

Scenarios in the design process

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The Safety Science Group of Delft University of Technology has developed a method by which the input of safety in the design process is structured through the application of use-scenarios and hazard patterns. The approach is illustrated with case studies in the field of agricultural equipment (pneumatic pruning shears, power chain saws and power-take-off shafts). Use-scenarios and hazard patterns result from safety problem analyses and give structure to the problem space and assist in the explanation of accidents. Selection of solutions is facilitated by a matrix scheme which links technical design options and measures of a social and organisational nature into a set of coherent measures. In the evaluation of designs, the application of use-scenarios and hazard patterns is helpful as a predictor of residual risks. Incorporating safety in the design process is a dynamic decision-making process. The decisions involved and the role of the safety expert in this process are discussed.

Application of the method to the design of tools and consumer products seems very promising, although several problems remain. Valid accident data for use in the method are scarce; the technique for the translation of safety requirements into design specifications is still not fully developed and the first projects are only now being carried through to the implementation stage.

Keywords: Design, safety, risk, agricultural equipment, use scenarios

Introduction

In the light of the European Community Directive on product liability and the coming revision of the Dutch Commodity Act, which governs product safety in the Netherlands, 'foreseeable misuse' of consumer products is becoming increasingly important as a factor in safety.

Strategies for product safety in the past have mostly concentrated on risk awareness, individual motivation and instruction of users. Injury compensation and risk delegation through the limitation of liability by contract or transfer of risk to insurance companies are no longer seen to be satisfactory as the only instruments through which to manage safety problems arising from defective products and equipment. Emphasis in safety strategies is beginning to shift from damage and injury reduction to accident prevention. Designers must also be able to translate the feedback of user experience into design improvements, before accidents occur (Stoop, 1987). Manufacturers and designers are increasingly being compelled to improve the safety of their products before they are placed on the market.

This paper emphasises the engineering and scientific aspects of product safety within the management of product design (Abbott, 1987). We restrict ourselves to the design process as commonly applied in product design (Cross, 1989).

The Safety Science Group works closely with the Department of Industrial Engineering in co-operative projects. Problems of tool redesign have arisen out of the research, projects being carried out as case studies to develop the methodology. Some case studies are used at intervals in this

paper in order to illustrate points. At the request of a fruit grower consultant, the pruning shear was selected as a case study because of hand and finger injuries during the winter pruning of orchards. The power chain saw was chosen as an in-depth study in the field of vibrating tools and equipment. The power-take-off was redesigned at the request of an agricultural insurance group.

Safety problem analysis

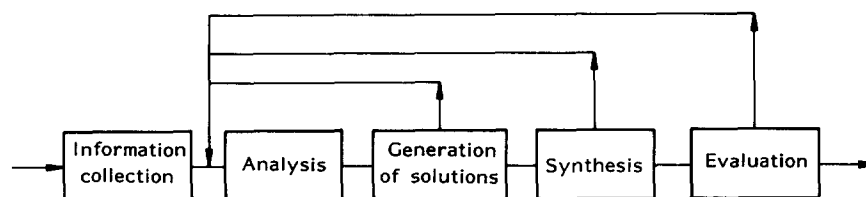
The problem-solving cycle

Accidents are usually seen as the main indicator of system disturbances or operation and design failures. Therefore, the starting point of most safety analyses is a retrospective approach, focusing on the user and product involved in an accident. The effectiveness of the solutions generated through this approach is limited, since it lacks predictive potential, especially for new products and new technologies.

Factors which contribute to accidents can originate during the development, production, distribution, use or the disposal of products. The relevant factors need to be determined both by analysing previous accidents and by analysing the normal use process, examining any undesired deviations during the life cycle of a product. In particular, we study the actual use of a product and compare this with the designers' intended use, to find out whether the use was foreseen in the design process and whether the real users were the actual target group defined by the designer.

The approach is based upon the basic process cycle of problem solving of Fig. 1 (Hale, 1985). The early requirements in the cycle are to produce a descriptive model of the

Fig. 1 Basic problem-solving process (after Hale, 1985)



problem in the context of the socio-technical system in which the problem occurs (Robinson, 1982).

