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Impact of cooperation uncertainty on the robustness of manufacturing service system

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A B S T R A C T

The cooperation between enterprises is actually at a certain risk of interruption, which has a significant impact on the robustness of manufacturing service system (MSS). Evaluating MSS' robustness is integral to production and service provisioning, and thus the influence mechanism should be clearly revealed for assisting professionals in the company in improving the robust performance. In this paper, we present an effective methodology for explicating the impact of cooperation uncertainty on the robustness of MSS from a complex system standpoint. This methodology characterizes MSS as a topological network consisting of serval service subsystems, and constructs the measure metrics system of which the validity and applicability are proved theoretically from the dimension of structure and performance. Furthermore, it simulates the cooperation interruption from four different scenarios with algorithms, and finally takes an elevator manufacturing service network as the case to illustrate this novel methodology. The simulation findings suggest that identifying the critical paths in MSS and standardizing the cooperation mechanism within and among core manufacturing service principals outperform the other measures in improving the robustness of MSS.

A R T I C L E   I N F O

Keywords:
Manufacturing service system;
Complex system;
Robustness;
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1. Introduction

The area of manufacturing service management has gained increased attention in recent years [1]. Under a strong trend towards servitization, no enterprise can complete all business process from the initial acceptance of customer orders to the final provision of products or services. Accordingly, meeting the specific service requirements can't do without the efficient synergy of multiple service principals, which together constitute a Service-oriented Manufacturing Network (SMN) [2]. From a complex system standpoint, MSS can be defined as an alliance system with a temporary interest bargain, formed through the dynamic coupling of all heterogeneous enterprises in SMN. Compared to the traditional manufacturing, this new pattern emphasizes the synergy between service principals. But as a greatest obstacle of synergy, the loosely coupling with or between enterprises has been in an urgent need of attention, which may severely disrupt the robust operation of MSS [3]. In practice, these loosely coupling phenomena are particularly prominent and common. Inconsistency of collaborative manufacturing, interactive interruption of information system, termination of customer participation and uncertainty of partnership, especially in a service-oriented logic market, will lead to a huge fluctuation in the structure and performance of MSS.

Unexpected changes make the cooperation have a certain risk in reality. Whether cooperation continues and gains benefit or not, they depend not only on the complementarity of technologies and resources and the risk of technologies and market, but also on the relationship management between partners. It's certain that the cooperation uncertainty have an effect on the robustness of MSS, reflected in service quality, service cost and service response time. As such, adopting what kinds of measures to guarantee system robustness requires us to reveal the influence mechanism in different scenarios. The findings can provide the professionals in the company with a basic theoretical support for the follow-up network planning and construction of cooperative management mechanism. The related researchers mostly focus on the specific design of contract and the revelation and perfection of relational governance mechanism [4, 5], or focus on the robust operation process from the technology control perspective [6], and rarely pay attention to the impact of cooperation uncertainty on the robustness of MSS.

On account of the fact that MSS is a complex system, this paper focuses on how MSS' robustness is affected by cooperation uncertainty and taking what kinds of measures to guarantee system robustness. The remainder of this paper is in the following format. In Section 2, an overview of the relevant researches is presented. Section 3 discusses serval typical manifestations of cooperation uncertainty in the service-oriented environment, while Section 4 develops the model based on complex network theory and proposes four different simulation strategies with algorithms. Section 5 conducts case analysis and simulation. The concluding remarks and comment relating to future research directions are provided in Section 6.

2. Literature review

2.1 Cooperation uncertainty

Cooperation can be defined as a kind of joint action of reciprocity and mutual benefit from an economic perspective, what both sides concern is the benefits of joint action [7]. High satisfactions, timely and accurate distribution, faster speed of development, have been proved to be the critical sources of competitive advantage in a service-oriented logic market [8, 9]. Ring *et al.* found that cooperation mainly faces two types of risk, respectively the future environment risks and cooperation risks [10]. Future environment risks come from the uncertainty of internal and external environment, such as the changes in the market environment, the enterprise strategy adjustment, the uncertainty of natural and artificial calamities, while cooperation risks are mainly embodied in two aspects: relationship risk and performance risk. The former refers to the possibility that the partners' incomplete cooperative behaviours are harmful to cooperation, such as various opportunistic behaviours, information asymmetry, and unanticipated benefit which makes the phenomenon of moral hazard and adverse selection occurrence frequently [11]. The latter mainly refers to that the uncertainty of cooperation still exists with the partners' complete cooperative behaviours by reason of the unfulfilled expected returns. In addition, the cases of terminating voluntarily cooperation relationships are often occurred in business practice.

