Complementary External Resource Allocation to Information Security in Smart Cities

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With the rapid development of technologies, such as big data, artificial intelligence, and cloud computing, the work cooperation among cities and the resources involved in business exchanges are deeply complementary. At the same time, information security has become one of the challenges for smart cities, which is ubiquitous and easy to cause public security issues. For this reason, this research modeled the actual problems and then made decisions on resource allocation by considering full cooperation and non-cooperation situations. Their influence with respect to city size, probability of intrusion by illegal users, and propagation probability of one-time intrusion were analyzed. Based on these foundation works, this research proposed incentive mechanisms to ensure the optimized information security for smart cities. These mechanisms ensure that cities not only voluntarily increase the intensity of resource allocation to information security, but also make the cooperation in line with the reality. Therefore, this balances the advantages and disadvantages of non-cooperation and full cooperation, so as to ensure that the information security level of urban agglomerations reaches the optimal state.

Keywords：smart cities, information security, resource allocation, incentive mechanism

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INTRODUCTION

A modern smart city cannot be a closed system, and its communication will not be limited in the interior. In the actual operation, its external sharing and communication will sometimes be even more extensive than the internal communication. Therefore, it is necessary to strengthen studies on external resource allocation of the city on the premise of thorough research on internal resource allocation of the city [1-3].

With the rapid development and wide application of big data and artificial intelligence and the continuous integration and development of all walks of life [4-5], information security has become a huge challenge for smart cities at present [6-8]. It is not an isolated and separate issue, but is ubiquitous and can easily develop into a public security problem [9-13]. The cooperation in information security and business contacts between cities make urban resources be complementary to a certain extent [14-16]. After illegal users intrude into a city, they need to intrude into another city linked to obtain the corresponding benefits.

PROBLEM DESCRIPTION AND MODELING

Problem Description

Because resources between cities are complementary, if illegal users intrude into a city, but fail to intrude into cities linked, complementarity of resources guarantees all or partial information security, so that it is difficult for illegal users to fully benefit, thus avoiding heavy loss of the cities. At present, most scholars mainly focus on the research of resource allocation to information security in cities under the condition of information sharing. In fact, cities will also consider input and output and if the disadvantages of cooperation outweigh the advantages, they tend to choose not to cooperate. Therefore, it is necessary to study the optimal resource allocation in the case of non-cooperation [17].

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This section mainly studied the problem that multiple cities with complementary external resources suffer from multiple propagation and intrusion by illegal users in the actual operation of smart cities. Firstly, the optimal resource allocation schemes were compared under non-cooperation and full cooperation situations and then government's compensation mechanisms and information sharing mechanisms were introduced. Furthermore, a numerical analysis was carried out.

Problem Modeling

Any game problem can be described as $GT = \{P, St, Ut\}$. For complementary external resources, cities are linked with each other and they may be attacked by illegal users. Even if cities are not attacked directly, they can also be attacked indirectly through propagation. Any problem of complementary external resource allocation can be transformed into a game problem through the propagation probability.

Assumption 1: When the propagation probability of one-time intrusion between cities is same and set as α, illegal users can attack another city directly linked thereto by using the probability.

Assumption 2: Illegal users do not have any prior information about the vulnerability for information security construction in cities. Therefore, the probabilities of illegal users intruding into all cities are same, and the value is β..

Assumption 3: The losses borne by cities intruded by illegal users are same, namely L.

Assumption 4: When resources are not allocated to information security in cities, the probabilities of intrusion by illegal users are same across cities and value v.

It is assumed that there are n cities forming complementary external resources and the probability of intrusion by illegal users after allocating resources to information security in the $j(j = 1,2,\cdots n)$ th city is p_j. Moreover, the volume of resource allocation to information security is e_j, loss rescued by amount of money per unit is E and the expected loss after allocating resources to information security in cities is set as C_j. By improving the model proposed by Gordon [14], the probability p_j of intrusion by illegal users in the jth city can be obtained.

$$p_j = \beta v^{Ee_j+1} \tag{1}$$

Considering complementarity of resources between cities, that is, if illegal users intrude into one or several cities linked, but not all cities linked, it is acceptable to the whole information security system to a certain extent. Therefore, if illegal users want to maximize their profits, they have to intrude into all cities linked.

PROPOSED METHODS

Resource Allocation to Information Security in Cities under Non-Cooperation

This section mainly analyzes strategies for allocation of complementary external resources under non-cooperation between smart cities. Based on the assumptions in the above section and Formula (1), it is known that the probability of intrusion by illegal users in the $j(j = 1,2,\cdots n)$ th city is $1-(1-p_j)\prod_{k=1,k\neq j}^{n}(1-\alpha^{k-1}p_k)$, so the minimum expected loss C_j of the city is taken as a loss function.

$$Min\ C_j = \left[1-(1-p_j)\prod_{k=1,k\neq j}^{n}(1-\alpha^{k-1}p_k)\right]L + e_j \tag{2}$$

By substituting Formula (1) into Formula (2), the following formula can be obtained.

$$Min\ C_j = \left[1-(1-\beta v^{Ee_j+1})\prod_{k=1,k\neq j}^{n}(1-\alpha^{k-1}\beta v^{Ee_k+1})\right]L + e_j \tag{3}$$

Because $\prod_{k=1,k\neq j}^{n}(1-\alpha^{k-1}\beta v^{Ee_k+1})$ in Formula (3) is independent of e_j, let $\Phi = \prod_{k=1,k\neq j}^{n}(1-\alpha^{k-1}\beta v^{Ee_k+1})$, the following formula can be obtained by solving the partial derivative of Formula (3):

$$\frac{\partial C_j}{\partial e_j} = \beta EL\Phi v^{Ee_j+1} lnv + 1 \tag{4}$$

By further solving the partial derivative of Formula (4), the second-order derivative of Formula (5) can be obtained.

$$\frac{\partial^2 C_j}{\partial e_j^2} = \beta E^2 L\Phi v^{Ee_j+1}(lnv)^2 \tag{5}$$

It can be seen from Formula (5) that $\frac{\partial^2 C_j}{\partial e_j^2} \geq 0$ is always established. Therefore, when $\frac{\partial C_j}{\partial e_j} = 0$, the minimum value of the loss function C_j can be ob-

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tained, thus obtaining the following Conclusion 1.

