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Cross-impact analysis using group decision support systems: an application to the future of Hong Kong[1]

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Abstract

When several interdependent events affect the future of an organization, an industry, or a society, it is often useful to know how these events may affect each other. Determining the impact of external events on other such events, called a cross-impact analysis, is usually accomplished by asking knowledgeable people to (1) discuss any relationships among the events and (2) provide subjective estimates of conditional probabilities relating the events. However, there are two possible problems. First, in some political environments people may be reluctant to discuss the events openly. Second, the subjective probability estimates may violate the laws of probability theory, such as Bayes' theorem. We present a simple method, using group decision support systems (GDSS), for eliciting anonymous comments and preparing consistent probability estimates concerning interdependent events. We then illustrate our method by using it to perform a cross-impact analysis concerning the future of Hong Kong.

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1. Introduction

The futures of organizations are determined not only by such organizational activities as introducing new products and investing in new technologies, but also by a variety of external events over which the organizations have little or no control. Examples are consumer response to corporate marketing efforts, competitive price changes, and government regulatory activities. Events such as these may be partially dependent on each other, and it is useful to investigate any relationships among them. Such an investigation is called a cross-impact analysis [1, 2].

Cross-impact analyses are often performed by estimating quantitatively the impact of each variable of interest on each other such variable. One way of doing this is to construct a mathematical model relating the variables, such as an input–output model [3], a sequence-dependent (decision tree) model [4, 5], or a dynamic (multistage) model [6]. Another approach is to ask knowledgeable people to provide subjective estimates of the relationships among the variables, usually in the form of a matrix of conditional probabilities [7, 8]. In the latter case, the cross-impact method is sometimes combined with the Delphi method: the persons providing probability estimates are periodically asked to justify or revise any of their estimates that differ substantially from the group norm, in an attempt to obtain a consistent set of estimates for the group [9–11].

There are three difficulties with these approaches to cross-impact analysis. First, the data needed to construct formal models may not be forthcoming, so that informal discussions of relationships and subjective estimation of conditional probabilities become necessary. Second, the Delphi method allows anonymity among the experts being consulted but does not allow for discussion and a dynamic interchange of ideas. In other words, the participants cannot easily present ideas, critique the ideas of others, and respond to critiques of their own ideas. Third, requesting subjective estimates of marginal and conditional probabilities may result in inconsistent estimates—that is, estimates that violate the laws of probability theory, such as Bayes' theorem.

We present here a methodology for cross-impact analysis that allows for anonymous discussion and that produces consistent probability estimates. Our method makes use of group decision support systems (GDSS). GDSS allow groups of people seated at personal computers, integrated through a local area network, to engage in anonymous discussions by entering comments and responding to the comments of others. The users may also enter data, such as subjective probability estimates or preference rankings, which are then processed by the GDSS.

We begin in the following section with a brief overview of GDSS. Then we present our methodology for cross-impact analysis using GDSS. Finally we illustrate our methodology by applying it to the future of Hong Kong.

2. DSS and GDSS

The field of DSS research and practice has undergone substantial changes during the past 25 years [12,13]. During its early days (approximately, 1975–1985), most developers and users of DSS assumed that DSS were to be used by an individual manager or analyst, such as a marketing manager or a financial analyst. Most DSS were user-friendly data retrieval and display systems or systems that contained interactive decision models. Although the information generated by these early DSS might be used by a group of people (e.g., a management committee), the separate identities of the users were not considered in the design of the DSS.

All of this changed with the development of GDSS [14–16]. The purpose of GDSS is to integrate the separate decision processes of the members of a group of managers or analysts, such as a committee, the members of a department, or an ad hoc team. Each participant (i.e., member of the group) is seated in front of a desktop (client) computer connected to a server. The participants can enter comments, view the comments of others, and respond to them if they wish. The process is both anonymous and simultaneous. When a participant enters a comment, the comment is numbered by the GDSS software, but the participant is not identified. Thus, the participants respond to numbered comments, not to named individuals. This allows the participants to engage in frank and open discussion about controversial subjects and to focus on ideas rather than on personalities. In addition, participants enter their comments simultaneously, which is far more efficient for larger groups than is the case with face-to-face meetings, in which only one person is supposed to speak at a time [17].

There are several ways in which electronic discussions can take place in a GDSS. If there is a single topic for discussion, then all of the participants' comments would be entered and would appear on a single screen. If the topic consists of several subtopics and it is important to obtain comments on all of them, then a second approach may be used. The participants would be presented with a screen containing several electronic folders, each containing a discussion screen that corresponds to one of the subtopics. The participants can move back and forth between folders participating in the various discussions. The disadvantage of this method is that the group may collectively devote a disproportionate amount of effort to a few folders and ignore the remainder.