The general description of uncertainty is the probability of the value of a variable or of the occurrence of an event, and also is unpredictable in advance. As long as there is cooperation, the probability of the occurrence of cooperation interruption exists. In order to minimize the impact of uncertainty, the correlation between the evolution of organization cooperation pattern and uncertainty [12], uncertainty in R&D (Technology) innovation cooperation [13], the optimization of job-shop scheduling [14], and the impact of market uncertainty on the cooperation behaviours and performances [15], had gotten a lot of attention. Through sorting out the relevant researchers, studying cooperation uncertainty from a holistic or a complex system standpoint still lacks.

2.2 Robust operation

The researches on robust operation in management field concentrate mainly on supply chain system and manufacturing system. Of this, supply chain system observes and studies the situations of parameter, time-lag and exogenous destabilization [16, 17], and manufacturing system follows with interests of uncertain situations of resource-constrained [18], time-constrained

[19], changing demand [20]. More related researches of robust management mainly discuss how to guarantee the robustness of product and manufacturing process by technology control [21], framework design [22], and robust system development [23]. Most are achieved by using state-space analysis method or structured analysis tools. Although these methods have the shortcomings of high computational complexity in the context of dynamic systems, they do improve the ability of working smoothly in accordance with robustness measure and robustness analysis under an uncertain environment.

A commonly-held definition for robustness in manufacturing system is: "*the ability of maintain working smoothly within an acceptable range under the expected or unexpected changing*" [24]. As mentioned above, the available literature offers up a wide range of robustness metrics. Some focus mainly on graph theory concepts such as node degree, connectivity, network efficiency, clustering coefficient and two-terminal reliability [25, 26], while others consider the services supported by R value, or stability, or elasticity, or net variation [27, 28]. The selection of specific robustness metrics is usually in accordance with the characteristics of research object, which is proved be efficient.

3. Cooperation uncertainties in MSS

3.1 Uncertainty of R&D cooperation

The key difference between cooperative R&D and traditional R&D organized by a single enterprise lies in the uncertainty of partner. It is clear that an important feature of service-oriented manufacturing mode is the provision of personalized products and services for customers, which is not only dependent on its own power, but also the cooperation of upstream and downstream partners and the participation of customers. With the exception of the inherent uncertainty of market and technology, there still exists the uncertainty in behaviours arising from trading costs in the process of cooperation. In practice, the appearance of behaviour uncertainty such as leakage of knowledge, hitchhiking and ripping off, may result in the final termination of cooperation, furthermore, would have a direct effect on the manufacturing process and the response time to customers' demands, which deviates from the service philosophy of this new manufacturing pattern.

3.2 Uncertainty of collaborative manufacturing

Collaborative manufacturing is the core content of service-oriented manufacturing, mainly reflected in three aspects: synergism of all departments and information systems, collaborative manufacturing between all sub factories and collaborative manufacturing based on the whole supply chain. These factors such as complex relationships of structure, interest paradox between nodes and information asymmetry, would make the entire process of collaborative manufacturing with greater uncertainty. For instance, there will be a Butterfly effect caused by collaboration uncertainty, the lack of effective communication and coordination among departments, sub factories, and supply chain partners. Also, there will be a Matthew effect arising from purchasing uncertainty, information opaque and individual consummate interest, while running uncertainty and multipoint concurrency of producing tasks would lead to a Bottleneck effect of resources. In addition, there still exists much purchasing and producing uncertainty caused by natural or man-made disasters.