Conclusion 1: Under non-cooperation between smart cities with complementary external resources, the Nash equilibrium solution can be obtained through games when the optimal volume of resource allocation in each city is $y^* = (e_1^*, e_1^*, \cdots, e_1^*)$, in which e_1^* meets Formula (6).

$$e_1^* = \frac{-ln(-\beta EL\Phi v ln v)}{E ln v} \quad (6)$$

In accordance with Formula (6), the effects of factors, such as size of linked cities, probability of intrusion by illegal users and propagation probability of one-time intrusion on resource allocation to information security in cities can be further analyzed. Based on Conclusion 1, e_1^* meets $\beta EL\Phi v_j^{Ee_1^*+1} ln v_j + 1 = 0$. Furthermore, $\frac{\prod_{k=1,k\neq j}^{n}(1-\alpha^k \beta v^{Ee_{k+1}+1})}{\prod_{k=1,k\neq j}^{n}(1-\alpha^{k-1}\beta v^{Ee_k+1})} = 1 - \alpha^n \beta v^{Ee_{k+1}+1} < 1$ is always established. For this reason, the relationship between size of linked cities and resource allocation to information security in cities is analyzed by combining with characteristics of complementary resources and considering the same volume of resource allocation between smart cities under non-cooperation based on relevant assumptions in Section 2.2. On this basis, the following Conclusion 2 can be made.

Conclusion 2: Under non-cooperation, with the increase of size of cities linked in complementary external resources of information security, the optimal volume e_1^* of resource allocation to information security in cities reduces correspondingly, that is, e_1^* is negatively correlated with n.

The reason is that with the increase of n, $\prod_{k=1,k\neq j}^{n}(1 - \alpha^{k-1}\beta v^{Ee_k+1})$ decreases, which raises $p_j = \beta v^{Ee_j+1}$. In addition, because $v \in [0, 1]$, e_1^* is bound to decrease accordingly. This suggests that the volume of resource allocation in each city reduces correspondingly with the increase of size of cities with complementary resources. However, this can greatly increase the probability of illegal users to intrude into a single city, so that the information security level of all smart cities significantly reduces. Although more linked cities can share the risks, such a behavior of reducing the volume of resource allocation decreases the information security level. If the size of linked cities reaches to a certain critical value, it is not necessary for smart cities to allocate resources to information security, which is unrealistic in practice. Therefore, it is necessary for the government to coordinate the relevant departments in each city and allocate resources to information security after weighing the advantages and disadvantages.

By analyzing the relationship between the probability of intrusion by illegal users and resource allocation to information security in cities, Conclusion 3 can be made as follows:

Conclusion 3: Under non-cooperation, for any probability $\beta \in [0, 1]$ of intrusion by illegal users, the optimal volume e_1^* of resource allocation to information security in cities monotonically rises, namely $\frac{\partial e_1^*}{\partial \beta} > 0$ is always established.

Conclusion 3 indicates that the volume of resource allocation to information security in cities increases with the probability of intrusion by illegal users in the model of complementary external resource allocation in smart cities, which confirms with the common sense. When the probability of intrusion by illegal users rises, cities will invest more to prevent illegal intrusion, thus raising their information security level.

By analyzing the relationship between the propagation probability of one-time intrusion between cities and resource allocation to information security in cities, Conclusion 4 can be made as follows:

Conclusion 4: Under non-cooperation, for any propagation probability $\alpha \in [0, 1]$ of one-time intrusion between cities, the optimal volume of resource allocation to information security in cities monotonically reduces, that is, $\frac{\partial e_1^*}{\partial \alpha} < 0$ is always established.

Conclusion 4 indicates that with the increase of the propagation probability of one-time intrusion between cities, the optimal volume of resource allocation to information security in cities decreases correspondingly. This verifies the conclusion proposed in the existing study [x] that network communication has a negative impact on the optimal strategy of resource allocation. This implies that the power of cities to resource allocation to information security can be reduced with the increase of the propagation probability of one-time intrusion between cities. In the case of non-cooperation, it needs to adjust the network structure between cities and try to avoid indirect intrusion by illegal users due to network connection with other cities.

Based on Conclusions 2 and 4, with the increase of city size and propagation probability of one-time intrusion between cities, the probability of intrusion by illegal users in cities rises. However, through the above analysis, instead of increasing resource allocation, cities reduce investment, which leads to a vicious circle of information security in cities. The main reason is that some cities have free-riding behaviors in the construction of information security in other cities, because the resource allocation in these cities not only has an effect on information security of themselves, but also exerts a positive influence on cities linked thereto. Due to the free-riding behaviors, marginal benefits of cities with resource allocation to information security decrease.