Information collection

To build an appropriate problem-model, an information collection strategy is required. To derive several independent approaches to the problem, four dimensions or angles of approach are applied. These dimensions provide a model of the system in which the product is used, describing its structure, culture, context and contents. The dimensions are:

- a. Historical: this provides an insight into the dynamics of the system, trends, general demands and the boundary of the system to be defined.
- b. The product life cycle: development – production – distribution – use – disposal. This gives an insight into the links between stages, feed-forward and feed-back of knowledge and experience, and the criteria for improvements and modifications.
- c. The activities in which tools are used: this gives insight into tasks, performance, tools, conditions and their interactions.
- d. The system structure: the system is defined by its nature as leisure, transport, occupational or technologically complex. This provides insight into the system objectives, the role and functioning of the system components, and the interests, characteristics, capabilities and position of those involved (the 'stakeholders').

The four dimensions provide a qualitative insight into the system and together describe the relevant factors that may contribute to accidents, as well as the conditions for the normal functioning of the system (Stoop, 1983). In considering the four dimensions we use data collected from the literature, expert opinions, aggregated data from accident recording systems and, if available, incidents, complaints, information about occupational diseases and on-the-spot information.

In the pruning shear case study, consideration of the four dimensions enabled the problem of hand and finger injuries to be examined in the absence of any accident data being collected.

Analysis

The analysis stage of the process aims to generate a set of relevant accident factors, together with an overall view of the way accidents can occur. In the search for factors contributing to accidents it is undesirable to pay greater attention *a priori* to any one factor – 'person', 'machine' or 'environment' – above the others, since we are looking for combinations of factors which are significant.

The use of the four dimensions leads to a refined problem description. The factors contributing to the accidents, as well as their effects, are defined in terms of a

system model which lays the basis for the next step in the problem-solving approach.

In the pruning-shear case study, the redefined problem not only included the hand and finger injuries, but also revealed postural problems, a severe vibration load on the wrist, arms and shoulders, and a potential loss of hearing from the noise of release of compressed air.

In more complex problem situations, such a problem description is lacking in several respects. The analysis does not necessarily give a detailed enough answer as to why or how certain factors contribute in practice to accidents. It does not guarantee an adequate accident hypothesis and explanation for three reasons. First, the use of aggregated accident data from existing recording systems lacks specific detailed information about the sequence of events during the accident itself. Only a case study analysis of accidents of the relevant type can reveal the necessary details for a goal-directed intervention in an accident sequence. A more detailed analysis is therefore required as a second step. Second, to formulate and test accident hypotheses there is often a need for specific knowledge about deeper underlying causal models – for instance, human error theory, fracture mechanics, etc. This requires an in-depth study to provide the data on which risk-control decisions can be made. Finally, the problem descriptions derived from aggregated data are often too broad and therefore unmanageable. It is simply impossible to solve problems defined so globally as 'falling down stairs', 'chain saw accidents' or 'power take-off injuries'. The system models for such broad definitions are too large to be manipulated.

There is an urgent need to divide the overall problem into manageable sub-problems, and a need to mobilise specific and detailed knowledge in doing so.

The use-scenario concept

We use the concept of use-scenario as an instrument to break the problem down into manageable sub-problems and to assist in decision making. The system is described in terms of its constituent elements and their relationships in answering such questions as: who is involved, with what processes and products, under what circumstances, and in the presence of what hazards? We define 'use-scenarios' as the sub-system within which hazard patterns are grouped. Scenarios must be specific and they must be mutually exclusive, but the number of use-scenarios for any given product should be limited to a workable number of 5–15. We are then able to select, on the basis of severity, nature and extent of the problem, one or more use-scenarios for in-depth investigation. (For further discussion on scenarios see also Drury and Brill (1983), Gelderblom (1988), Jungerman and Thuring (1987), and Kaplan and Garrick (1981).)

In the chain saw case study, five different hazards could be allocated to six use-scenarios. The specific capabilities of the users, the use conditions, and the characteristics of

the equipment proved to be the determining factors in the composition of the use-scenarios for the chain saw (Stoop, 1985, Fig. 2).