3.3 Uncertainty of cooperative marketing

To enhance the quick response ability to market demand, service-oriented manufacturing enterprise needs to integrate the transversal and longitudinal superior resources, and strengthen cooperative marketing among manufacturing enterprise, salesman and the third party logistics enterprises (e.g., cooperative marketing among Apple, eBay and USPS or among Huawei, Tmall and SF-express). Nevertheless, the ability of marketing partners, communication and coordination, lack of credibility, unrealistic expectations, etc., would cause greater uncertainty in cooperative marketing and further may lead to the final cooperation termination that has an unpredictable loss.

4. Robustness measurement

4.1 Model setup of system topology structure

As shown in Fig. 1, MSS can be divided into three subsystems: service production subsystem, production service subsystem and customer management subsystem. Each subsystem covers a cluster of similar or complementary work, formed through dynamic coupling of all the isomeric and heteroid enterprises in SMN, which has the main characteristics of a complex system. Compared to traditional manufacturing network, SMN has a wider range of source choices, and its structure has changed from tree structure to multi-loop network structure. Similarly, the relationship between network organization and synergetic effect is not a simple linear one. For the reasons mentioned above, it's more suitable and more efficient to use network analysis theory, method and tools to study the robustness of MSS.

As such, we can analyze the impact of cooperation uncertainty on the robustness of MSS based on complex network theory. Complex network is the abstract representation of a complex system, so we can regard the cooperative enterprises as the network nodes and the collaborative relationships as the network edges. Hence, the manufacturing service network can be expressed by the undirected network graph G(V, E). $V = \{v_1, v_2, v_3, \dots v_n\}$ and $E = \{(v_i, v_j), i, j = 1,2, \dots, n\}$, respectively, denote the node set and the edge set of SMN. In addition, we use $\mathrm{W} = (\mathrm{w}_{ij})_{n\times n}$ to represent the adjacency matrix of network. If there exists collaborative relationship between network nodes v_i and v_j, $w_{ij} = 1$, else $w_{ij} = 0$.

