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Information System Control Selection Using Spreadsheet Optimization

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ABSTRACT

Today even the smallest organization depends heavily on information systems (IS) to support achievement of its objectives. Thus there exists a need for tools and techniques for choosing controls, or IS components that assure system dependability. Several researchers have developed quantitative models of controls. One such model for choosing controls incorporated the trade-off between the cost of establishing controls and the cost of not having them. The model was a refinement of the "control evaluation table" method used by auditors, enhanced with a probability model of control effectiveness, and formulated as a 0-1 nonlinear optimization problem. This paper presents a brief review of the model formulation and then goes on to provide a spreadsheet model solution.

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INTRODUCTION

Controls are procedures built into an information system (IS) for the purpose of increasing its dependability. Decisions about what controls to incorporate into an IS are usually made during the design of the system. Walls (1992) formulated a 0-1 nonlinear optimization model for selecting the "right" set of controls for an IS (from a cost-benefit point of view). He found that to determine an optimal solution for the model required the use of a relatively obscure software package (MINOS) and nearly an hours worth of mainframe computing time. To avoid these issues, Walls and Turban (1992) implemented heuristics for finding good solutions in the form of logic programs in the Prolog programming language.

Today's powerful personal computers and sophisticated spreadsheet software provide tools for finding an optimal solution to the control selection problem that are readily available to everyone. This paper describes the use of a straightforward Microsoft Excel spreadsheet model that employs the Solver© add-in to select a set of IS controls.

CONTROL SELECTION MODEL

Walls (1992) formulated a control selection model that was a refinement and extension of the control evaluation table method used by auditors to evaluate the collection of internal controls found in an IS. The auditors' method involved the use of a set of matrices containing a list of possible controls, the hazards each counteracted, and subjective assessments of the effectiveness of each control in counteracting each hazard. An example of a control is the use of a user name/password procedure to restrict access to information contained in an IS. Theft of confidential company data is an example of a hazard.

The control selection model takes into account the tradeoff between the cost of including each control in the IS and the expected value of the financial impact of the hazards to which the system is exposed. The equation below reflects the total cost, TC, of a set of controls incorporated into an IS:

$$\text{TC} = \text{TCC} + \text{TRR} = \sum_{i=1}^{s} C\left(X_i\right) + \sum_{j=1}^{q} R\left(Z_j\right) \prod_{i=1}^{s} \left[1 - E\left(X_i, Z_j\right)\right]$$

In this equation, X_i is a control, $C(X_i)$ is the cost of control X_i, Z_j is a hazard, $R(Z_j)$ is the economic risk associated with hazard Z_j, and $E(X_i,Z_j)$ is the effectiveness of control X_i in counteracting risk Z_j. As may be seen from the above equation, adding controls to an IS increases total control cost (TCC) and decreases total residual risk (TRR). Eventually, a point may be reached where the cost of adding control exceeds the savings due to risk reduction associated with including it. Derivation of this equation as well as a discussion of other analytical models proposed for selecting and evaluating controls may be found in Walls (1992). (Ideas underlying the equation are also summarized in the Appendix.)

To determine the best level of control, the above equation may be reformulated as an optimization problem. For any particular IS, there are many controls that could be implemented. The problem was formulated as a 0-1 integer optimization problem with a nonlinear objective function. This was accomplished by introducing a decision variable X_i which may assume a value of either 0 or 1. If $X_i = 0$ then the control X_i is not used. If $X_i = 1$ then the control is used. The problem may be formulated as:

Minimize: $\sum_{i=1}^{s} C_i X_i + \sum_{j=1}^{q} R_j \prod_{i=1}^{s} \left[1 - E_{ij}\right]^{X_i}$

where

X_i ε {0, 1}

$0 \le E_{ij} < 1$

$0 \le R_j$

$0 \le C_i$

Note that in this formulation there is an important trade-off between control cost and effectiveness. At one extreme, if all controls are implemented ($X_i = 1$ for all *i*), the total control cost will assume its maximum value and uncontrolled risk its minimum value. At the other extreme, of no controls are implemented ($X_i = 0$ for all *i*) then the cost of using controls will be at its lowest level but the risk level will be at its maximum. Therefore, solving the above equation finds an appropriate balance between control cost and the level of risk. This is done by using a common denominator (money) to relate control cost and risk.