Resource Allocation to Information Security in Cities under Full Cooperation

The case of full cooperation is greatly different from the case of non-cooperation. Due to full cooperation, it is supposed that the probability of intrusion by illegal users after allocating resources to information security in cities is set as p and the volume of resource allocation to information security in cities is e. Therefore, the loss function of urban agglomerations in this case can be derived as follows:

$$Min\ C = [1-(1-p)\prod_{k=2}^{n}(1-\alpha^{k-1}p_k)]L + ne \quad (7)$$

The following formula can be obtained by substituting Formula (1) into Formula (7).

$$Min\ C = [1-(1-\beta v^{Ene+1})\prod_{k=2}^{n}(1-\alpha^{k-1}p_k)]L + ne \quad (8)$$

Let $\Omega = \prod_{k=2}^{n}(1-\alpha^{k-1}p_k)$, the following formula can be obtained by solving the partial derivative of Formula (8).

$$\frac{\partial C}{\partial e} = \beta nEL\Omega v^{Ene+1}lnv + n \quad (9)$$

The second-order derivative of Formula (8) can be obtained by further solving the partial derivative of Formula (9).

$$\frac{\partial^2 C}{\partial e^2} = \beta n^2E^2L\Omega v^{Ene+1}(lnv)^2 \quad (10)$$

It can be observed from Formula (10) that $\frac{\partial^2 C}{\partial e^2} \geq 0$ is always established. The minimum value of the loss function C can be taken when $\frac{\partial C}{\partial e} = 0$, thus making the following Conclusion 5.

Conclusion 5: In the case of full cooperation between smart cities with complementary external resources, the Nash equilibrium solution can be obtained through games when the optimal volume of resource allocation in cities is $e_2^* = \frac{-\ln(-\beta EL\Omega v\ln v)}{nE\ln v}$.

By comparing the optimal volumes e_1^* and e_2^* of resource allocation obtained in Conclusions 1 and 5, it is obvious that $e_1^* > e_2^*$. In the meanwhile, the following Conclusion 6 is made by comparing expected costs in the two cases.

Conclusion 6: When the loss borne by cities after being intruded by illegal users is $L > -\frac{1}{p'\Phi}$, then $\frac{\partial C_j}{\partial e_j} < 0$. Moreover, the volume e_1^* of resource allocation in the case of non-cooperation of cities is larger than that e_2^* under full cooperation. Therefore, the expected cost $C_j(e_1^*)$ of cities under non-cooperation is lower than that $C(e_2^*)$ under full cooperation.

Conclusion 6 indicates that when the loss of cities caused by intrusion by illegal users is greater than a certain threshold, the volume of resource allocation of cities with complementary external resources under non-cooperation is higher than that under full cooperation. Moreover, the expected cost is lower than that under full cooperation. In the case of full cooperation, there is a specific minimum threshold for the expected cost of a city. If the expected cost is lower than the threshold, the city will not allocate resources. If it is higher than the threshold, the expected cost of the city will rise with the increase of the volume of resource allocation. Therefore, cities allocate resources to information security not in all cases. For example, when the expected cost of the city is very low and the risk borne by is controllable, it is unnecessary to carry out resource allocation. However, when very serious accidents about information security may be induced at very high expected cost of the city, the optimal volume of resource allocation in the city tends to be stable. In other words, the increase of expected cost of the smart city does not significantly raise the volume of resource allocation in the city. In this case, the city can adopt other risk control methods instead of wasteful investment.

By further analyzing the influences of each parameter on the optimal volume of resource allocation in the case of full cooperation, Conclusions 7 and 8 are made as follows:

Conclusion 7: Under full cooperation, with the increase of size of related cities with complementary external resources of information security, the optimal volume e_2^* of resource allocation to information security in cities decreases correspondingly, that is, e_2^* has a negative correlation with n and $\frac{\partial e_2^*}{\partial n} < 0$.

It can be seen from Conclusions 2 and 7 that for cities with complementary external resources of information security, although more sharing information can be obtained with the increase of city size, the optimal volume of resource allocation will not rise either under non-cooperation or full cooperation. This can raise the probability of intrusion by illegal users and reduce the information security level of cities. Therefore, the advantages and disadvantages of city size should be weighed in any cases.

Conclusion 8: Under full cooperation, for any propagation probability $\alpha \in [0,1]$ of one-time intrusion in cities, the optimal volume e_2^* of resource allocation to information security in cities is negatively correlated with α, namely $\frac{\partial e_2^*}{\partial \alpha} < 0$ is always established.

Conclusion 8 illustrates that under full cooperation, the optimal volume of resource allocation decreases with the increase of the propagation probability of one-time intrusion, which is consistent with the trend under non-cooperation in Conclusion 4. The increase of the propagation probability of one-time intrusion will inevitably make information security in cities more vulnerable, so that illegal users are more easily to intrude into cities. However, under non-cooperation, a city will not consider that being intruded damages other cities, thus leading to negative factors in resource allocation strategies of the cities, which to some extent encourages the free-riding behavior among cities.

In conclusion, when cities with complementary external resources of information security make decisions independently rather than cooperatively, they only consider their own gains and losses; while, they do not consider overall benefits of urban agglomerations and damages to other cities due to their own vulnerability. If cities cooperate well and coordinate with each other in information security to minimize the overall expected cost of urban agglomerations, they are required to reduce the expected loss of urban agglomerations by increasing the volume of resource allocation. Therefore, under full cooperation, due to the sharing of resources between cities, this can reduce the investment of each city to a certain extent, but also increases the expected loss of cities.