A third method, sometimes called 'electronic brainstorming', is intended to overcome this disadvantage. This is the method we will use for cross-impact analysis. Each participant is presented with a different screen containing instructions to comment on a particular subtopic. After the participant has entered a comment, the screen for that subtopic is transmitted electronically to another participant, selected at random. This process continues until a sufficient number of comments have been generated or until a preselected time limit is reached. The advantage of electronic brainstorming is that a large number of subtopics can be presented to the group, with fairly uniform coverage of each.

GDSS can be used not only for discussion but also for voting. The participants may be asked to enter numerical or qualitative data representing probabilities or preferences. They may also be asked to rank various items in terms of likelihood or importance. Voting, like discussion, is both anonymous and simultaneous. The GDSS software manages the voting process by checking the input data for errors (e.g., ensuring that probabilities are between zero and one) and by aggregating the results—for example, in the form of averages, standard deviations, and rank sums.

A GDSS session is usually managed by a facilitator. The facilitator does not participate in the discussion or voting. Rather, he or she decides when to terminate one part of a session and to initiate another. This often consists of terminating a discussion and initiating a vote on some feature of the topic just discussed. The facilitator may also instruct the GDSS to record the discussion and voting, with anonymity preserved, for subsequent analysis.

3. Cross-impact analysis using GDSS

There are five stages to the use of GDSS in cross-impact analysis (Fig. 1). Fig. 1(a) illustrates the five stages in temporal sequence, showing the various times at which the stages start and stop. Fig. 1(b) illustrates the five stages in logical sequence, showing the information being passed between the various stages.

In Stage I we identify an appropriate set of events for analysis. Since we are concerned with ordered pairwise relationships among the events, a set of N events will result in $R = N(N - 1)$ possible relationships to be analyzed. As we shall see in the second stage, R should be approximately equal to the size of the group, which suggests that there should be four ($R = 12$) or five ($R = 20$) events in the set. The events may be selected by the person or persons performing the cross-impact analysis or they may be identified during a previous GDSS session.

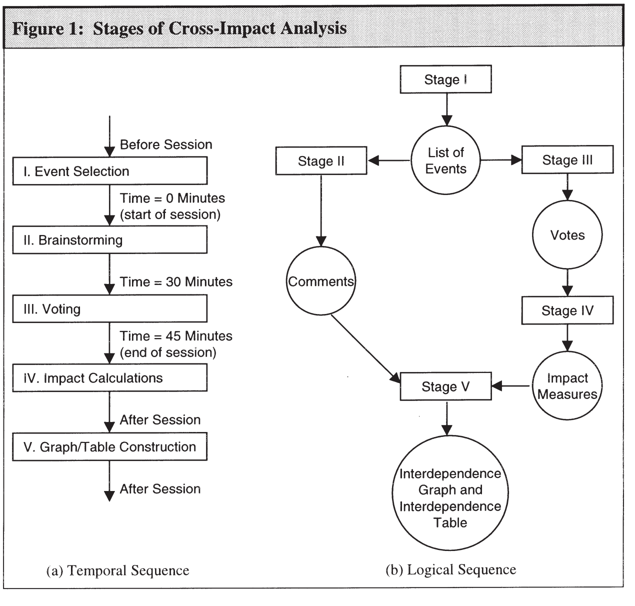

Fig. 1. Stages of cross-impact analysis. (a) Temporal sequence, (b) logical sequence.

In Stage II electronic brainstorming is used to elicit comments about the R possible relationships among the N events of interest. Each participant is presented with a screen asking him or her to comment on the possible impact of one of the N events on one of the remaining $N - 1$ events. Therefore, there should be approximately R participants in the electronic brainstorming session. At the top of the screen a message of the following form will appear:

> Assume that the following event has occurred: {description of one of the events}. Would it have any impact on the likelihood of this event: {description of another event}? If so, please state the reasons.

Some of this information will appear in the Cross-Impact Table, as described below.

The purpose of Stage III is to obtain quantitative impacts of each of the N events on each of the remaining $N - 1$ events. Specifically, we wish to obtain (1) a set of N marginal probabilities for the N events, (2) a set of R conditional probabilities for each of the N events given that each of the remaining $N - 1$ events occurs, and (3) a set of R conditional probabilities for each of the N events given that each of the remaining $N - 1$ events does not occur. If we let α and β denote two events, we wish to determine (1) N probabilities of the form $p(\beta)$, (2) R conditional probabilities of the form $p(\beta|\alpha)$, and (3) R conditional probabilities of the form $p(\beta|\neg\alpha)$, where $\neg\alpha$ means that α does not occur. Thus, we wish to obtain N marginal probability estimates and $2(N^2 - N)$ conditional probability estimates.