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Walls (1992) reported that finding an optimal solution to a design problem of realistic size took over forty three minutes of processor time running the MINOS nonlinear optimization package on an Amdahl mainframe. Today with powerful microprocessors and the Solver© add-in, solution times are dramatically reduced.

A COMPUTATIONAL EXAMPLE

This section presents a small example with five hazards, three consequences, and nine controls that illustrates the application of the model. The example is taken from a customer order processing system. Figure 1 is a spreadsheet that lays out the details of the example.

Figure 1

A	B	C	D	E	F	G	H	I
1	Order Processing Example - Dependability							
2								
3	Hazards			1. Inaccurate	2. Inappropriate	3. Lost	4. Unsupportable	5. Open
4				Payment	Payment	Customer	billing	access to
5				Input	Processing	File	statement	A/R record
6	Hazard Likelihood			0.025	0.135	0.029	0.240	0.280
7	Hazard Opportunity			1,000	1,000	200	1000	200
8	Consequence	Potential Loss		Consequence Likelihood				
9	1. Customer never billed	$ 20.00		0.990	0.600	0.050	0.025	0.050
10	2. Revenue reported incorrectly	$ 40.00		0.050	0.050	0.050	0.200	
11	3. Loss of resource	$ 200.00			0.200	0.050		0.100
12				Uncontrolled Risk				
13	Total Uncontrolled Risk	$ 11,126.40		$ 545.00	$ 7,290.00	$ 75.40	$ 2,040.00	$1,176.00
14	Control	Control Cost		Control Effectiveness				
15	1. Turnaround billing document	$ 500.00		0.850				
16	2. Batch balancing of statements	$ 500.00		0.014				
17	3. Reasonableness check on payments	$ 500.00		0.240	0.400			
18	4. Readback of payment transaction	$ 500.00		0.765	0.280			
19	5. Approval of customer payment	$ 500.00		0.400	0.012		0.450	0.460
20	6. Reconciliation of payments to account balance	$ 500.00		0.480	0.080		0.872	
21	7. Aging of receivables	$ 500.00		0.060	0.080		0.060	
22	8. Matching of payments to billing data	$ 500.00		0.582	0.080		0.060	
23	9. Periodic verification of payment processing	$ 500.00		0.420	0.350	0.490	0.540	0.270
24	Net Effectiveness			0.998	0.784	0.490	0.971	0.606
25	Residual Risk			$ 1.02	$ 1,574.87	$ 38.45	$ 58.37	$ 463.58
26	Total Residual Risk	$ 2,136.30						
27	Total Control Cost	$ 4,500.00						
28	Total Cost	$ 6,636.30						

In this example, hazards listed in Table 1 were identified. Hazard opportunities and likelihoods for each were then identified and entered into the spreadsheet. For example, the likelihood of "Inaccurate payment input" is 0.025 (cell E6) and the opportunity for the hazard is 1,000 (cell E7) times per time period.

Table 1
Hazards
Inaccurate payment input
Inappropriate payment processing
Lost customer file
Unsupportable billing statement
Open access to A/R record

The consequences listed below were also identified. One consequence of "Inaccurate payment input" is "Customer never billed". As may be seen in the spreadsheet, the likelihood of this consequence is 0.99 (cell E9) and, if it were to occur, the loss would be $20 (cell C9).

Table 2
Consequences
Customer never billed
Revenue reported incorrectly
Loss of resource

Remaining parameters and calculation results may be found in the upper part of the spreadsheet of Figure 1. The lower portion of the figure lists nine controls (such as a "Turnaround billing document") that could be used to counteract the hazards identified in Table 1. In the body of the figure (cells E15:I23) are the effectiveness of these controls. Row 24 shows the Net Effectiveness of this set of controls and row 25 the Residual Risk after this set of controls is applied.