The use-scenarios were generated from aggregated accident data bases and expert opinions, and by applying functional and task analyses of the normal process of using a chain saw. (Goossens and Heimplatzer, 1986; Hoefnagels and Bouwman, 1989.)

The hazard pattern concept

To meet the need for specific knowledge about the precise sequence of events in accidents, in terms of mechanism and causality, we use the concept of 'hazard patterns' (Drury and Brill, 1983). Hazard patterns describe the characteristics of hazards, their 'activation' as accidents, and possibilities for intervention. An in-depth investigation of several typical accidents and events is necessary to determine these hazard patterns. A major role in the analysis is given to the detection of deviations from normal use (Kjellen, 1984). The result is a detailed description and a satisfactory explanation of the sequence of events.

For the in-depth investigation phase, several techniques are available. These include observation, film or photographs, questionnaires, check lists, on-the-spot investigation, expert opinions, task and product analysis, and dose-effect measurements.

In the pruning-shear case study, the in-depth analysis clarified questions about the precise functioning of the shear blades (i.e. did they chop or shear?), and revealed the relevant geometrical parameters such as wedge angle and squeeze angle. The origin of the vibrating load in the equipment and its transfer to the wrist was clarified, as well as the required anthropometric parameters and the variety of uses of the safety devices. Eventually, five hazard patterns were identified: the normal pruning process, (dis)connection of the shear from the air hose, sharpening and greasing the blades, slipping and tripping during transport, and danger to children and animals. A typical instance of the latter was where a dog accompanied his master into the orchard. The dog wanted to play with his master by retrieving the pruning shear which laid on the ground. The shear was activated and cut off one of his legs.

We define an 'accident scenario' as the combination of the use-scenario and the hazard pattern. The objective of our analyses of safety problems is to produce frequency distributions of hazard patterns over the use-scenarios, so leading to scenario-specific problem descriptions (Hoefnagels and Bouwman, 1989).

The development of accident scenarios through to their final version can, of course, be a major project in itself; the causal relations between factors can be complicated because

of the number of factors involved, or can be difficult to derive because of the ordering, quality or quantity of accident data available (Goossens and Heimplatzer, 1986; Hoefnagels, 1986, 1987).

Generation of solutions — the solution matrix

Existing or modified solutions may be derived through the literature or by consulting experts. New solutions can be generated from known principles in problem solving and application of experience in related problem fields. A database which links use-scenarios to principles of technology could be of great help here.

The range of potential solutions must be specified and classified. A matrix is used to put existing and newly generated solutions in order and to enable decision making in the selection of solutions. The matrix relates the level of intervention to different intervention strategies, and contains prevention measures of a technical as well as an organisational and social nature.

Using a systems approach, three levels are defined at which intervention in the system is possible. The first is the micro-level which describes the users in their direct interaction with the product — e.g. the farmer with his agricultural equipment. The second level is the meso-level, at which the managers and decision makers are involved — e.g. the power-take-off manufacturer. The meso-level describes the system at the level of a production unit or company. The third level is the macro-level, of the legislator, the government, professional organisations and industrial associations — e.g. insurance companies or the Labour Inspectorate.

Prevention measures can be classified into five intervention strategies (Hale and Glendon, 1987).

Strategy 1 aims at the elimination of the hazard. This strategy is to change the energy source, the technological principles used, or the basic materials.

Strategy 2 aims to isolate the hazards in order to prevent the destabilisation of the system. Deviations and unwanted events are to be prevented by built-in barriers.

Strategy 3 aims to protect against damage and injury, through the early detection and recovery of unwanted deviations during the build-up phase of the accident, before damage and injury can occur.

Strategy 4 aims at the reduction of damage and injury, by the control of the damage and injury process whilst the damage event is proceeding.

Strategy 5 aims at the recovery of the system after the exposure to the hazard, and permits a return to normal operation through rescue and recovery measures.

Scenarios		Forestry	Public grounds	Construction and building industry	Fruit growers	Farmers	Do-it-yourself
Hazard patterns	Posture	xx	x	x			
	Accidents	x	xx	xx	xx	xx	xx
	Exhaust	xx			xx		xx
	Fumes						
	Noise	xx	xx	xx	xx	xx	xx
	Vibrations	x	xx		x		

Fig. 2 Hazards and use-scenarios for chain-saw use

Fig. 3 shows one solution matrix derived for pruning-shear use by workers in the fruit growing industry during winter pruning. This contains one use-scenario and shows 17 potential solutions.