One way to obtain these estimates is to ask the participants in the GDSS session to supply them directly. There are two problems with this. First, the number of estimates may be quite large. For example, if there are five events ($N = 5$), then the participants will be asked to provide five marginal probability estimates and 40 conditional probability estimates. Second, these estimates will almost certainly violate the laws of probability theory, and there may be many instances of such violations. Examples of violations are given in Appendix A.

Several methods have been developed for modifying a set of marginal and conditional probabilities in order to minimize inconsistencies [18–21]. However, there is a simple method for obtaining consistent estimates while placing a minimal burden on the participants. Each participant is asked to estimate whether each event will or will not occur. Thus, each participant is asked to enter N yes/no estimates. Then:

1. $p(\beta)$ is the number of participants who estimated that β will occur divided by the total number of participants;
2. $p(\beta|\alpha)$ is the number of participants who said that α and β will both occur divided by the number of participants who said that α will occur;
3. $p(\beta|\neg\alpha)$ is the number of participants who said that α will not occur but β will occur divided by the number of participants who said that α will not occur.

Although this method avoids the inconsistencies referenced above and summarized in Appendix A, it has two limitations. These limitations are not serious for most cross-impact studies and do not present a problem for the Hong Kong study described below. The first limitation is that there must be a sufficient number of participants that the denominators of these ratios be of reasonable size. We recommend that there be approximately 20 participants, which is the number used in our Hong Kong study. This will allow for sufficiently large denominators in the probability estimates.

The second limitation is that the events under consideration must not be extremely likely (i.e., with a probability very close to 1) or extremely unlikely (i.e., with a probability very close to 0). Otherwise, the numerators or denominators of some of these ratios will be zero, even with a large number of participants, and the corresponding conditional probabilities will be undefined. However, one would seldom select such extreme events for a cross-impact analysis. If it is agreed that an event will almost certainly occur, one would generally not wish to estimate conditional probabilities based on the assumption that the event will not occur. Similarly, if an event will almost certainly not occur, one would generally not wish to estimate conditional probabilities based on the assumption that the event will occur.

This did not present a problem in our Hong Kong study. The range of marginal probabilities, presented below, was 0.3 to 0.8, which suggests that our events were somewhat controversial. That is, reasonable and knowledgeable people could argue that the events will occur or that the events will not occur. These are the kind of events that one would expect to encounter in a cross-impact analysis.

During Stage IV we construct a measure of the impact of each event on each other event. For any pair of events, α and β, there are three probability estimates for β: $p(\beta|\alpha)$, $p(\beta|\neg\alpha)$, and $p(\beta)$. We note that $p(\beta)$ is bracketed by the two conditional probabilities—that is, $p(\beta)$ lies between $p(\beta|\alpha)$ and $(\beta|\neg\alpha)$. This is proven in Appendix B. Therefore, we will define the impact of α on β as the difference between the two conditional probabilities, and we will denote it as IMP(α, β). Thus, IMP(α, β) $= p(\beta|\alpha) - p(\beta|\neg\alpha)$. We note that IMP($\alpha$, β) can be positive, negative, or zero. It will be zero if and only if α and β are independent. We also note that in general IMP(α, β) will not equal IMP(β, α).

During Stage V the impact measures are used to construct an Interdependence Graph and an Interdependence Table. The graph will consist of nodes (circles) corresponding to the events and arcs (arrows) connecting them whenever the corresponding impact measure exceeds a certain threshold. The threshold is determined by the persons performing the cross-impact analysis so as to highlight the most salient relationships. We recommend that there be two thresholds, one separating high impacts from medium impacts, and one separating medium impacts from low impacts. The high and medium impacts will be denoted in the Interdependence Graph by solid thick and dashed thin arrows, respectively. We suggest that the low impacts not be represented in the Interdependence Graph.

The symbols ‘ + ’ and ‘ − ’ may be used to denote positive or negative impact measures. If for any two events, α and β, IMP(α, β) and IMP(β, α) are high and/or medium (i.e., neither one of them is low), then the ‘ + ’ or ‘ − ’ sign need be drawn only once, since the sign (positive, negative, or zero) of IMP(α, β) is the same as that of IMP(β, α). This is demonstrated in Appendix C.

The Interdependence Table will list each of the arcs in the Interdependence Graph (i.e., each ordered pair of events for which the impact measure is high or medium), along with selected comments about the relationships between them taken from the electronic brainstorming session in the second stage of this process. As with the Interdependence Graph, we suggest that the low impacts not be represented in the Interdependence Table.

We note that the Interdependence Graph and the Interdependence Table need not be in complete agreement. For example, the participants may appear to argue for a strong positive relationship in the Interdependence Table, yet the impact measure based on their votes may be negative, or vice versa. We suggest that in this case it will be difficult to draw any conclusions about the relationships between the probabilities of the corresponding events. Thus, the Interdependence Graph and the Interdependence Table are complementary sources of information about the direction and strength of relationships, but they may be contradictory.