Note that the total cost of this control system is $6,636.30, which includes the cost of implementing all nine controls plus the Residual Risk remaining even when all controls are in place.

Figure 2 is a restructuring of Figure 1 where variable names Z, Q, and X have replaced the descriptions of hazards, consequences and controls respectively. This spreadsheet is set up to take advantage of the Solver© add-in which supports the solution of optimization problems in the context of spreadsheet software (Winston and Albright, 2004). To accomplish this end, a set of 0-1 variables is introduced in column D to permit selection of particular controls to be brought into an optimal solution Furthermore, the

Net Effectiveness row has been modified to incorporate the 0-1 variables into the computation using expressions like

=1-(1-E16*D16)*(1-E17*D17)*(1-E18*D18)*(1-E19*D19)*

(1-E20*D20)*(1-E21*D21)*(1-E22*D22)*(1-E23*D23)*(1-E24*D24).

Figure 2 shows an optimal solution where only controls X_3, X_4, X_6 and X_9 have been selected for a total cost of \$4,929.68. This is a reduction of \$1,706.62 or 26% compared to the cost of the system with all controls in place. Figure 3 is a screenshot of the Solver© dialog box showing minimization of TotalCost by changing SelectedControls subject to the constraint that SelectedControls is binary. Figure 4 is a screenshot of the Solver© options box showing the default settings indicating that the model is not linear. Although not included in this model, additional constraints could be added to indicate, for example, that certain controls must be used with other controls or that some controls are mutually exclusive (Walls and Turban, 1992).

Figure 2

Order Processing Example - Control Selection

Hazards			**Z_1**	**Z_2**	**Z_3**	**Z_4**	**Z_5**
Hazard Likelihood			0.025	0.135	0.029	0.240	0.280
Hazard Opportunity			1,000	1,000	200	1000	200
Consequence	Potential Loss		Consequence Likelihood				
Q_1	\$ 20.00		0.990	0.600	0.050	0.025	0.050
Q_2	\$ 40.00		0.050	0.050	0.050	0.200	
Q_3	\$ 200.00			0.200	0.050		0.100
			Uncontrolled Risk				
Total Uncontrolled Risk	\$ 11,126.40		\$545.00	\$7,290.00	\$75.40	\$2,040.00	\$1,176.00
Control	Control Cost		Control Effectiveness				
X_1	\$ 500.00	**0**	0.850				
X_2	\$ 500.00	**0**	0.014				
X_3	\$ 500.00	**1**	0.240	0.400			
X_4	\$ 500.00	**1**	0.765	0.280			
X_5	\$ 500.00	**0**	0.400	0.012		0.450	0.460
X_6	\$ 500.00	**1**	0.480	0.080		0.872	
X_7	\$ 500.00	**0**	0.060	0.080		0.060	
X_8	\$ 500.00	**0**	0.582	0.080		0.060	
X_9	\$ 500.00	**1**	0.420	0.350	0.490	0.540	0.270
Net Effectiveness			0.946	0.742	0.490	0.941	0.270
Residual Risk			\$ 29.36	\$1,883.27	\$38.45	\$ 120.12	\$ 858.48
Total Residual Risk	\$ 2,929.68						
Total Control Cost	\$ 2,000.00						
Total Cost	**\$ 4,929.68**						

