?
(*b*) Negative support: if E fails what are the chances that H will also fail regardless of the evidence for other sub-processes?

Figure 3, gives guidance. Note that $p(H/-E) = 1-p(-H/-E)$.

Now

$$p(H) = [Hl, \; Hu] \text{ and } p(H/E) = [Sn(H/E), \; Sp(H/E)] = s = [sl, \; su]$$

where

$$Sn(H/E) = sl, \; Sp(H/E) = su$$

Likewise if the probability of not H is $p(-H)$ then

$$p(-H/-E) = [Sn(-H/-E), \; Sp(-H/-E)] = n = [nl, \; nu]$$

so

$$Sn(-H/-E) = nl, \; Sp(-H/-E) = nu$$

Using probability theory it can be seen that

$$p(-H/E) = 1 - s = [Sn(-H/E), \; Sp(-H/E)] = [1 - su, \; 1 - sl]$$

and

$$p(H/-E) = 1 - n = [Sn(H-E), \; Sp(H/-E)] = [1 - nu, \; 1 - nl]$$

Calculate $p(H)$ using a variation on the total probability theorem as derived by Marashi[2] as follows

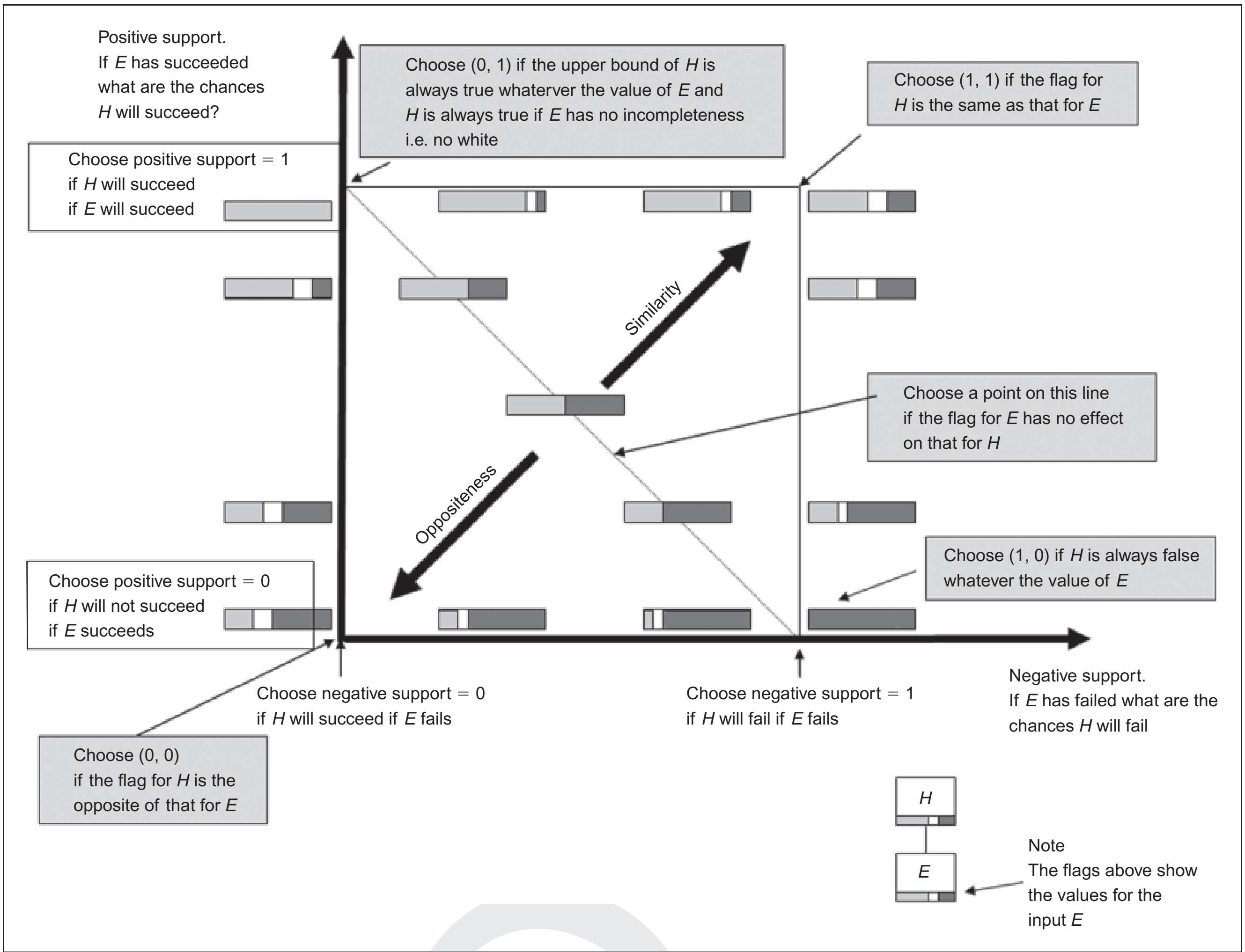

Fig. 3. How to choose support values for the warrant of *E* on *H*

1	$p(H) = p(H/E)g + p(H/-E)r + (p(H/E)\,p(H/-E))w$

2	$p(-H) = p(-H/E)g + p(-H/-E)r + (p(-H/E)\,p(-H/-E))w$

A simple interval version of the total probability theorem cannot be used because some of the basic probability constraints would be violated, as illustrated by the example below. To avoid these inconsistencies it is necessary to operate separately on the three intervals: *g, w* and *r* . The conditional probabilities operate on the *g* and *r*, but the white *w* is assumed to be a quantity independent of both conditionals, that is with least bias.

To find the upper bound on *H* the upper bound on $p(H/E)$ is used, that is, *su* operating on *g* and the upper bound on $p(H/-E)$, that is $(1-nl)$ operating on *r*. Thus using equation (1)