INCENTIVE MECHANISMS

The analysis in the above two cases shows that if cities do not cooperate, they may work in their own ways, which is not conducive to the improvement of the information security level of urban agglomerations. However, full cooperation is bound to raise the volume of resources allocation in cities. Moreover, it is difficult to achieve full cooperation in reality. Therefore, how to make cities voluntarily increase the intensity of resource allocation to information security and the cooperation situation in line with the reality has become a problem that has to be solved. This study mainly considers to solve non-cooperation between cities through government's compensation mechanisms and to ensure the volume of resource allocation to be in line with the reality based on information sharing mechanisms.

Government's Compensation Mechanisms

It is assumed that through a certain means, the government can detect the intrusion by illegal users or can directly identify whether the intrusion is direct or indirect, or the affected cities can prove that the loss is caused by the propagation of other cities. Cities can appeal to government agencies to make up for the loss they suffered because of the involvement, and the loss is paid by the city directly intruded. Supposing that the city appeals successfully, the compensation that it can get from the linked city is γL, where γ represents the compensation coefficient of the city.

If City j is implicated by City i and intrusion is indirectly propagated to City j because City i is directly intruded by illegal users, the loss of City j has nothing to do with other cities, then the government can request City i to compensate for City j. In this case, the loss function of City B can be obtained as follows:

$$Min\ C_B = \left[1-(1-p_i)\prod_{k=1,k\neq i}^{n}(1-\alpha^{k-1}p_k)\right]L + e_i + \sum_{j=1,j\neq i}^{n} p_i\alpha(1-p_j)\gamma L - \sum_{j=1,j\neq i}^{n} p_j\alpha(1-p_i) \quad (11)$$

where, the first two terms have the same meanings as those in Formula (2), separately indicating the loss caused by intrusion into City B by illegal users and volume of resource allocation to information security. The third term represents the compensation for other cities due to indirect intrusion through City B and the fourth term denotes the compensation for City B because of indirect intrusion through other cities.

By processing Formula (11), the following formula can be obtained.

$$Min\ C_B = \left[1-(1-p_i)\prod_{k=1,k\neq i}^{n}(1-\alpha^{k-1}p_k)\right]L + e_i + \sum_{j=1,j\neq i}^{n} \alpha(p_i-p_j)\gamma \quad (12)$$

By substituting Formula (1) into Formula (12), let $\Psi = \prod_{k=1,k\neq i}^{n}(1-\alpha^{k-1}p_k)$, the following formula can be obtained.

$$Min\ C_B = [1-(1-\beta v^{Ee_i+1})\Psi]L + e_i + \sum_{j=1,j\neq i}^{n} \alpha\beta\gamma L\left(v^{Ee_i+1} - v^{Ee_j+1}\right) \quad (13)$$

By solving the partial derivative of Formula (13), the following formula is expressed as

$$\frac{\partial C_B}{\partial e_i} = \beta L E \Psi v^{Ee_i+1} lnv + 1 + (n-1)\ \alpha\beta\gamma L E v^{Ee_i+1} lnv \quad (14)$$

The second-order derivative of Formula (13) can be obtained by further solving the partial derivative of Formula (14).

$$\frac{\partial^2 C_B}{\partial e_i^2} = [\Psi + (n-1)\alpha\gamma]\beta E^2 L v^{Ee_i+1}(lnv)^2 \quad (15)$$

It can be seen from Formula (15) that $\frac{\partial^2 C_B}{\partial e_i^2} \geq 0$ is always established, so the minimum value of the loss function C_B can be obtained when $\frac{\partial C_B}{\partial e_i} = 0$, thus calculating the optimal volume e_3^* of resource allocation of each city. e_3^* meets Formula (16).

$$e_3^* = \frac{-ln[-\beta L E v(\Psi + n\alpha\gamma - \alpha\gamma)lnv]}{Elnv} \quad (16)$$

By comparing e_3^* with e_1^* under non-cooperation, it is evident that $e_3^* > e_1^*$. In other words, under the restriction of government's compensation mechanisms, the optimal volume of resource allocation in urban agglomerations is higher than that in the case of non-cooperation, so the information security level of urban agglomerations can be improved through government regulation. In the meanwhile, by comparing the expected cost under compensation mechanisms with that under non-cooperation and supposing that cities with complementary external resources are homogeneous, namely $p_i = p_j$, the loss function C_B can be degraded into C_j. When the loss borne by the city after intrusion by illegal users is $L > -\frac{1}{\beta E \Psi v^{Ee_i+1} lnv}$, then $\frac{\partial C_B}{\partial e_i} < 0$. In this case, $C_B(e_3^*) < C_j(e_1^*)$, that is, the expected cost obtained under regulation of government's compensation mechanisms is lower than that under non-cooperation, so Conclusion 9 can be made as follows:

Conclusion 9: When the loss borne by the city after being intruded by illegal users is $L > -\frac{1}{\beta E \Psi v^{Ee_i+1} lnv}$, if illegal users directly intrude into City i and indirectly intrude into City j through City i, the volume of compensation for City j by City i under government's compensation mechanisms is γL. In this case, the optimal volume of resource allocation in urban agglomerations is higher than that under non-cooperation and the expected cost $C_B(e_3^*)$ is lower than that $C_j(e_1^*)$ under non-cooperation.

Conclusion 9 indicates that the unified regulation of government's compensation mechanisms can not only improve the information security level, but also reduce the expected cost of urban agglomerations.