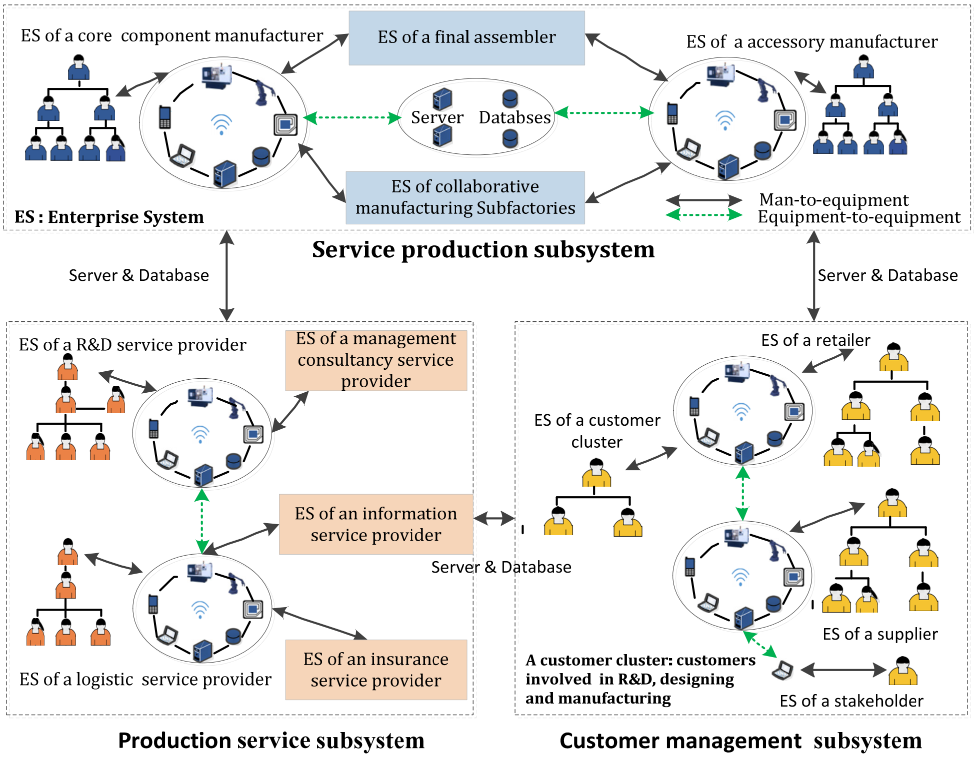

Fig. 1 A framework of MSS

4.2 Robustness metrics

In terms of MSS, there are a large number of random, fuzzy and uncertain factors, which may lead to a decline in collaboration among service principals and be seriously likely to a disruption of partnerships and also a loss of its structural functions. Before introducing our methodology, it's important to define the robustness of MSS, which is: "*the ability to maintain its basic structure and performance under the termination of collaboration relationships caused by random or targeted factors*". Accordingly, learning the robustness ought to be from the structural and performance dimensions.

Structural robustness. The definition of structural robustness is: "*the ability to resist the decline of network connectivity caused by the inactivation of service nodes*". We choose natural connectivity as the structural robustness metric, firstly proposed by Wu *et al.* in 2010. It's easy to understand that the higher the redundancy of alternative routes is, the better the connectivity of network structure and the structural robustness will be. Especially in a service-oriented market environment, the main way to deal with the interference of uncertainties is to enhance the elasticity of MSS, while the guarantee of elasticity depends on the proper redundancy of system structure. Taking account of the complexity of MSS, the existing mature structural robustness metrics, such like maximum connected graph, node connectivity, algebraic connectivity, either have the limitation to sensitivity decline of node inactivation or edge blocking, or are difficult to distinguish the difference of the minimum degree, and also ignore the factor that there are a lot of peripheral nodes in SMN.

Natural connectivity can be used to describe the redundancy of alternative routes between vertices by quantizing the weighted sum of numbers of closed walks, and also has a clear physical meaning. As such, with redundancy as the breakthrough point, the structural robustness of MSS can be effectively characterized by natural connectivity, which can be represented by the average eigenvalue of the network graph adjacency matrix [29]:

$$\bar{\lambda} = \ln\left(\frac{1}{n}\sum_{i=1}^{n} e^{\lambda_i}\right)$$

In which n and λ_i respectively represent the node number and the characteristic roots of adjacency matrix $\mathrm{A}_{\mathrm{n*n}}$ of graph G. In order to eliminate the impact of network size on natural connectivity, we can make the normalization treatment in the following:

$$\tilde{\lambda} = \frac{\bar{\lambda}}{n - \ln n}$$

Performance robustness. The definition of performance robustness is: "*the ability to resist the decline of system performance caused by the inactivation of service nodes*". We choose endurance to describe the ability of an organism to withstand an adverse situation in order to remain active for a certain period of time, which is a time-dependent property. Compared with the traditional performance robustness metrics, it is more concerned with the frequent perturbations of low-scale network elements (nodes or edges) in practice. In order to clear the reason for choosing endurance as the performance robustness metric, we firstly give the definition of endurance ξ as follows [30]:

$$\xi(a,b) = \frac{\sum_{n=a+1}^{b} A(a,n)}{\sum_{n=1}^{b-a} n}, \qquad b > a \tag{1}$$

$$A(p,q) = \sum_{n=p}^{q-1} \frac{C(n) + C(n+1)}{2}, \qquad q > p \tag{2}$$

a, b, p, q represent the proportion of the removed network elements, and $C(n)$ is a normalized function that represents the value of service parameters when removing n% network elements. Obviously, the endurance value is normalized over the interval [0, 1]. When the selected service parameters (e.g. network efficiency) are inversely proportional to the number of the removed network elements, $\xi = 1$ means the best performance robustness, whereas $\xi = 0$ means the non-existence of robustness. In contrast, ξ=0 and 1 express a opposite meaning of the former when the service parameters (e.g. blocking rate) are proportional to the number of the removed network elements.

Theorem:

(i) if $C(n)$ is a decreasing function of n, then$\xi(a,b) \geq A(a,b)/(b-a)$;

(ii) if $C(n)$ is a increasing function of n, then $\xi(a,b) \leq A(a,b)/(b-a)$.