$$Hu = Sp(H) = su\,g + (1-nl)r + (1-(1-su)nl)\,w$$

To calculate *Hl*, do the same but use the other bounds on *s* and *n*, that is *sl* and *nu* to calculate $-H$ before obtaining the bounds on *H*. Thus the maximum of $-H$, that is $-Hu$, is calculated and then subtracted from 1 using equation (2) and

$$\begin{aligned} Hl = Sl(H) &= 1 - Sp(-H) \\ &= 1 - \{(1-sl)g + nu\,r + (1 - sl(1-nu))w\} \end{aligned}$$

Here the upper bound is used on $p(-H/E)$ or $(1-s)$, that is $(1-sl)$, to maximise the green on $-H$ in order to minimise the green on *H*. The upper bound is used on $p(-H/-E)$ or *nu* to minimise the red on $-H$ and hence maximise the red on *H*.

In summary

$$p(H) = [Sn(H),\ Sp(H)] = [Hl,\ Hu]$$

where

$$Hl = 1 - \{(1-sl)g + nu\,r + (1-sl(1-nu))w\}$$

$$Hu = su\,g + (1-nl)r + (1-(1-su)nl\,w$$

Thus as an example
If *p(E)* = [0·3, 0·7], that is $g = 0{\cdot}3$, $r = 0{\cdot}3$, $w = 0{\cdot}4$

$$[sl, su] = [0{\cdot}4, 0{\cdot}6]$$

$$[nl, nu] = [0{\cdot}4, 0{\cdot}8]$$

A simple interval calculus produces inconsistent results because

$$p(H) = [0{\cdot}4,\ 0{\cdot}6] \times [0{\cdot}3,\ 0{\cdot}7] + [1 - 0{\cdot}8,\ 1 - 0{\cdot}4] \times [0{\cdot}3,\ 0{\cdot}7] = [0{\cdot}18,\ 0{\cdot}84]$$

and hence $p(-H) = [1-0{\cdot}84, 1-0{\cdot}18] = [0{\cdot}16, 0{\cdot}82]$

Whereas alternatively $p(-H) = [0{\cdot}4, 0{\cdot}6] \times [0{\cdot}3, 0{\cdot}7] + [0{\cdot}4, 0{\cdot}8] \times [0{\cdot}3, 0{\cdot}7] = [0{\cdot}24, 0{\cdot}98]$ and hence $p(H) = [0{\cdot}02, 0{\cdot}76]$