Based on further analysis, the relationship between the optimal volume of resource allocation and the compensation coefficient under such mechanisms can be explored. Through Formula (16), the partial derivation of the optimal volume of resource allocation to the compensation coefficient can be calculated as follows:

$$\frac{\partial e_3^*}{\partial \gamma} = -\frac{(n-1)\alpha}{Elnv[\Psi + (n-1)\alpha\gamma]} \quad (17)$$

Formula (17) obviously shows that $\frac{\partial e_3^*}{\partial \gamma} > 0$ is always established, so the optimal volume of resource allocation rises with the increase of the compensation coefficient.

Information Sharing Mechanisms

To further improve the information security level, in addition to the use of compensation mechanisms, more attention should be paid to improving the information sharing between cities. The personal credit investigation of the banking system is a good example of information sharing among multiple banks and cities. Therefore, it is necessary to explore benefits of information sharing mechanisms to urban agglomerations, so as to guide the resource allocation to information security of urban agglomerations.

Assumption 5: There is no information leakage between cities because of information sharing. A city can obtain the corresponding shared information from other cities linked with it, that is, the city can share the resource allocation in other cities. Assuming that $\delta \in [0,1]$ represents the sharing rate of information of City j with other cities, the volume of resource allocation to information security obtained by City j from other cities is $\delta \sum_{k=1,k\neq j}^{n} e_k$.

Supposing that Assumption 5 is established, the loss function C_g of City j is shown as follows:

$$Min\ C_g = \left[1-(1-p_j)\prod_{k=1,k\neq j}^{n}(1-\alpha^{k-1}p_k)\right]L + e_j \quad (18)$$

Let$\Gamma = \prod_{k=1,k\neq j}^{n}(1-\alpha^{k-1}p_k)$, by substituting Formula (1) into Formula (18), the following formula can be obtained.

$$Min\ C_g = \left[1-\left(1-\beta v^{E\left(e_j+\delta\sum_{k=1,k\neq j}^{n}e_k\right)+1}\right)\Gamma\right]L+e_j \quad (19)$$

By comparing e_4^* with the optimal volumes e_1^* and e_2^* of resource allocation under non-cooperation and full cooperation, it is found that $e_1^* > e_4^* > e_2^*$, indicating that the optimal volume of resource allocation in urban agglomerations under information sharing is smaller than that under non-cooperation, but is larger than that under full cooperation. Therefore, such mechanisms can effectively improve the information security level and make resource allocation more in line with the actual situations. In the meanwhile, by comparing the expected costs, when the loss borne by the city intruded by illegal users is $L > -\frac{1}{p''\Gamma}$, then $\frac{\partial C_g}{\partial e_j} < 0$. The expected cost $C_g(e_4^*)$of the city under such conditions is lower than that $C_j(e_1^*)$under non-cooperation. Therefore, under information sharing mechanisms, urban agglomerations can not only improve the information security level, but also meet the actual needs of resource allocation and reduce the expected cost. The following Conclusion 10 can be made.

Conclusion 10: Under information sharing of urban agglomerations, if the loss borne by the city intruded by illegal users is $L > -\frac{1}{p''\Gamma}$, the optimal volume $e_4^*$of resource allocation in the city is larger than that e_1^* under non-cooperation, but smaller than that e_2^*under full cooperation. Moreover, its expected cost $C_g$is lower than that C_j under non-cooperation.

It can be easily seen from Conclusion 10 that if loss of cities is larger than a certain threshold, compared with non-cooperation, information sharing in cities can not only improve the information security level of urban agglomerations, but also reduce the expected cost, which well solves the actual problems.

By further analyzing the relationship between the optimal volume of resource allocation and the propagation probability of one-time intrusion in this case, Conclusion 11 can be obtained as follows:

Conclusion 11: Under information sharing of urban agglomerations, if $\delta > -E\Gamma lnv$, the optimal volume $e_4^*$of resource allocation in urban agglomerations is positively correlated with the propagation probability α of one-time intrusion, that is, $\frac{\partial e_4^*}{\partial \alpha} > 0$ is always established.

Conclusion 11 implies that once the sharing rate of information in urban agglomerations reaches a certain threshold, the optimal volume of resource allocation in cities increases with the propagation probability of one-time intrusion. In other words, after the sharing rate of information reaches the threshold, the propagation probability of one-time intrusion plays a positive role in the construction of information security in urban agglomerations.

By analyzing the relationship between the optimal volume of resource allocation and the sharing rate of information, the following Conclusion 12 can be made.

Conclusion 12: Under information sharing in urban agglomerations, if $\delta > -E\Gamma lnv$, the optimal volume $e_4^*$of resource allocation in urban agglomerations is negatively correlated with the sharing rate δ of information, that is, $\frac{\partial e_4^*}{\partial \delta} < 0$ is always established.

According to Formula (19), when $\delta = 0$, then $e_4^* = e_1^*$, that is, if there is no information sharing at all, it is degraded into the case of non-cooperation; when $\delta = 1$, then $e_4^* = e_2^*$. In other words, if information is shared at a rate of 100%, the situation evolves into the full cooperation. Based on analysis, it can be observed that information sharing mechanism is an effective incentive means to solve problems that cities do not cooperate and to ensure the volume of resource allocation confirming to the actual situations.

EXPERIMENTAL RESULTS AND ANALYSIS

Through a simulation experiment, the above conclusions can be conveniently and clearly verified. This section mainly deeply discusses the following problems.

(1) Based on the numerical simulation, the optimal volumes of resource allocation and expected costs under non-cooperation and full cooperation of cities are compared. The

influence trends of city size n, probability β of intrusion by illegal users and propagation probability α of one-time intrusion on the optimal volume of resource allocation and expected cost are numerically studied and analyzed, that is, numerical analysis under different conditions.