Proof:

(i) For $A(a,b) = \sum_{n=a}^{b-1} \frac{C(n)+C(n+1)}{2}$, and $C(n)$ is a decreasing function of n, we can obtain that:

$$\frac{A(a,a+2)}{a+2-a} = \frac{C(a)+C(a+2)}{4} + \frac{C(a+1)}{2} \leq \frac{C(a)}{2} + \frac{C(a+1)}{2} = \frac{A(a,a+1)}{a+1-a}$$

Furthermore, we can obtain the following conclusion:

$$\frac{A(a,a+1)}{1} \geq \frac{A(a,a+2)}{2} \geq \cdots \geq \frac{A(a,b)}{b-a}$$

Also for $\xi(a,b) = \frac{\sum_{n=a+1}^{b} A(a,n)}{\sum_{n=1}^{b-a} n}$, then

$$\xi(a,b) = \frac{A(a,a+1)+A(a,a+2)+\cdots+A(a,b)}{1+2+\cdots+(b-a)} \geq \frac{\frac{A(a,b)}{b-a} + \frac{2A(a,b)}{b-a} + \cdots + \frac{(b-a)A(a,b)}{b-a}}{1+2+\cdots+(b-a)} = \frac{A(a,b)}{b-a}$$

That is $\xi(a,b) \geq A(a,b)/(b-a)$, prove up.

(ii) The proof is similar to (i), so the process is omitted.

According to the theorem (i), we know that performance robustness measured with endurance is higher than that measured with service parameters. Because of the decreasing property of $C(n)$, the larger the value of ξ is, the better the performance robustness will be. In reality, the probability of a large-scale interruption of cooperation is low, while the probability of a low-proportion interruption is high. To these, MSS has a good tolerance for the fully expectation of the above frequent uncertainties, and it is more in line with reality to assess the performance robustness of MSS with endurance.

It can also be seen from the definition that endurance has a strong compatibility with some common performance robustness metrics, such like service quality, service reliability, network efficiency and blocking rate. When discussing other complex networks with different features, we can take those metrics as the QoS parameters. Furthermore, the evaluation of performance robustness should be not only in a specific instant of time, but also in a period. Therefore, the above facts make it more suitable and more objective as the performance robustness metric.

A simple example is presented below to explain how endurance can be computed. We take network efficiency as the QoS parameter and assume that $C(n)$ satisfies the changing rule in Fig. 2.

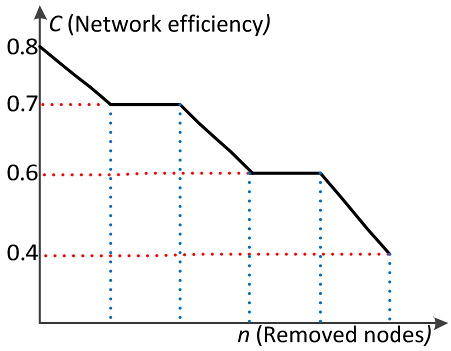

Fig. 2 The function diagram of *C* and *n*

From Fig. 2, the endurance can be calculated as depicted from the following formulas. Finally the performance robustness of such a network is of $\xi = 0.68$.

$$A(0,1) = \sum_{n=0}^{0} \frac{C(n)+C(n+1)}{2} = \frac{0.8+0.7}{2} = 0.75$$

$$A(0,2) = 1.45, A(0,3) = 2.1, A(0,4) = 2.7, A(0,5) = 3.2$$

$$\xi(0{,}5) = \frac{\sum_{n=1}^{5} A(0,n)}{\sum_{n=1}^{5} n} = \frac{A(0{,}1) + A(0{,}2) + A(0{,}3) + A(0{,}4) + A(0{,}5)}{1+2+3+4+5} = 0.68$$

If we use network efficiency to measure the robustness, the normalized value is $A(0{,}5)/5 = 0.64$. This value results to be worse than the one computed by endurance because the nature of endurance is related to the fact that the network tolerates better those failures which have a lower probability of occurring. Consequently, it's further proved that taking endurance as the performance robustness metric is appropriate.