These inconsistencies are removed using the formulae above so that

$$\begin{aligned} Hl &= 1 - \{(1 - 0{\cdot}4) \times 0{\cdot}3 + 0{\cdot}8 \times 0{\cdot}3 \\ &\quad + (1 - 0{\cdot}4 \times (1 - 0{\cdot}8)) \times 0{\cdot}4 \\ &= 1 - \{0{\cdot}788\} = 0{\cdot}212 \end{aligned}$$

$$\begin{aligned} Hu &= 0{\cdot}6 \times 0{\cdot}3 + (1 - 0{\cdot}4) \times 0{\cdot}3 \\ &\quad + (1 - (1 - 0{\cdot}6) \times 0{\cdot}4) \times 0{\cdot}4 \\ &= 0{\cdot}18 + 0{\cdot}18 + (1 - 0{\cdot}16) \times 0{\cdot}4 \\ &= 0{\cdot}36 + 0{\cdot}84 \times 0{\cdot}4 = 0{\cdot}696 \end{aligned}$$

and so

$$p(H) = [0{\cdot}212, 0{\cdot}696]$$

6. PROPAGATION OF EVIDENCE BY PAIRWISE COMBINATION

Now calculate the Italian flag of evidence $p(H)$ for a process H, which has sub-processes $E1$, $E2$, $E3$ and so on with associated supporting evidence flags of $p(E1)$, $p(E2)$, $p(E3)$ and so on.

A sub-process may be declared as jointly sufficient or jointly necessary. If a sub-process is declared as being jointly sufficient then the flag for any process calculated using that sub-process will not have a lower bound less than the lower bound for this sub-process. This means that, in this condition, the green must be as least as big as the green for the sub-process. Likewise if a sub-process is declared as being jointly necessary then the flag for any process calculated using that sub-process will not have an upper bound higher than the upper bound for that sub-process. This means that, in this condition, the red must be as least as big as the red for the sub-process.

The pairwise combination method begins by first calculating the evidence flag for a process based on the flag for each sub-process flag separately using the total probability theorem as described above. Any requirements of joint sufficiency or necessity are not included at this stage.

This therefore results in a series of separate estimates of $p(H)$ based on Ei, referred to as $p1(H)$, $p2(H)$, $p3(H)$.

These separate estimates are then combined in pairs. Dependency values λ need to be input for each pair combination.[2] The dependency values are a measure of the overlap or commonality between processes and are used to reduce the likelihood of 'double counting'. The dependency values range between total dependency, through independence to mutual exclusion and maximum perversity.

The first modelling assumption as set out in Fig. 4 is made by assuming that the dependency between $pi(H)$ and $pj(H)$ is as between $p(Ei)$ and $p(Ej)$.

If there is some support for H and also for $-H$ then this is conflicting evidence. This is automatically redistributed by the algorithm to the incomplete white range. Any conditions of joint sufficiency or necessity are included by checking the sizes of the green and red. This may result in inadmissible conflict which occurs when inputs are logically inconsistent. When this happens a blue section appears in the Italian flag, indicating its relative size. The only way to resolve this is by changing the input values.

A series of results $pij(H)$ are now available and they must be combined into a single answer. This leads to a second modelling assumption with two alternatives suitable for different purposes. The first is to assume that the results $pij(H)$ are all totally dependent. Here the minimum green (smallest positive evidence) and minimum red (smallest negative evidence) are taken and this produces maximum white (maximum don't know). The second is that average green and the average red are taken to give an indication of the total effect of the positive and negative support for H. Any requirements of joint sufficiency or necessity are included at this stage.