4. The Hong Kong transition

On July 1, 1997 the British Dependent Territory of Hong Kong became the Hong Kong Special Administrative Region of the Peoples' Republic of China. Prior to this change in sovereignty Hong Kong had one of the most vigorous laissez faire capitalist economies in the world, with little government interference in business and an emphasis on the creation of wealth rather than on its redistribution. China, on the other hand, is one of the few remaining Communist countries in the world, committed in large measure to a dictatorship of the proletariat by means of a powerful one-party state and a tight (but gradually loosening) public control of the means of production and distribution.

There are two other important differences between pre-transition Hong Kong and China. First, although Hong Kong has had a history of corruption, within the past 25 years it has taken stern measures, through a powerful Independent Commission Against Corruption, to root out and punish corrupt practices, especially bribery of public officials. China, on the other hand, is widely regarded as one of the most corrupt countries in Asia, and there is concern that China's corruption will find its way across the border into Hong Kong. Second, Hong Kong has been fairly tolerant of public dissent, especially during the past 15 years, whereas China severely punishes people who publicly disagree with its system of government or with decisions made by those in authority. There is concern that people in Hong Kong will be increasingly reluctant to speak freely about important issues. The principal reason will probably not be overt restrictions on free speech but rather a general desire to be 'redder than red' and to avoid any possibility of offending Communist Party officials in Beijing.

Because of these and other differences, there is a variety of opinions among knowledgeable people concerning the future of Hong Kong under Chinese rule. Some observers argue that China needs a successful Hong Kong for economic and political reasons (the principal political reason being to facilitate the recovery of Taiwan) and therefore, that it will not intervene excessively in Hong Kong affairs [22,23]. Other observers are more pessimistic, arguing that China does not understand how a free economy and a democracy works and that it will inadvertently or deliberately take actions detrimental to Hong Kong [24,25]. Other factors, such as the possibility that the U.S. may at some point revoke China's most favoured nation status (MFN), may also affect Hong Kong's future.

This suggests a need to (1) identify events that are important to the future of Hong Kong, (2) determine how these events may affect Hong Kong, and (3) determine how these events may affect each other. We are concerned here only with the last of these three—that is, with cross-impact analysis. In previous work we have examined the use of GDSS in identifying important events and in assessing their impact on Hong Kong [26,27].

The principal reason for using a GDSS in this work is the need for anonymity, with efficiency as a secondary consideration. It has been suggested that the need for anonymity is already becoming apparent in Hong Kong, in that public officials and journalists are beginning to restrict their speech in order to please officials in China [28,29]. However, many people seem unconcerned about these implicit political restrictions as long as the Hong Kong economy remains healthy. In the words of a popular satirical book about Hong Kong, consisting of excerpts taken from a newspaper comic strip whose author was fired for being too outspoken, "Let's all shut up and make money" [30].

5. A cross-impact analysis of Hong Kong

Five months after the transfer of sovereignty a GDSS session was held with 20 middle managers in Hong Kong to perform a cross-impact analysis on five events relevant to the business future of Hong Kong. The GDSS was GroupSystems by Ventana Corporation [31], which is one of several commercially-available GDSS [32]. The participants were residents of Hong Kong working for multinational corporations, mostly in the financial community. The session lasted 45 minutes.

In Stage I we selected five events for the cross-impact analysis. The events are defined in Table 1. We selected the events based on our previous experiences in

Table 1
List of events

- *China loses MFN status*. The US President and Congress decide not to renew MFN status for China. They suggest that the US will not grant MFN status to China for many years.
- *Corruption becomes widespread in Hong Kong*. Many government officials demand and receive bribes. The ICAC is unable to stop them.
- *The peg between the Hong Kong dollar and the US dollar is removed*. As a result, the Hong Kong dollar floats on the open currency market.
- *China intervenes in the Hong Kong economy*. The intervention is informal but strong. Political and business leaders in Hong Kong find it necessary to consult with political leaders in Beijing before making major decisions.
- *Conflict between China and Taiwan escalates*. Chinese military exercises in the Taiwan Straits escalate to the point that they become a virtual blockade of Taiwan.

performing political event studies and scenario development in Hong Kong, as was mentioned above.

In Stage II we used electronic brainstorming to obtain comments about the possible impact of each of these events on each of the other events. One of the 20 comment screens appears in Fig. 2.

In Stage III we asked the participants to vote on whether each of the events would or would not occur. The voting screen is illustrated in Figs. 3 and 4. The votes of the 20 participants appear in Table 2. The marginal probabilities $p(\beta)$ and the conditional probabilities $p(\beta|\alpha)$ and $p(\beta|\neg\alpha)$ appear in Tables 3 and 4.

In Stage IV we calculated the impact coefficients IMP(α, β). These appear in Table 5.