Figure 3

Screenshot of Solver© Dialog Box

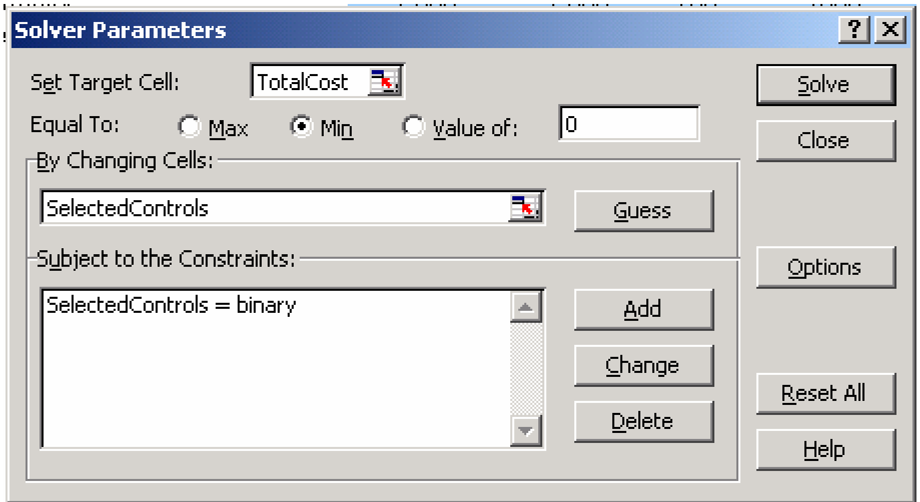
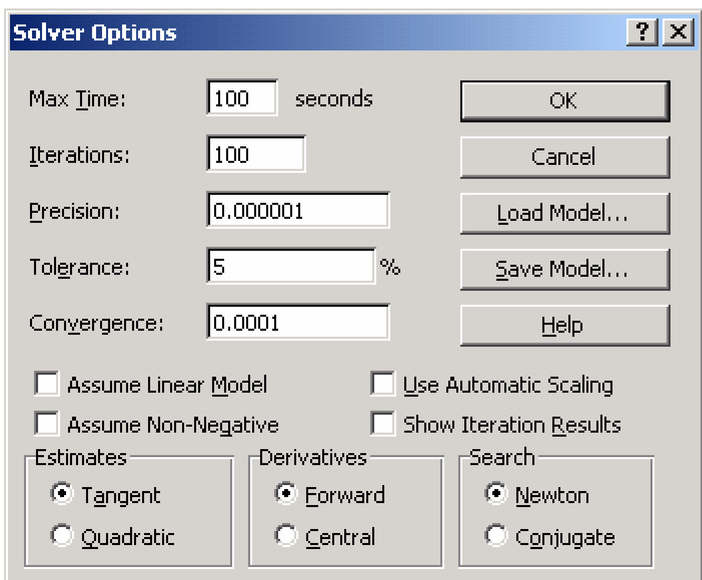


Figure 4

Screenshot of Solver© Options Box



CONCLUSION AND FUTURE RESEARCH DIRECTIONS

This paper began with a reprise of prior research showing how design of information systems controls of interest to accounting and information systems people could be formulated as an optimization model that attempted to find an optimal solution to a problem of ongoing importance. Because the computational effort involved in solving this model can be very high due to the combinatorial nature of the model, earlier research resulted in heuristics that could considerably reduce this effort. In this paper, the problem is formulated in such a way that an optimal solution can be determined using spreadsheet software.

A numerical example was presented that includes five risks and nine controls. In a realistic situation there will be many more risks and controls. Since the model assumes hazards and controls are given in lists, there is no theoretical limit to the size of the problem that could be solved using this approach. All one needs to do is add rows and columns to the spreadsheet corresponding to controls and hazards and data about loss, effectiveness, and cost. There is a practical upper limit to problem size, however, because there is an upper limit to the number of variables and constraints that Solver© can accommodate in Excel.

To simplify the model, all data was included in the cells of the spreadsheet. The model could be enhanced to obtain data interactively from the user. Another possible extension would be to provide the user with tools such as the Analytic Hierarchy Process (Saaty, 1988) which can facilitate estimating risk levels and placing a monetary value on residual risk. The user could also be permitted to review and/or override effectiveness measures. Although the values used for costs and effectiveness measures in the example are arbitrary, expert opinions could be incorporated into the model.