The choice of which way to combine the $pij(H)$ will be made according to the needs of the process players. It is important to remember that the purpose of this methodology is not to provide accurate predictions of the future—rather it is to enable the players to understand the sources of uncertainty and hence to make appropriate decisions to improve the chances of attaining success. Both of these assumptions can reveal different particular insights.

7. A STRUCTURAL EXAMPLE: PROCURING A NEW BUILDING

Assume that the main area of interest is the risks to the procurement of a new building. Although structural engineers may often not be concerned with such a high-level process, it is a critical context for the success of their work. Following the process methodology described by Blockley and Godfrey[1] the first task is to identify a process model, as shown in Fig. 5. Note that, owing to space restrictions, the model shown in the figure is incomplete and it is not possible to describe the methodology in any great detail. The first point to note is that the model is hierarchical and so will include the totality of the design as a

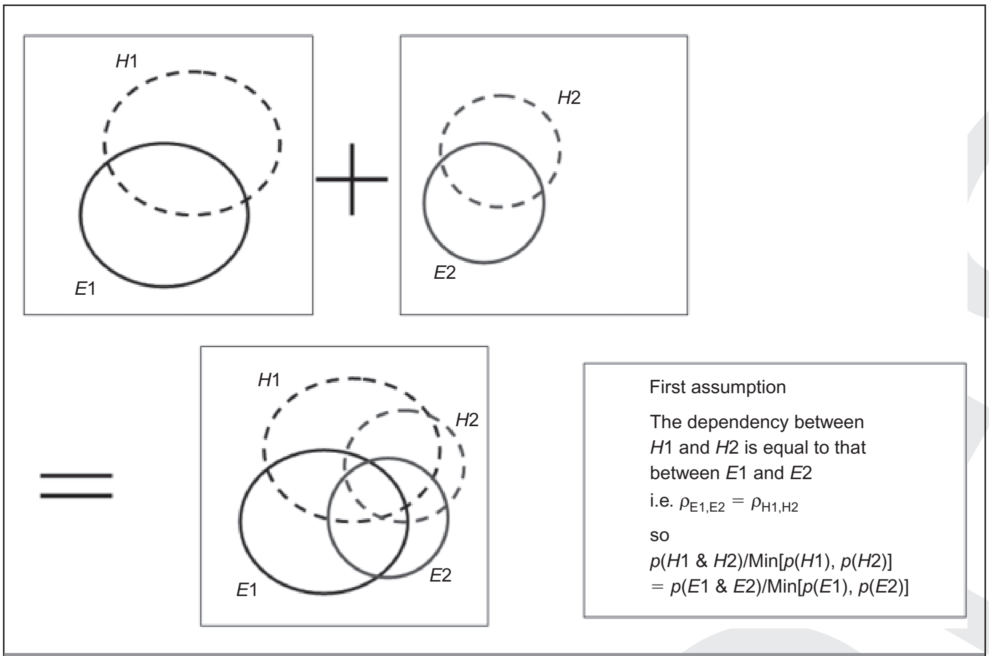

Fig. 4. Nature of first assumption

sub-process, which will in turn include the structural design. The process is therefore 'procuring a new building' and represents the whole of the project recognising the complexity of all of its emergent properties. Its associated Italian flag is therefore an indicator of the total risk to the success of the whole project and will change in time as evidence about the risks change. Formally the flag illustrates an interval probability measure of the dependability that the available evidence indicates that the process will be successful. Of course that means that success has to be defined precisely. Before the start of the project there is evidence at all about