4.3 Simulation strategy and algorithm

As mentioned above, there are a lot of uncertain factors in MSS, which may cause some service principals to fail to complete their role functions, and also lead to a termination of collaboration relationships. In this paper, we divide the factors into two categories: random cooperation interruption and targeted cooperation interruption. Random cooperation interruptions mainly refer to the random uncertainties among the internal and external service principals, such like the cooperation termination caused by natural disasters or man-made accidents. Targeted cooperation interruptions generally refer to the subjective and purposeful termination, such like competitors poaching and unexpected returns. Depending on where the interruption happened, we will discuss two typical kinds of cooperation interruptions: interruption occurring in the interior of nodes and interruption occurring in the edges among nodes, which can be respectively simulated by deleting nodes and deleting edges. The specific strategies and algorithm are as follows:

Strategy 1: If random cooperation interruptions occur in the interior of MSS' nodes, then select network nodes randomly and delete these nodes.

Strategy 2: If random cooperation interruptions occur in the edges among nodes, then select network edges randomly and delete these edges.

Strategy 3: If targeted cooperation interruptions occur in the interior of MSS' nodes, then select and delete the nodes with higher node degree. (The reason for this is that node degree reflects the importance of nodes in the network. The nodes with higher node degree often have the position of "central point", which face a more external and internal inferences for its strong position in cooperation).

Strategy 4: If targeted cooperation interruptions occur in the edges among nodes, then select network edges according to the descending order of the product ($d_i d_j$) of node degree. The bigger the value of $d_i d_j$ is, the greater the probability of being attacked is, whereas d_i and d_j denote the node degree value of joint nodes.

Table 1 Simulation algorithms with strategy 1 and 3

Algorithm1

Input: w_{ij}, n (i, j←1, 2⋯n) and the maximum percentage of removed nodes N
Output: $\tilde{\lambda}$, ξ ,the adjacency matrix W, and all nodes degree $D_{1\times n}$
begin{
  for k from 1 to N
    if strategy 1
      $\mathrm{B}_{1\times k} \leftarrow \mathrm{randperm(N, k)}$;
      for m from 1 to k
        $w(B_m:) \leftarrow [], w(:B_m) \leftarrow []$;
      end for
      computing the new value of natural connectivity $\widetilde{\lambda_1}$ and endurance ξ_1
      $\tilde{\lambda} \leftarrow \widetilde{\lambda_1}, \xi \leftarrow \xi_1$;
    else if strategy 3
    $[r, c]$ ←find(max(D))
      for m from 1 to k
        $w(r:) \leftarrow [], w(:c) \leftarrow []$;
        $W \leftarrow (w_{ij})_{(n-m)\times(n-m)}$
        computing $\widetilde{\lambda_1}$ and ξ_1
        $\tilde{\lambda} \leftarrow \widetilde{\lambda_1}, \xi \leftarrow \xi_1$;
      end for
    end else if
  end if
} **end** of the algorithm1

Table 2 Simulation algorithms with strategy 2 and 4

Algorithm2

1: **Input**: w_{ij}, n (i, j←1, 2⋯n) and the maximum percentage of removed edges M
2: **Output**: $\tilde{\lambda}, \xi$,W , $D_{1\times n}$
3: **begin**{
4: **for** k from 1 to M
5: B←find(W), $[a, b] \leftarrow$ size(B);
6: **for** m from 1 to a
7: **if** B(m,1)=B(m,2)
8: B(m:) ← []; $B \leftarrow (B)_{(a-m)\times 2}$;
9: **else**
10: $B \leftarrow (B)_{a\times 2}$;
11: **end if**
12: $[r, c] \leftarrow$ size(B);
13: **end for**
14: **If** Strage2
14: $C_{1\times k} \leftarrow$ randperm(r, k);
15: **for** d from 1to k
16: $m \leftarrow C(1, d), m \leftarrow B(m, 2), W(\mathrm{h}, \mathrm{m}) \leftarrow 0, W(\mathrm{m}, \mathrm{h}) \leftarrow 0; W \leftarrow (w_{ij})_{(n-k)\times(n-k)}$;
17: computing $\widetilde{\lambda_1}$ and ξ_1
18: $\tilde{\lambda} \leftarrow \widetilde{\lambda_1}, \xi \leftarrow \xi_1$;
19: **end for**
20: **else if** Strage 4
21 **for** i from 1 to r
22: $D1(1, i) \leftarrow D(1, B(i, 1)) * D(1, B(i, 2))$;
23: **end for**
24: r1 ←find(max(D1));
25: $h \leftarrow B(r1,1), m \leftarrow B(r1,2), W(\mathrm{h}, m) \leftarrow 0, W(m, \mathrm{h}) \leftarrow 0; W \leftarrow (w_{ij})_{(n-k)\times(n-k)}$
26: computing $\widetilde{\lambda_1}$ and ξ_1
27: $\tilde{\lambda} \leftarrow \widetilde{\lambda_1}, \xi \leftarrow \xi_1$;
28: **end else if**
29： **end if**
30: **end for**
31: } **end** of the algorithm2