(2) The influences of the compensation coefficient γ and sharing rate δ of information in cities on the optimal volume of resource allocation and expected cost are discussed, that is, numerical analysis of incentive mechanisms.

According to the actual conditions, there cannot be too many cities that are linked together and have complementary external resources, generally no more than four, so the city sizes are set as $n = 3$ and $n = 4$ in the numerical simulation in this section. Because it is impossible and unnecessary to consider all values of some experimental parameters in the actual numerical simulation, this section only takes several representative values into account. It is supposed that $L = 400$, $v = 0.5$ and $E = 0.1$.

Numerical Analysis under Different Conditions

Resource allocation under non-cooperation

When $n = 3$, the propagation probability α of one-time intrusion between cities and the probability β of intrusion by illegal users are set to be 0.1~0.9, with an increase amplitude of 0.1, to analyze the influences of α and β on resource allocation. The volume of resource allocation and the expected loss are listed in Tables 1 and 2. By further analyzing Tables 1 and 2, when α is 0.1 and β values $[0.1, 0.9]$ as well as β is 0.1 and α is $[0.1, 0.9]$, the results in Figs. 1 and 2 can be obtained.

Fig. 1
Influences of β on the volume e_1^*

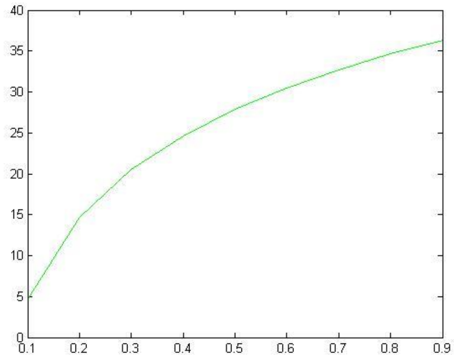
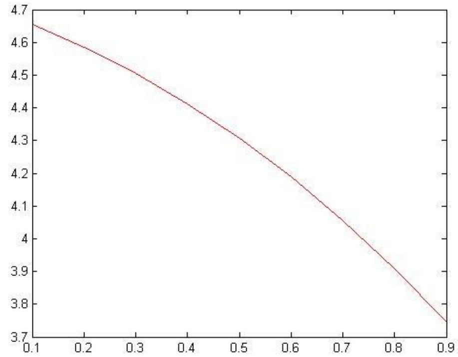


Fig. 2
Influences of α on the volume e_1^*



It can be obviously observed from the above figures that with the constant increase of β, the volume e_1^* of resource allocation continuously rises, which verifies the correctness of Conclusion 3; as α constantly rises, the volume e_1^* of resource allocation continuously decreases, verifying that Conclusion 4 is correct. When $n = 4$, by setting the propagation probability α of one-time intrusion between cities as 0.1~0.9, with an increase amplitude of 0.1 and the probability β of intrusion by illegal users as 0.1, the volume of resource allocation and the expected loss are attained, as shown in Table 3.

Table 1
Influences of α and β on the volume e_1^* of resource allocation under non-cooperation

α \ β	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	4.6548	14.6548	20.5044	24.6548	27.8741	30.5044	32.7283	34.6548	36.3540
0.2	4.5860	14.5860	20.4356	24.5860	27.8052	30.4356	32.6595	34.5860	36.2852
0.3	4.5055	14.5055	20.3551	24.5055	27.7248	30.3551	32.5791	34.5055	36.2048
0.4	4.4130	14.4130	20.2626	24.4130	27.6323	30.2626	32.4866	34.4130	36.1123
0.5	4.3078	14.3078	20.1575	24.3078	27.5271	30.1575	32.3814	34.3078	36.0071
0.6	4.1894	14.1894	20.0390	24.1894	27.4086	30.0390	32.2629	34.1894	35.8886
0.7	4.0567	14.0567	19.9063	24.0567	27.2760	29.9063	32.1303	34.0567	35.7560
0.8	3.9089	13.9089	19.7585	23.9089	27.1282	29.7585	31.9825	33.9089	35.6082
0.9	3.7447	13.7447	19.5944	23.7447	26.9640	29.5944	31.8183	33.7447	35.4440

Table 2

Effects of α and β on the expected loss under non-cooperation

α \ β	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	20.6745	30.6745	36.5241	40.6745	43.8938	46.5241	48.7481	50.6745	52.3738
0.2	22.5016	32.5016	38.3512	42.5016	45.7209	48.3512	50.5752	52.5016	54.2009
0.3	24.6258	34.6258	40.4754	44.6258	47.8450	50.4754	52.6993	54.6258	56.3250
0.4	27.0537	37.0537	42.9033	47.0537	50.2730	52.9033	55.1273	57.0537	58.7530
0.5	29.7939	39.7939	45.6435	49.7939	53.0132	55.6435	57.8674	59.7939	61.4931
0.6	32.8566	42.8566	48.7062	52.8566	56.0759	58.7062	60.9302	62.8566	64.5559
0.7	36.2545	46.2545	52.1041	56.2545	59.4737	62.1041	64.3280	66.2545	67.9537
0.8	40.0026	50.0026	55.8522	60.0026	63.2219	65.8522	68.0762	70.0026	71.7019
0.9	44.1193	54.1193	59.9690	64.1193	67.3386	69.9690	72.1929	74.1193	75.8186

By comparing results in Table 3 with Tables 1 and 2, it can be seen that with the increase of n, the volume $e_1^*$of resource allocation reduces, while the expected loss increases, verifying that Conclusion 2 is correct. By comparing results in Table 3 with Tables 1 and 2, with the increase of n, the volume $e_1^*$of resource allocation decreases, while the expected loss rises, proving that Conclusion 2 is correct.