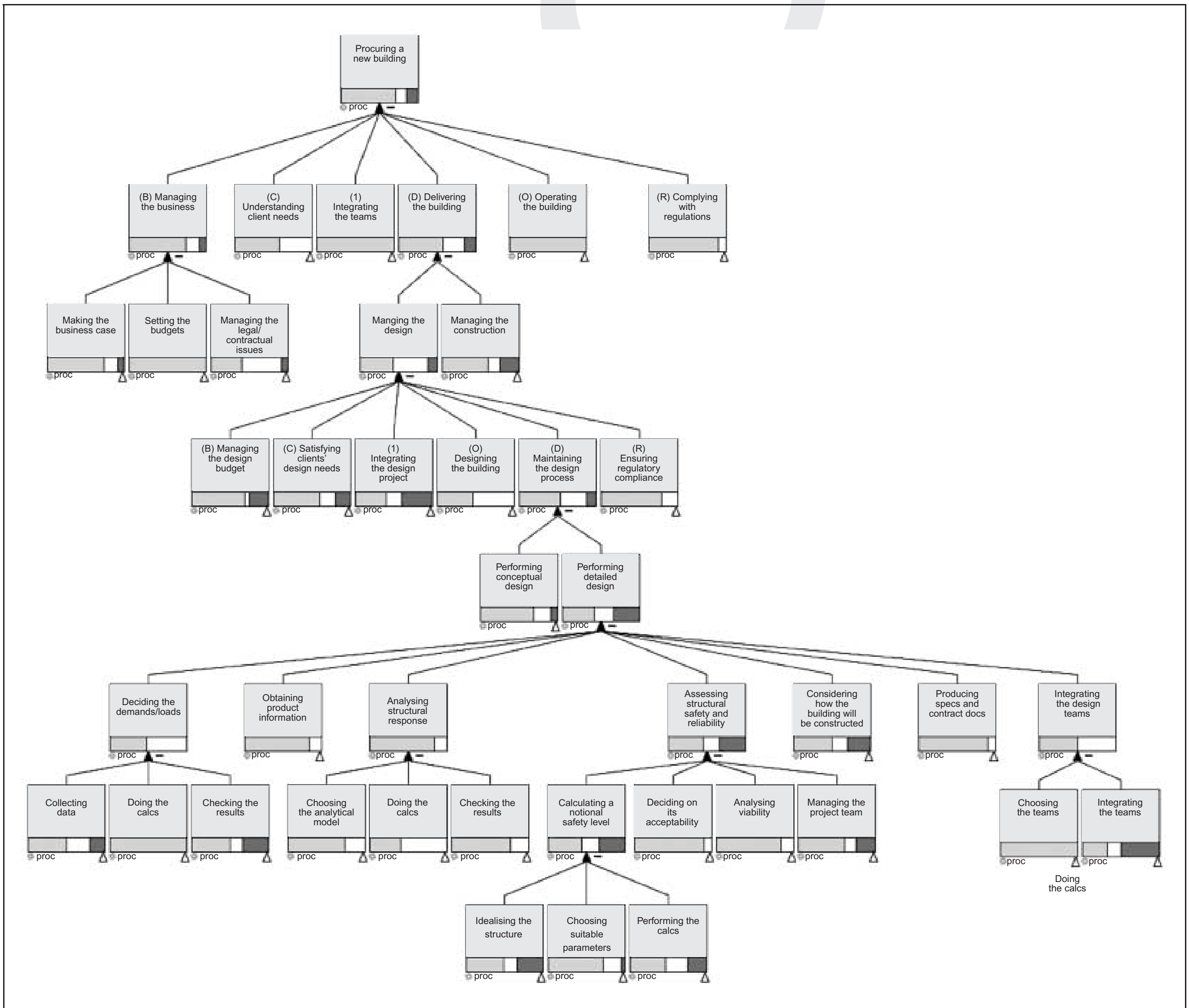

Fig 5. Example process model—procuring a new building (part)

the risks and so the flag will be completely white.