In Stage V we used the impact coefficients to construct an Interdependence Graph (Fig. 3), and we used the comments from Stage II to construct an Interdependence Table (Table 6). Our threshold for a high impact was 0.3 in absolute value, and our threshold for a medium impact was 0.25 in absolute value. Any impacts below 0.25 in absolute value were considered low. Of the 20 ordered pairs of events, three had high impact, five had medium impact, and 12 had low impact. The 12 ordered pairs of events having low impact do not appear in the Interdependence Graph or in the Interdependence Table.

The principal conclusion of this study is that loss of MFN status by China will

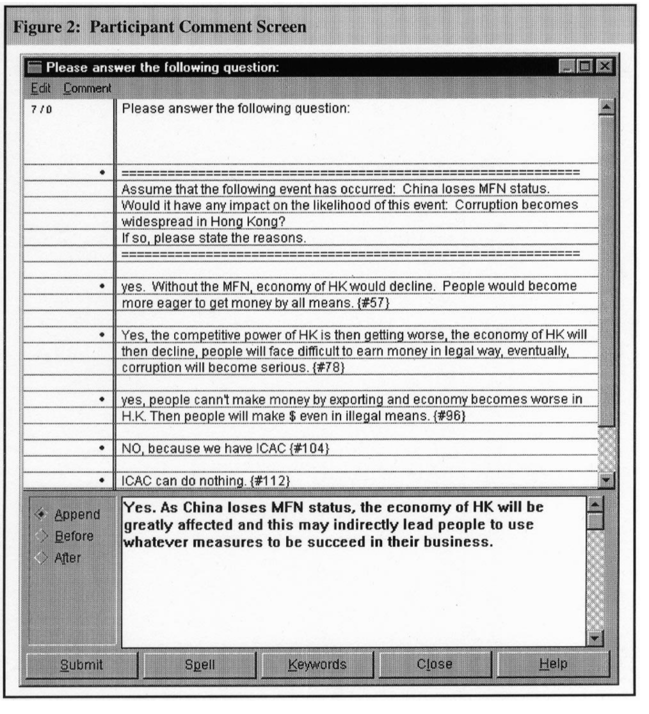

Fig. 2. Participant comment screen.

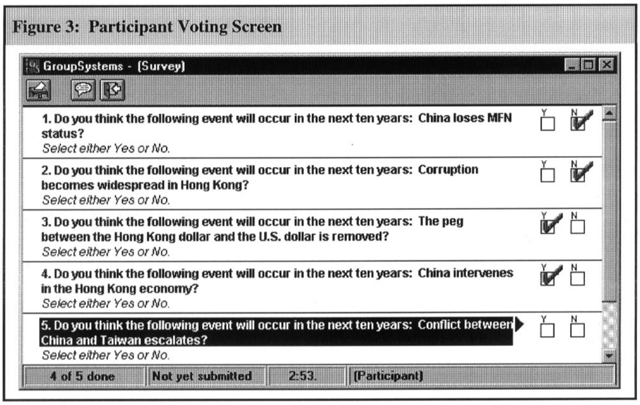

Fig. 3. Participant voting screen.

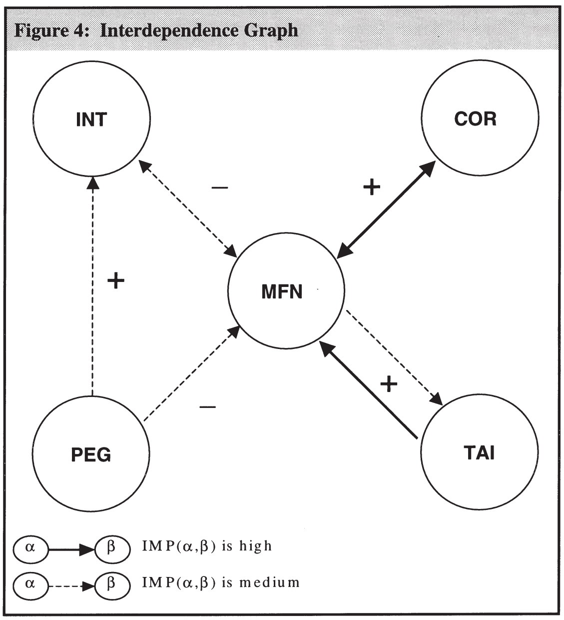

Fig. 4. Interdependence Graphy.

impact and be impacted by three other events: widespread corruption in Hong Kong, conflict between China and Taiwan, and interference by China in the Hong Kong economy.