Although the intent of the model is to aid in the design of new IS, it could be modified to be used by auditors to evaluate controls in an existing system. Application to an existing system would also allow one to fine tune it to make it more cost effective. The model can also be easily adopted to non-computerized systems. After all, not all information systems are computer-based. Such systems also have a need for cost-effective controls.

In order to generalize the implementation of this model the following research directions are recommended: (a) develop a methodology for quantifying the residual risk; (b) experiment with models of varying numbers of controls and risks to investigate practical upper limits on the size of model that can be solved with Excel; (c) develop a methodology for assessing the effectiveness of the various controls; (d) identify potential applications for the model; and (e) expand the model to deal with special situations.

In summary, the chief advantage of using a spreadsheet package to find an optimal solution to the problem of selecting IS controls is that such tools are widely available today and very familiar to business professionals. Furthermore, the approach presented here can be implemented very quickly in any internal control system, assuming the availability of the necessary parameters. One need only substitute in the existing parameters characterizing the situation to be modeled.

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Appendix

QUANTIFYING DEPENDABILITY

UNCONTROLLED RISK

A *hazard* is an event likely to result in failure to meet a business objective. There are two parameters associated with each hazard: likelihood and opportunity. Hazard likelihood is the probability that a hazard will occur given an opportunity. For example, if one hundredth of one percent of all customer order transactions is lost, then hazard likelihood is 0.0001. The hazard opportunity is the number of times a processing task subject to a hazard is performed during a time interval. If ten thousand transactions are processed during a given period, then the hazard opportunity is ten thousand. To formalize these ideas, let $Z = \{Z_j \mid j = 1,\ldots,q\}$ be a set of hazards associated with a business objective. The hazard opportunity for Z_j is denoted $T(Z_j)$ and the hazard likelihood by $A(Z_j)$.

A *consequence* is an outcome which may arise from any of several hazards and which may be assigned a monetary value. Multiple consequences may arise from a single hazard and multiple hazards may result in a single consequence. For example, loss of a customer order transaction (hazard) may result in a loss of the revenue arising from that order (consequence). To facilitate formal discussion of consequences, let Q be a set of consequences associated with the set Z: $Q = \{Q_k \mid k = 1,\ldots,r\}$. There are two parameters associated with a consequence: consequence likelihood and potential loss. Consequence likelihood $M(Q_k|Z_j)$ is the conditional probability that a consequence, Q_k, will occur given that the corresponding hazard, Z_j, has occurred. For example, if when a customer order transaction is lost it results in loss of revenue forty percent of the time, then the conditional likelihood of lost revenue given a lost order is 0.4. The second parameter associated with a consequence is its potential loss, denoted by $L(Q_k)$, which is defined to be the monetary loss associated with a consequence.

The *uncontrolled risk*, R, for a hazard Z_j is the expected monetary loss associated with the occurrence of Z_j if no controls are in place. It is calculated using the parameters of hazards and consequences:

r

$R(Z_j) = A(Z_j)T(Z_j) \sum_{k=1} M(Q_k|Z_j)L(Q_k)$

CONTROL EFFECTIVENESS

Let $X = \{X_i | i = 1,\ldots,s\}$ be a set of s controls and $Z = \{Z_j | j = 1,\ldots,q\}$ be a set of q hazards. We define the effectiveness, $E(X_i, Z_j)$, of a control X_i in counteracting a hazard Z_j as the probability the X_i will be successful in counteracting Z_j. This probability is designated as:

$P(X_i$ succeeds with respect to $Z_j)$.

To understand the mathematics of combining controls, we will examine the interaction of two preventive controls that counteract the same hazard (Cushing, 1974). For convenience, we temporarily drop the notation related to the hazard, Z_j, in the discussion below. Let:

$S(X_i) = P(X_i$ succeeds with respect to $Z_j)$ and
$F(X_i) = P(X_i$ fails $) = 1 - S(X_i)$.