Two explicit decisions must be made by the safety expert in using the matrix. The first decision deals with the selection of the use-scenarios and the selection of those hazards and hazard patterns which are dominant in each of the use-scenarios with respect to the safety problem and the design assignment. The second deals with the allocation of potential solutions to each of the use-scenarios, hazards and hazard patterns involved. Each solution may contain technical, social and organisational measures.

As this paper places emphasis on the implementation of safety requirements in technical design, the re-integration of non-technical aspects of the solution is discussed later where residual risks are examined. The accident scenarios are part of an intermediate stage between the safety problem and the design assignment; the relevant factors, grouped in accident scenarios, are translated into the design assignment as functional demands with regard to safety and health.

Synthesis: Safety in the design process

Incorporation of safety

Safety becomes explicit in the design process at several decision points. First is the selection of relevant use-scenarios, based upon the severity, nature and extent of the hazards involved. The choice must take into account (1) the user group that is the designer's target, (2) the competence, power and resources of 'stakeholders' and (3) the estimated cost/benefit ratio of the safety measures. This decision occurs during the formulation of the design assignment.

Second is the decision as to which technological principle and energy source to select for further development. This

decision occurs during the conception phase. For example, whether to shear, saw or chop branches in pruning and whether to select hydraulic, pneumatic or electrical power transmission defines the overall character of the product.

Alterations on this level create a complete new product which could become a competitor to the pneumatic pruning shear. The technological principles and energy sources each have their own inherent characteristic hazards. This second decision therefore determines the presence or elimination of many of the technological hazards.

The third decision is which hazards are to be dealt with and, consequently, which hazard patterns. This decision occurs during the product conception and detailing phases. The question is, at which point should we intervene in each of the hazard patterns present in the use-scenarios? Major changes in product safety characteristics may be feasible in order to eliminate major safety problems and to change use-scenarios drastically.

In the power-take-off case-study, the dominant problem was the existence of two independent linkages, one for the power-take-off shaft and the other the towing bar of the equipment or the lifting device of the tractor. The effects of interaction between these two independent linkages were the same in all of the accident scenarios and caused many of the injuries and most of the damage. The movements of the tractor and the equipment during normal operation caused the power-take-off shaft to be crushed by the towing bar or the lifting device of the tractor, and consequent damage to or destruction of the protective sleeve. The operator could thus get caught by the rotating shaft and injured severely.

In addition, the coupling and uncoupling of the towing bar and of the power-take-off shaft forces the operator to work in an inconvenient posture between tractor and equipment. This causes back injuries because of the heavy workload, as well as hand and foot injuries occurring during the coupling procedure.

	Elimination	Isolation	Detection	Reduction	Recovery
Macro	Different tree shape	Labour put out to contract	<ul style="list-style-type: none"> • Testing • Certification + standards • Education + instruction 		
Meso	Different pruning technology	Remote control	<ul style="list-style-type: none"> • Labour reorganisation • Proper choice of tools/equipment 		
Micro	Legal prohibition	<ul style="list-style-type: none"> • Mechanisation • 'Both hands' operated tools • Different propulsion power • Different pruning technique 	<ul style="list-style-type: none"> • Redesign • Improved maintenance 	Personal protection	First aid

Fig. 3 Matrix for pruning-shear use by fruit-growing industry workers

The solution to both these problems was generated in the conception phase of the design and led to a completely new design. An automatic coupling device with the power-take-off shaft is now contained within the towing bar. It is therefore no longer necessary for the operator to be inside the coupling area, and the power-take-off shaft becomes inaccessible.

Design solutions, aimed at intervention within a hazard pattern, accept the technology and energy source with their characteristic hazards as given, and consequently do not aim to eliminate the hazard completely. The intervention through hazard patterns occurs in the detailing phase. A thorough knowledge of human error and the structure of human cognition as well as ergonomics principles forms the basis of such interventions (Ramsey, 1985). There is an obvious decrease in effectiveness in these interventions over time, since decisions made in a previous phase limit the freedom of choice in later phases. It is therefore important to stress the iterative and cyclic nature of the design process, in order to anticipate and limit the effects of such diminishing returns.