The model is developed by identifying at the second level down all of the sub-processes which together are necessary and sufficient for the top process to succeed. Each has its own Italian flag, which at the start are also white. One of the six sub-processes in Fig. 5 is 'delivering the building.' Then by looking at each second layer process in turn the third level processes are identified. Again they are the processes, the successes of which are together necessary and sufficient for the success of a specific chosen second level process. 'Delivering the building' has 'managing the design' as one of its six sub-processes. Again each has an Italian flag. The building of the model is repeated for further levels to an appropriate level of detail such as 'performing the calculations' in Fig. 5.

The Italian flags for the bottom processes in particular (or all processes in general) can either be input directly by the relevant process owner or derived from a performance indicator using a value function as described by Hall *et al.*[3] The flags for the higher process, right to the very top, are then calculated using the pair wise algorithm described earlier so that the effects of the lower flags on the higher flags become evident. At the same time, process owners will have their own interpretations of the evidence available to them and hence their own versions of the flags. Any important discrepancies as illustrated by Fig. 2 are highlighted and appropriate decisions taken in a timely manner.

The system is dynamic and constantly changing as new evidence arises and process owners change their flags. The systems is also a rich source of project information as each process has information attached to it (some of it emergent) under the labels 'who, what, where, when and how'. Perhaps the most important attribute is that each process has an 'owner' who monitors the flag and is responsible for identifying actions required to put the process back on track. This, of course, may well involve negotiating with others about changes they may need to make, since processes are interdependent.

Note that Fig. 5 includes all processes—both soft and hard. In other words the model is not restricted to the physical building but includes all information of all kinds. The pedigree of the information clearly varies enormously and that is catered for through the input data. Thus if a difficult judgement, which is necessarily imprecise, is put alongside information from a precise measurement or calculation then this can be allowed for by a suitable adjustment of the relationships between the measurement and the flag. The computer systems JUSTISE also allows notes to be written and links to be made to any relevant documents so that process owners and players as well as stakeholders with access permission can immediately see any changes.

So how is the model used and has it any relevance to a practising structural engineer? If implemented on a project intranet the model would be available to all participants in a project (with appropriate security safeguards) with read only or write access to their 'pieces of the action'. Process owners would be responsible for feeding in their latest data. After an initial input of contact details and other relatively stable information the major changes may be values of state variables (e.g. hard systems: movement of a foundation or dynamic responses of a bridge deck) key performance indicators (KPIs) (e.g. soft systems—judgements about team behaviour or loss of key personnel) and/or judgements about the Italian flags. The inputs can include the results of very detailed calculations such as finite element analysis or even notional probabilities of failure for example as well as all other detailed design and construction activities together with judgements and notes about the context and dependability of those calculations so that they can be interpreted and integrated into the total picture as dependably as possible.

A quick scan over all the flags will enable the spotting of possibly previously hidden interactions that could cause problems. In this way, decisions are taken by everyone involved in full awareness of the impact of other decision makers on total project success.

8. CONCLUSIONS

(*a*) The need to integrate different risks from different types of information has been highlighted. It has been argued that structural engineers have to understand and deal with the risks to their projects from the complex interactions between technical and non-technical issues.

(*b*) The use of process maps to connect data, information, people and functions and provide routes by which change can be managed has been described and illustrated with an example of the procuring of a building.

(*c*) The clear distinction between hard and soft systems has been made. It has been shown that they can be integrated by modelling them both as an interacting set of process holons.

(*d*) Italian flags based on interval probability theory are a practical way of representing the dependability of evidence in a process model. Some new mathematics of interval probability has been presented, which enables the interval values to be propagated up through the hierarchy of a process model.

(*e*) The Italian flag can be used as part of a social process to improve understanding of, and judgements associated with, incompleteness of knowledge.

REFERENCES

1. Blockley D. I. and Godfrey P. S. *Doing it differently*. Thomas Telford, London, 2000.
2. Marashi E. PhD thesis, University of Bristol, UK, 2006.
3. Hall J. W., Le Masurier J. W., Baker-Langman E. J., Davis J. P. and Taylor C. A. A decision-support methodology for performance-based asset management. *Civil Engineering and Environmental Systems*, 2004, 21, 51–75.