Assume that two controls, X_i and X_k, may counteract the same hazard. The hazard will be counteracted if either one or both controls succeed:

$S(X_{i,} X_k) = P(X_i$ succeeds, or X_k succeeds, or both succeed $)$

The hazard will not be counteracted if both controls fail:

$F(X_i, X_k) = P(X_i$ fails and X_k fails $)$.

Thus, $S(X_i, X_k) = 1 - F(X_i, X_k)$.

Assuming that $F(X_i)$ is independent of $F(X_k)$ yields:

$$S(X_i, X_k) = 1 - F(X_i)F(X_k) = 1 - [1 - S(X_i)][1 - S(X_k)].$$

Net effectiveness (NE) is the combined effectiveness of all controls which counteract a hazard. This, the net effectiveness of a pair of controls X_i and X_k, for a hazard Z_j, can be defined as:

$$\text{NE}((X_i, X_k), Z_j) = 1 - [1 - E(X_i, Z_j)][1 - E(X_k, Z_j)]. \qquad (1)$$

Generalizing to a set of s controls that counteract the same hazard, Z_j, this analysis can be extended to yield:

$$\text{NE}(X, Z_j) = 1 - \prod_{i=1}^{s} [1 - E(X_i . Z_j)] \qquad (2)$$

Where $X = \{X_i | i = 1, \ldots, s\}$.

This model assumes the independence of the effectiveness of different controls. Practically speaking, this means that failure of one control to counteract a hazard is associated with neither an increase nor a decrease in the likelihood that a second control will counteract the hazard. This assumption is valid in most cases. For example, if both password identification and encryption are being used to prevent unauthorized access to data, the fact that a perpetrator has obtained a password does not necessarily mean that he can decrypt the data. The fact that a limit check on a value has failed does not imply that a control total will also fail. Sometimes, however, failure of one control can be related to failure of another. A natural disaster, for example, may result in the destruction of a database together will all backups, transaction logs, and audit trails. In general, however, independence is a reasonable assumption and greatly reduces model complexity.

The preceding analysis assumed that a set of controls is successful if at least one control is successful. This is an appropriate assumption if all controls are preventive. Additional analysis is necessary when detective and corrective controls are introduced. A detective control signals the occurrence of a hazard, but does nothing to counteract it (Hall and Singleton, 2005). A corrective control must be applied to counteract the detected hazard. To see this, consider the following example. Comparing a "total" generated during on-line transaction processing with one generated manually is called a "control total" and can be used to detect data entry errors. A control total is an example of a detective control. An associated corrective control might involve reviewing the data entered to determine where the error was made and correcting it by re-entering the data. Thus, for the hazard to be counteracted, both the detective and corrective control must be successfully applied.

Let X_d be a detective control and X_c be a corrective control. (Again, for convenience, we have temporarily dropped the notation related to the hazard, Z_j.) The probability model for success in this case is then:

$$S(X_d, X_c) = P(X_d \text{ succeeds and } X_c \text{ succeeds}).$$

If we assume the independence of the probability of success of X_d and X_c then:

$$S(X_d, X_c) = S(X_d)S(X_c).$$

If X_d and X_c counteract Z_j then:

$$S(X_d, X_c) = S(X_d)S(X_c) = E(X_d, Z_j)E(X_c, Z_j). \qquad (3)$$

Now further suppose that a preventive control, X_p also counteracts Z_j and is independent of the combination of X_d and X_c. The combined effectiveness of the three controls X_p, X_d, and X_c can be calculated, Using Eqs. (2) and (4), to be:

$$\text{NE}(X, Z_j) = 1 = \lfloor 1 - E(X_d, Z_j) E(X_c, Z_j) \rfloor \lfloor 1 - E(X_p, Z_j) \rfloor \qquad (4)$$

where $X = \{X_d, X_c, X_p\}$.. Other controls can be added in a similar manner.