Table 3
Partial results of the volume of resource allocation and expected loss when $n = 4$ under non-cooperation

α	Resource Allocation e_1^*	Expected Loss
0.1	4.6542	20.6885
0.2	4.5817	22.6138
0.3	4.4910	25.0069
0.4	4.3782	27.9642
0.5	4.2385	31.5893
0.6	4.0668	35.9963
0.7	3.8568	41.3140
0.8	3.6006	47.6927
0.9	3.2882	55.3142

Resource allocation under full cooperation

As $n = 3$, the propagation probability α of one-time intrusion between cities and the probability β of intrusion by illegal users are set to be 0.1~0.9, with an increase amplitude of 0.1, so as to analyze their effects on resource allocation. The volume of resource allocation and the expected loss are demonstrated in Tables 4 and 5. By further analyzing Tables 4 and 5, when α is set as 0.1 and β is $[0.1, 0.9]$ as well as β is set to be 0.1 and α values $[0.1, 0.9]$, the results in Figs. 3 and 4 can be obtained.

It can be obviously seen from the above figures that as β constantly rises, the volume $e_2^*$of resource allocation continuously increases; with the continuous increase of α, e_2^*constantly decreases, confirming correctness of Conclusion 4. When $n = 4$, the propagation probability α of one-time intrusion between cities is set as 0.1~0.9, with an increase amplitude of 0.1 and the probability β of intrusion by illegal users is 0.1. Based on this, the obtained volume of resource allocation and the expected loss are illustrated in Table 6.

Fig. 3
Effects of β on the volume e_2^*

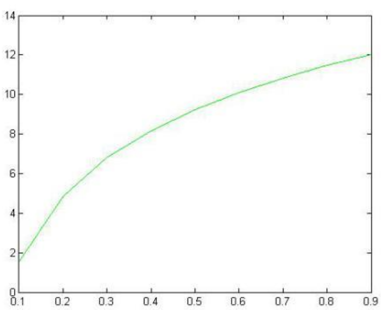


Fig. 4
Effects of α on the volume e_2^*

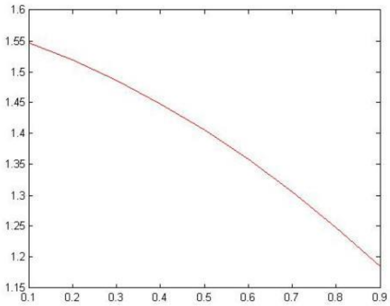


Table 4
Impacts of α and β on the volume e_2^* of resource allocation under full cooperation

α \ β	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	1.5470	4.8662	6.8043	8.1771	9.2404	10.1080	10.8406	11.4745	12.0329
0.2	1.5186	4.8210	6.7446	8.1045	9.1558	10.0121	10.7338	11.3573	11.9057
0.3	1.4857	4.7681	6.6747	8.0191	9.0559	9.8985	10.6071	11.2178	11.7538
0.4	1.4481	4.7074	6.5941	7.9203	8.9399	9.7660	10.4587	11.0540	11.5748
0.5	1.4056	4.6386	6.5022	7.8070	8.8064	9.6129	10.2865	10.8630	11.3654
0.6	1.3582	4.5612	6.3982	7.6782	8.6537	9.4369	10.0876	10.6413	11.1209
0.7	1.3057	4.4747	6.2813	7.5324	8.4797	9.2351	9.8580	10.3837	10.8349
0.8	1.2478	4.3786	6.1503	7.3677	8.2816	9.0034	9.5922	10.0829	10.4982
0.9	1.1843	4.2722	6.0038	7.1817	8.0557	8.7365	9.2826	9.7288	10.0968

Table 5
Impacts of α and β on the expected loss under full cooperation

α \ β	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.1	24.4941	46.0607	61.5813	74.3402	85.4518	95.4444	104.6155	113.1509	121.1759
0.2	26.6774	49.4661	65.9768	79.5924	91.4686	102.1565	111.9674	121.0966	129.6763
0.3	29.1983	53.3993	71.0549	85.6616	98.4228	109.9154	120.4669	130.2837	139.5055
0.4	32.0565	57.8596	76.8146	92.5462	106.3120	118.7181	130.1104	140.7074	150.6580
0.5	35.2522	62.8480	83.2572	100.2482	115.1388	128.5680	140.9018	152.3727	163.1393
0.6	38.7865	68.3668	90.3869	108.7738	124.9117	139.4760	152.8548	165.2960	176.9689
0.7	42.6610	74.4201	98.2111	118.1341	135.6464	151.4625	165.9953	179.5091	192.1852
0.8	46.8778	81.0141	106.7409	128.3465	147.3671	164.5603	180.3655	195.0653	208.8537
0.9	51.4402	88.1571	115.9919	139.4355	160.1099	178.8188	196.0314	212.0498	227.0832

By comparing results in Table 6 with Tables 4 and 5, as n increases, the volume e_2^* of resource allocation decreases, while the expected loss rises, verifying that Conclusion 7 is correct.