During the evaluation phase, technical solutions must be considered in the light of their interaction with social and organisational factors, since each decision may have consequences with respect to residual risks and side effects.

Role of the safety expert

Having described the nature of safety decisions within the design process, we must consider the question of who is involved in the design process, to see how in practice decision making may be influenced.

The role of the safety expert is to make explicit the decisions, the factors involved, their weighting and the consequences of the decisions. The safety expert has a responsibility in safety problem solving and, consequently, a role in guiding the design process. They should therefore be acquainted with the 'language' of the designer and other decision makers to ensure an effective dialogue. The extent to which the safety expert and designer are restricted in safety problem solving is dependent on the following factors.

The complexity of the problem may restrict the scope of the solutions since only sub-problems may be solved. Several use-scenarios or hazard patterns may not be dealt with because the problem has to be divided into manageable sub-problems.

In the chain-saw case study, the problem of 'kickback injuries' cannot be solved in one redesign attempt. These injuries result within all of the use-scenarios, with different types of chain saw and with different types of hazard patterns. Different solutions are required in the various use-scenarios; there is no general single solution to the kickback hazard which can disregard context.

The importance of other design demands may dominate the safety demands. There is a continuous weighing of numerous design demands, resulting in compromises between what is best and what is acceptable with respect to safety.

For reasons of acceptability by the fruit growing community in the Netherlands, the principle of using pneumatic power for pruning shears could not be changed. Hence vibration load, noise, and hand and finger injuries exist as intrinsic potential hazards and can only be reduced by

palliative measures. They still remain to be dealt with effectively.

The existence of technical limitations may restrict the influence of the safety expert and exclude solutions which are desirable purely from the standpoint of safety.

In the pruning-shear case, for each hazard pattern arising from the use of pneumatic power, a design strategy could be developed which incorporated several technical solutions (Eijkelenboom, 1985). For example, placing a cheap rubber buffer ring at the end of the piston stroke and optimising the shape of the cutting blades, reduced the vibration load to one-seventh in the most harmful axis, that of the piston. However, despite extensive attempts, all the solutions for noise reduction proved inadequate, giving a considerable loss of blade closing velocity with little effect on the noise level.

Among the five hazard patterns leading to hand injury with the pruning shears, that which lead to injury during the normal pruning process yielded no acceptable solution. The other four hazard patterns – (dis)connection, sharpening and greasing, slipping and tripping, and danger to children and animals – yielded several independent and satisfactory design solutions.

The control of the decision making process by the safety expert and the designer will depend on their relationship with, or their position within, the organisation which commissions the design. The design process is often determined by contradictory interests, and by stakeholders who may overrule the designer's and safety expert's opinions. On complicated design assignments, safety experts and designers are only employees, and by no means are decision makers on a policy level. However, they should be able to formulate the problem in such a way that policy decisions can be made by others.

The product life cycle restricts the influence of designer and safety expert. Changing a production process, moulds, jigs or tools, even for slight modifications, can be very expensive and can hurt profits or market share.

The potential costs for a casting mould in the production of a pruning shear put the decision to change the mould beyond discussion, and severely restricted the redesign options for the shear.

Alterations in a product in its early days as a concept on the drawing board will not be very expensive, and can be very effective. Changes in product design at this point can involve a wide range of possible costs and benefits. Only minor product modifications are usually possible, though, where a design is dominated by questions of expected market share or liability claims.

A number of modifications in the chain-saw design were developed based on the safety argument. These, though, were held back up to the moment that modifications could serve as a factor in assisting market share in a replacement market.

Evaluation

Residual risks

Technical design solutions can be rated for their effectiveness as safety devices by examining their residual risks and

foreseeable effects. Questions to be answered include:

- a. Which hazards and hazard patterns are eliminated?
- b. Is the relationship between the subjective and the objective safety of the design unambiguous?
- c. Is the design vulnerable to foreseeable misuse or inappropriate use?
- d. Does the design provoke risk compensation in its users?
- e. Does it introduce new hazards?