While the complexity of expression (4) grows rapidly as the number of controls increases, it is still feasible to define and evaluate such an expression, given a particular hazard and a single set of controls. The control selection problem addressed in this paper, however, is actually more complex. Given a particular hazard, and N potential controls to counteract it, then there exist 2^N possible combinations of controls, each of which yields the complex evaluation expression (4). The computations required to select the best combination of controls for a single hazard grows exponentially with the number of controls. Therefore, the selection of the optimal set of controls for a given set of hazards for problems of real world size is computationally complex and costly.

Equation (1) is multiplicative in (1-E). Similarly, Eq. (3) is multiplicative in E. Equation (4), however, is more complex than either (1) or (3). A simplifying assumption, that at least one corrective control is always used whenever a detective control is applied, allows Eq. (4) to be expressed in the form of Eq. (1). Since it makes little sense to spend money to detect a hazard if nothing is going to be done to correct it (once it has been detected), then the above simplifying assumption is basically realistic. A possible drawback of this simplification is that there may be more than one possible corrective control that may be chosen to be combined with a detective control. When this case arises, each corrective control can be combined with the detective control to form a combination that becomes one of the alternatives to be evaluated. This assumption allows a detective-corrective control combination to be considered as a single unit that behaves mathematically like a preventive control in Eq. (1).

Transforming the problem from Eq. (4) to Eq. (1) is especially advisable when problems are large. Anyone attempting to solve Eq. (4) will face a nonlinear equation whose optimization will take a great deal of time even with today's computing technologies. Equation (1), which is also non-linear, is more readily solved.

Cost is the second important attribute of a control. Control cost $C(X_i)$ is the present value of the cost of developing and operating a control, X_i. Total control cost (TCC) is the sum of the costs of all controls in a system of controls:

$$\text{TCC} = \sum_{i=1}^{s} C(X_i). \quad (5)$$

Now that we have formulated the effectiveness and cost components of the model, we return to the element of risk presented earlier. Let $R(Z_j)$ be the anticipated monetary loss associated with the occurrence of a hazard Z_j when *no controls* are used. If in a given context there exist q hazards, the total uncontrolled risk (TUR) is the sum of the uncontrolled risk for all hazards:

$$\text{TUR} = \sum_{j=1}^{q} R(Z_j) \quad (6)$$

We will relate the notion of uncontrolled risk (R) to that of net effectiveness (NE) be defining a new concept called *residual risk* (RR) for a hazard Z_j that is measured in monetary units and defined as:

$$\text{RR}(Z_j) = R(Z_j)[1 - NE(X, Z_j)]. \quad (7)$$

Note that the independence of hazard occurrence and control effectiveness mentioned earlier is implicit in Equation (7).

Total residual risk (TRR) is obtained by summoning all residual risks over all hazards:

$$\text{TRR} = \sum_{j=1}^{q} \text{RR}\left(Z_j\right) \tag{8}$$

A summary measure of the extent to which an IS achieves its dependability objectives is the dependability quotient (DQ) defined as:

DQ= (TUR- TRR)/TUR. (9)

In Eq. (9), DQ = 1 when total residual risk, TRR, is 0. This case would arise when a set of controls counteracted all hazards, making the IS completely dependable. Conversely, DQ = 0 implies that the total uncontrolled risk, TUR, is equal to TRR. This case would arise when no hazards were counteracted. Since most IS would include one or more controls but would not counteract all hazards, DQ would normally be greater than zero but less than one. The more dependable a system, the closer its dependability quotient is to one.

The total cost, TC, of the control system for an IS is then:

$$\text{TC} = \text{TCC} + \text{TRR} = \sum_{i=1}^{s} C\left(X_i\right) + \sum_{j=1}^{q} R\left(Z_j\right) \prod_{i=1}^{s} \left[1 - E\left(X_i, Z_j\right)\right] \tag{10}$$

The function arguments X_i and Z_j can be dropped from Eq. (10) to yield the slightly simpler notation:

$$\text{TC} = \sum_{i=1}^{s} C_i + \sum_{j=1}^{q} R_j \prod_{i=1}^{s} \left[1 - E_{ij}\right] \tag{11}$$