Numerical Analysis of Incentive Mechanisms

Resource allocation under government's compensation mechanisms

When $\alpha = 0.1$ and $\beta = 0.1$, the compensation coefficient γ between cities is set as 0.1~0.9, with an increase amplitude of 0.1 to analyze the influences of γ on resource allocation. The volume of resource allocation and the expected loss are displayed in Table 7. By displaying the results in Table 7 as graphs, the results in Fig. 5 and Fig. 6 can be obtained. The above figures obviously show that with the constant increase of γ, the volume e_3^* of resource allocation rises continuously, verifying the correctness that Formula (18) is always larger than zero. However, with the continuous change of γ, the expected loss firstly constantly reduces and then continuously rises after reaching a threshold at a certain point, proving that Conclusion 9 is correct.

Table 6
Partial results of the volume of resource allocation and expected loss under full cooperation

α	Resource Allocation e_7^*	Expected Loss
0.1	1.1596	25.0468
0.2	1.1366	27.3955
0.3	1.1081	30.2888
0.4	1.0729	33.8241
0.5	1.0299	38.0970
0.6	0.9778	43.2017
0.7	0.9152	49.2306
0.8	0.8406	56.2745
0.9	0.7523	64.4233

Table 7
Volume of resource allocation and expected loss under government's compensation mechanisms

γ	**Resource Allocation e_2^***	**Expected Loss**
0.1	4.9427	20.6470
0.2	5.2250	20.6261
0.3	5.5018	20.6112
0.4	5.7733	20.6020
0.5	6.0398	20.5980
0.6	6.3015	20.5988
0.7	6.5584	20.6042
0.8	6.8109	20.6137
0.9	7.0589	20.6272

Fig. 5
Impacts of on the volume

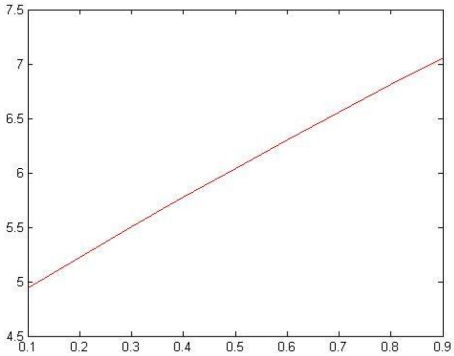
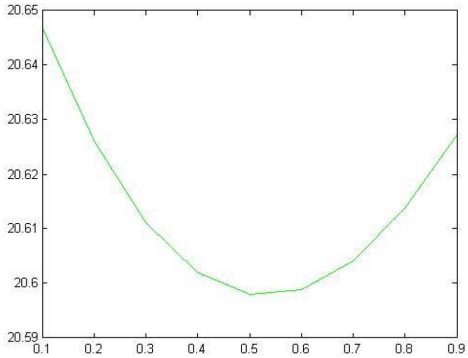


Fig. 6
Impacts of on the expected loss



Resource allocation under information sharing mechanisms

As $\alpha = 0.1$ and $\beta = 0.1$, the sharing rate δ of information between cities is set to be 0.1~0.9, with an increase amplitude of 0.1, to analyze effects of δ on resource allocation. The volume of resource allocation and the expected loss are demonstrated in Table 8.

Table 8
Volume of resource allocation and expected loss under information sharing mechanisms

δ	Resource Allocation e_4^*	Expected Loss
0.1	3.5959	14.0812
0.2	2.9181	14.9861
0.3	2.4551	15.7392
0.4	2.1187	16.3621
0.5	1.8634	16.8809
0.6	1.6629	17.3174
0.7	1.5013	17.6887
0.8	1.3684	18.0078
0.9	1.2571	18.2847

The results in Table 8 are displayed in graphs, thus obtaining results in Figs. 7 and 8. It can be obviously seen that the volume e_4^* of resource allocation constantly decreases and the expected loss also rises with the continuous increase of δ, proving the correctness of Conclusion 12.

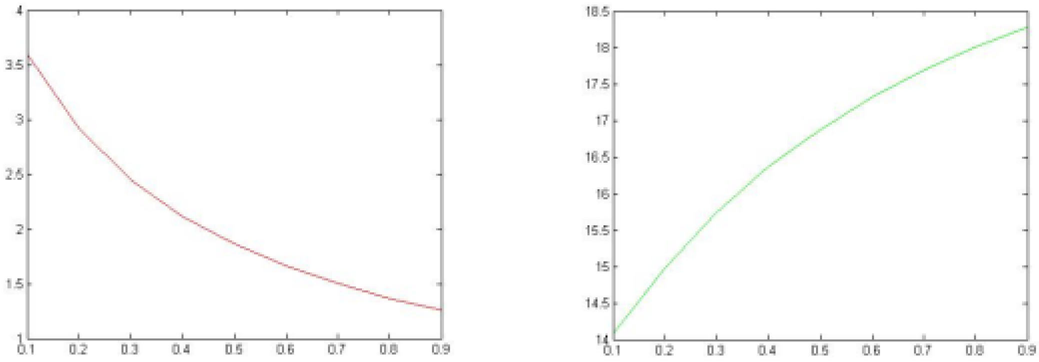


Fig. 7
Effects of on the volume

CONCLUSIONS AND SUGGESTIONS

This research mainly discussed the methods for resource allocation in the cases of non-cooperation and full cooperation of multiple cities. In addition, the effects of different influence factors, such as city size, propagation probability of one-time intrusion and probability of intrusion by illegal users on resource allocation in the two cases were also explored. In view of advantages and disadvantages of the two cases in the actual situations, the government's compensation mechanisms and information sharing mechanisms were proposed. These mechanisms ensure that cities not only voluntarily increase the intensity of resource allocation to information security, but also make the cooperation in line with the reality. Therefore, this balances the advantages and disadvantages of non-cooperation and full cooperation, so as to ensure that the information security level of urban agglomerations reaches the optimal state.

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