The first of these three consists of a pair of positive, high impact relationships—that is, an increase in the probability of China's losing MFN status will lead to an increase in the probability of widespread corruption in Hong Kong, and vice versa. To some extent, rationales for these impacts can be gleaned from the electronic

Table 2
Voting data

Event:	MFN	COR	PEG	INT	TAI
Raw data:	1	1	1	1	1
(N = 20)	1	1	1	1	1
	0	1	1	1	0
	0	0	1	1	1
	0	0	1	1	1
	1	1	0	1	1
	0	0	1	1	0
	1	0	1	0	1
	0	0	0	0	0
	0	0	1	0	1
	0	0	1	1	1
	1	0	0	0	1
	1	1	1	0	1
	0	0	1	1	1
	0	1	0	1	1
	0	0	1	1	1
	0	0	1	1	0
	0	1	1	0	1
	0	1	1	1	1
	0	0	1	1	1
Total:	6	8	16	14	16
Probability:	0.30	0.40	0.80	0.70	0.80

MFN: China loses MFN status.
COR: Corruption becomes widespread in Hong Kong.
PEG: The peg between the Hong Kong dollar and the US dollar is removed.
INT: China intervenes in the Hong Kong economy.
TAI: Conflict between China and Taiwan escalates.

brainstorming session as presented in the Interdependence Table. For example, the argument that a loss of MFN status for China will increase the probability of corruption in Hong Kong is that a loss of MFN status will cause the Hong Kong economy to decline, which in turn will induce people to engage in more illegal activities. On the other hand, none of the participants gave a rationale for the reciprocal impact (increased corruption in Hong Kong would lead to loss of MFN status for China), even though their voting behaviour results in a high positive impact.

The second of these consists of a pair of positive relationships: one high and one medium. An increase in the probability of losing MFN status will lead to an increase in the probability of conflict between China and Taiwan, and vice versa. The impact of conflict on MFN is high; the argument is that if a conflict begins, the United States will revoke MFN status in the hope that this will induce China to stop 'bullying' Taiwan. The impact of MFN on conflict is medium; the argument is that if China loses MFN status, it will have less incentive to leave Taiwan alone and may initiate a conflict.

The third of these is quite surprising: a pair of negative, medium impact relation-

Table 3
Probabilities of events assuming other events do occur

		The probability of this event becomes:				
		MFN	COR	PEG	INT	TAI
If this event occurs:	*Marginal probability*⟶	0.30	0.40	0.80	0.70	0.80
MFN:	China loses MFN status.		0.67	0.67	0.50	1.00
COR:	Corruption becomes widespread in Hong Kong.	0.50		0.75	0.75	0.88
PEG:	The peg between the Hong Kong dollar and the US dollar is removed.	0.25	0.38		0.75	0.81
INT:	China intervenes in the Hong Kong economy.	0.21	0.43	0.86		0.79
TAI:	Conflict between China and Taiwan escalates.	0.38	0.44	0.81	0.69	

Table 4
Probabilities of events assuming other events do not occur

		The probability of this event becomes:				
		MFN	COR	PEG	INT	TAI
If this event does not occur:	*Marginal probability*⟶	0.30	0.40	0.80	0.70	0.80
MFN:	China loses MFN status.		0.29	0.86	0.79	0.71
COR:	Corruption becomes widespread in Hong Kong.	0.17		0.83	0.67	0.75
PEG:	The peg between the Hong Kong dollar and the US dollar is removed.	0.50	0.50		0.50	0.75
INT:	China intervenes in the Hong Kong economy.	0.50	0.33	0.67		0.83
TAI:	Conflict between China and Taiwan escalates.	0.00	0.25	0.75	0.75	

ships. Specifically, an increase in the probability of China's losing MFN status will lead to a decrease in the probability of intervention by China in the Hong Kong economy, and vice versa. This is surprising because the arguments given by the participants suggest the opposite conclusion. That is, the participants argued that an increase in the probability of either of these two events would lead to an increase in the probability of the other. Since the quantitative votes and the narrative comments contradict each other, we probably cannot draw any conclusion about the relationship between MFN and intervention.

Another surprising result is the negative, medium strength impact concerning the

Table 5
Impact scores

High impact scores	IMP(MFN,COR)	0.38
	IMP(TAI,MFN)	0.38
	IMP(COR,MFN)	0.33
Medium impact scores	IMP(MFN,INT)	− 0.29
	IMP(MFN,TAI)	0.29
	IMP(INT,MFN)	− 0.29
	IMP(PEG,MFN)	− 0.25
	IMP(PEG,INT)	0.25
Low impact scores	IMP(MFN,PEG)	− 0.19
	IMP(INT,PEG)	0.19
	IMP(TAI,COR)	0.19
	IMP(COR,TAI)	0.13
	IMP(PEG,COR)	− 0.13
	IMP(INT,COR)	0.10
	IMP(COR,PEG)	− 0.08
	IMP(COR,INT)	0.08
	IMP(PEG,TAI)	0.06
	IMP(TAI,PEG)	0.06
	IMP(TAI,INT)	− 0.06
	IMP(INT,TAI)	− 0.05

peg between the Hong Kong and U.S. dollars and the loss of China's MFN status. Although the participants' votes result in a negative impact measure, they argued for the opposite. Therefore, we probably cannot draw any conclusion about the impact of removing the peg on a loss of MFN status.