In practice, a team of safety experts, designers and domain experts faces two main questions about residual risks:

1. What are the residual risks in any redesigns for each hazard and hazard pattern in the selected scenarios?
2. How can we cope with the residual risks in the other scenarios which were not selected for study, and in any foreseeable new scenarios?

To answer the first question there are two options. If the residual risk is not yet satisfactorily dealt with, it is necessary to go through the design cycle once more. Even if the residual technical risk is acceptable in practice, the hazards that can still emerge have to be limited in their effects by a well chosen residual risk strategy. Because the technical design options are, by definition, exhausted by this stage (otherwise there would have been a better design choice available), the solution matrix must be re-examined to see which social or organisational measures can be used to fit in with this strategy.

The implementation of the redesigned pruning shear required a number of additional measures:

- (a) Keeping a small-bladed tree saw in the hand not holding the shears, using it to remove or bend branches instead of using the hand itself; this would reduce hand injury risks.
- (b) Encouraging and enforcing the use of ear muffs to combat the noise hazard.
- (c) Providing user information about the equipment and its properties, with regard to noise and vibration load and to safety devices, in order to overcome market resistance and create a demand for safer shears.

Foreseeable use

We have tried in the case studies carried out to produce a coherent set of measures to deal with the safety problem in the use-scenarios we chose for the redesigns. In the pruning-shear case this set of measures dealt with the specific conditions prevalent in just one use-scenario: the fruit growers' community. At this point the designer might decide to consider the design as completed, since he or she has solved to the best of their ability the problem of hand and finger injury for professional fruit growers during the winter pruning process. However, the designer ought to address a second question of whether there are any other use-scenarios available in which it could be predicted that the product could be used. Due to changes in product liability legislation it is of vital importance that the designer tries to anticipate future product use to guard against a liability claim.

If the initial problem analysis did not reveal any other potential current uses for the product, this does not mean that such uses will not develop in the future. An attempt must be made to generate use-scenarios for completely new

applications of the product. Designers should be as inventive as their potential users in thinking of possible future uses.

Although it is not always possible to cover all future possibilities, the use of brainstorming techniques often reveals a remarkable variety of possible and credible product uses. In the case of the pneumatic pruning shear, outside the fruit growing and related industries, the shear could be used for cutting up chickens in slaughterhouses, sheet-iron cutting, in the upholstery business, in car repair shops or in households as an aid for handicapped people.

It might also be possible to generate use-scenarios by analogy with closely related problem areas and with solutions applied in these areas. Since there will be no accidents and injuries yet in the newly generated use-scenarios, it is necessary to rely on prospective techniques to predict effects. These techniques are not yet widely applied in design and are in the early stages of development (see Reason, 1985; Heinrich, 1988). However, a thorough knowledge of the possibilities and limitations of human behaviour is indispensable to foresee normal use and misuse, and to develop adequate prevention strategies. After all, technology should be adjusted to human performance and not vice versa.

Conclusions

Any intervention on the level of a socio-technical system will cause disturbances and introduce possibly unforeseen effects beyond the control of the individuals and organisations involved. The solution to a safety problem has a long-term dynamic component. The process described in this paper is an attempt to foresee use by consumers, those exposed most directly to risk. It does not describe the reaction of other 'stakeholders' to the safety problem.

Safety experts and designers have to accept that intervention can and probably will cause changes in the behaviour of any non-users involved.

In the pruning-shear case study, our work influenced the attitudes of the Labour Inspectorate, of the fruit growers' association and of the agricultural trade organisation to pruning hazards, and especially to the vibration load. Several intervention strategies were activated by this increase in attention. The fruit growers' association and agricultural trade organisation were given the possibility of a Working Place Improvement Grant, financed by the Labour Inspectorate; this was a 50% discount on the purchase of an 'ergonomic' pruning shear. As such a shear does not yet exist, manufacturers were invited to modify their products to comply with the vibration load standards set by the Labour Inspectorate. Such a grant and the setting of vibration load standards were, respectively, unforeseen and judged as very unlikely by the safety experts at the time they initially became involved in the project.

'Unforeseeable effects' are evidently as difficult a problem for a safety expert as they are for a designer.

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