There was only one high or medium impact that did not involve MFN. This demonstrates the importance of China's MFN status to Hong Kong business executives. The exception is the medium but positive impact of removing the dollar peg on China's intervention in Hong Kong. The argument is that Hong Kong may not be able to handle the resulting economic problems, causing China to intervene.

6. Conclusion

In performing cross-impact analyses it is useful to obtain confidential comments from knowledgeable people about possible relationships among important events. The method we have presented here allows these people to engage in confidential conversations about these relationships and to estimate whether these events will come to pass.

An interesting feature of our method is that the participants provide both narrative and quantitative information. The narrative information consists of arguments concerning relationships among the events of interest. The quantitative information consists of votes that can be used to calculate probabilistic impact measures. If both of them are in agreement, then our method will furnish (1) an estimate as to whether

Table 6
Interdependence table

Antecedent	Consequent	Impact coefficient	Impact code	Response to Question: Assume that the following event has occurred: *Antecedent*. Would it have any impact on the likelihood of this event: *Consequent*? If so, please state the reasons.
MFN	COR	0.38	H +	"Yes, the competitive power of HK is then getting worse, the economy of HK will then decline, people will face difficult to earn money in legal way, eventually, corruption will become serious."
COR	MFN	0.33	H +	"No, corruption now widespread in China which still enjoys MFN. Even corruption widespread in H.K., it will have no effect on MFN."
TAI	MFN	0.38	H +	"Yes, some stupid US senators may collectively bargain with Clinton to use it as a weapon to stop China bullying Taiwan."
MFN	TAI	0.29	M +	"The Beijing goverement has a restricted attitude toward the Taiwan independence taking the consideration of the US's MFN status. now, as the status lose, the Beijing found no necessary to care the US's feelings."
INT	MFN	−0.29	M −	"Yes. As HK's autonomy is highly monitored by the world and the US government has stressed that she will closely monitor the human rights and autonomous condition in HK. If China does intervene HK's autonomy, US may use the MFN treatment as a leverage on the issue."
MFN	INT	−0.29	M −	"Yes. If China loses MFN status the local economy will be affected which may affect the confidence of foreign investors and the successful implementation of the "One Country, two system" concept. To ensure this will not occur China will "intervene" the local economy secretly."
PEG	MFN	−0.25	M −	"Maybe. Removing the peg may allow HK dollar to depreciate. As a result, HK and China trading activities would increase. China may flood its goods to USA which make USA to take action against China."
PEG	INT	0.25	M +	"HK is historically or economically relied on the peg. If it is removed, our "ECONOMISTS" may be green to handle. China, as our parent country, may intervene. A way to show up."

MFN: China loses MFN status.
COR: Corruption becomes widespread in Hong Kong.
PEG: The peg between the Hong Kong dollar and the US dollar is removed.
INT: China intervenes in the Hong Kong economy.
TAI: Conflict between China and Taiwan escalates.
Impact code: H = high impact coefficient; M = medium impact coefficient; + , − is the algebraic sign of the impact coefficient.

the events will have a positive or negative relationship to each other, (2) an argument explaining the reason for the relationship, and (3) a quantitative estimate of the strength of the relationship. If they are not in agreement, then it will be difficult to draw any conclusions, and this may suggest a need for further investigation.

Our approach has two limitations. First, there must be a sufficient number of participants, approximately 20, to obtain meaningful estimates of the conditional probabilities. Second, the events being analyzed should not be virtually certain or virtually impossible. However, such events are generally not selected for cross-impact analysis.

In the decade since the end of the cold war, we have seen the rise of a growing number and variety of emerging nations [33,34]. Many of these nations offer economic opportunities in an environment of both risk and authoritarianism, so that public discussion of risks, to include potential problems and vulnerabilities to external events, often does not take place. The methodology we have presented here may prove to be helpful in performing cross-impact analyses in situations such as these.

Appendix A

There are two anomalies of interest here. The first is a simple form of Bayes' theorem. For any two events, α and β, we must have

$$p(\alpha|\beta)p(\beta) = p(\beta|\alpha)p(\alpha),$$

since both sides of the equation are equal to $p(\alpha \,\&\, \beta)$. In general, we cannot expect that subjectively estimated marginal and conditional probabilities will satisfy this relationship. Furthermore, we cannot estimate only three of these probabilities and then calculate the fourth, since the result could be a marginal or conditional probability that exceeds one.

Even if this relationship is satisfied, there may still be a violation of the laws of probability theory when the negation of events is considered. For example, we must have

$$p(\beta) = p(\beta|\alpha)p(\alpha) + p(\beta|\neg\alpha)p(\neg\alpha),$$

where $\neg\alpha$ is the negation of α—that is, $p(\neg\alpha) = 1 - p(\alpha)$. However, if $p(\alpha|\beta) = p(\beta|\alpha) = 0.8$ and $p(\alpha) = p(\beta) = 0.9$ (so that $p(\neg\alpha) = 0.1$), then the first equation above would be satisfied, but there is no feasible value of $p(\beta|\neg\alpha)$ that satisfies the second equation, since this equation would require that $p(\beta|\neg\alpha) = 1.8$.

Matters become even more complicated if combinations of three or more events are considered—for example, $p(\beta|\alpha \,\&\, \gamma)$. However, such situations are beyond the scope of this paper.

Appendix B

We demonstrate that for any two events, α and β, $p(\beta)$ is bracketed by (i.e., is in between) $p(\beta|\alpha)$ and $p(\beta|\neg\alpha)$. For any real number x, we define the sign of x as

$$\mathrm{SGN}(x) = \{+1, \text{for } x > 0; -1, \text{for } x < 0; 0, \text{for } x = 0\}.$$

Then $p(\beta)$ is bracketed by $p(\beta|\alpha)$ and $p(\beta|\neg\alpha)$ if and only if

$$\mathrm{SGN}(p(\beta|\alpha) - p(\beta)) = \mathrm{SGN}(p(\beta) - p(\beta|\neg\alpha)).$$

Here is the proof:

$$p(\beta|\alpha) - p(\beta) = \frac{p(\alpha \,\&\, \beta)}{p(\alpha)} - \frac{p(\alpha)p(\beta)}{p(\alpha)} = \frac{p(\alpha \,\&\, \beta) - p(\alpha)p(\beta)}{p(\alpha)}$$

Since

$$p(\beta) = p(\alpha \,\&\, \beta) + p(\neg\alpha \,\&\, \beta),$$

we have

$$p(\neg\alpha \,\&\, \beta) = p(\beta) - p(\alpha \,\&\, \beta).$$

We also note that $p(\neg\alpha) = 1 - p(\alpha)$. Therefore,

$$p(\beta) - p(\beta|\neg\alpha) = p(\beta) - \frac{p(\neg\alpha \,\&\, \beta)}{p(\neg\alpha)} = \frac{p(\beta)(1 - p(\alpha))}{1 - p(\alpha)} - \frac{p(\beta) - p(\alpha \,\&\, \beta)}{1 - p(\alpha)}$$

$$= \frac{p(\alpha \,\&\, \beta) - p(\alpha)p(\beta)}{1 - p(\alpha)}$$

Therefore, $\mathrm{SGN}(p(\beta|\alpha) - p(\beta)) = \mathrm{SGN}(p(\alpha \,\&\, \beta) - p(\alpha)p(\beta)) = \mathrm{SGN}(p(\beta) - p(\beta|\neg\alpha))$.

Appendix C

We demonstrate that for any two events, α and β, the impact of α on β has the same sign (positive, negative, or zero) as that of the impact of β on α. We recall that

$$\mathrm{IMP}(\alpha, \beta) = p(\beta|\alpha) - p(\beta|\neg\alpha)$$

and for any real number x

$$\mathrm{SGN}(x) = \{+1, \text{for } x > 0; -1, \text{for } x < 0; 0, \text{for } x = 0\}.$$

Therefore, we wish to show that

$$\mathrm{SGN}(\mathrm{IMP}(\alpha, \beta)) = \mathrm{SGN}(\mathrm{IMP}(\beta, \alpha)).$$

Here is the proof: as before, we note that

$$p(\beta) = p(\alpha \,\&\, \beta) + p(\neg\alpha \,\&\, \beta),$$

and thus

$$p(\neg\alpha \,\&\, \beta) = p(\beta) - p(\alpha \,\&\, \beta).$$

Therefore, we can write IMP(α, β) as

$$\mathrm{IMP}(\alpha, \beta) = \frac{p(\alpha \,\&\, \beta)}{p(\alpha)} - \frac{p(\neg\alpha \,\&\, \beta)}{p(\neg\alpha)} = \frac{p(\alpha \,\&\, \beta)}{p(\alpha)} - \frac{p(\beta) - p(\alpha \,\&\, \beta)}{1 - p(\alpha)}$$

$$= \frac{p(\alpha \,\&\, \beta) - p(\alpha)p(\beta)}{p(\alpha)(1 - p(\alpha))}$$

Similarly,

$$\mathrm{IMP}(\beta, \alpha) = \frac{p(\alpha \,\&\, \beta) - p(\alpha)p(\beta)}{p(\beta)(1 - p(\beta))}$$

Therefore, SGN(IMP(α, β)) = SGN(IMP(β, α)).

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