5. Case study

In the early stage, our team conducted an in-depth survey of 17 manufacturing enterprises in the Pearl River Delta region of China, mainly from luminaries, furniture, equipment, electronics and other industries. In the electronics and equipment industry, we found that the alliance with a temporary interest bargain is more common and faces a higher degree of cooperation uncertainty caused by non-standard coordination, discordant job schedule and asymmetric information. Considering the characteristics of high technology content, high added value and high degree of association, equipment manufacturing industry has a wider potential and space of service transformation, and its new value creation pattern is more typical and representative.

R is a joint venture company specializing in producing and designing elevator. Since 2012, this company has begun the pace of transformation to servitization, called"2.5 strategy", and has formed a complex and huge manufacturing service network in the last five years. Nevertheless, the cooperation interruptions resulting in a poor service quality and a high service cost often occur. Based on his own data statistics, R pays about ¥19 million per year on average for these uncertain expenditures.

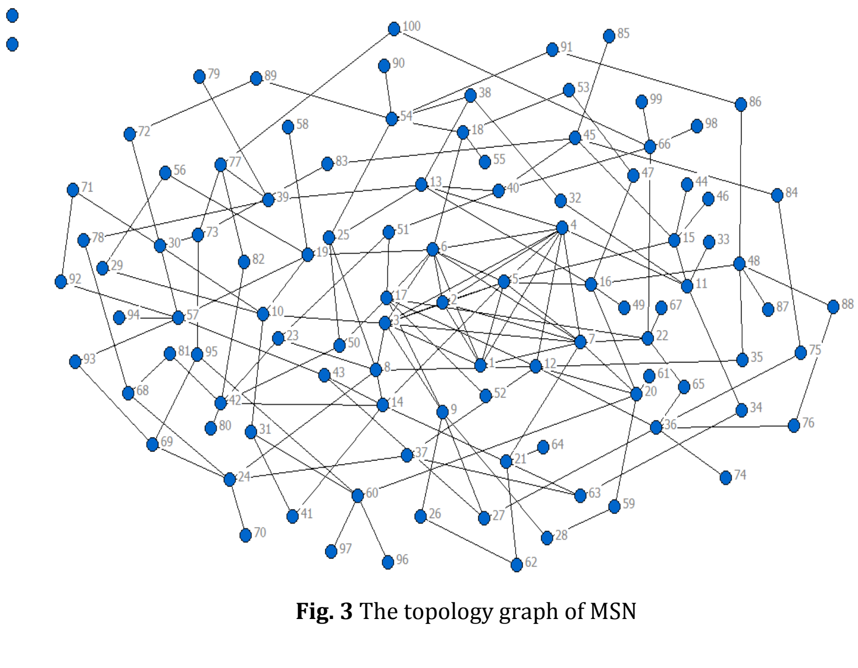

Fig. 3 The topology graph of MSN

At present, MSS has five manufacturing factories and two R&D centers in China, respectively described by nodes 1-7 in the topology graph. The others mainly refer to the primary partners and the secondary partners including service providers, outsourcing providers, suppliers and major product sellers. According to the modularized process flow and data flow of business, we can determine the collaborative relationship network among service principals, and further construct the adjacency matrix of MSN using the method described in 4.1. The following topology diagram (Fig. 3) is drawn with the NetDraw tool, which contains 100 nodes and 176 edges.

5.1 Simulation of structural robustness

In accordance with the type of cooperation interruption and the location, the 0-50 % node inactivation rate is simulated in turn. As shown in Fig. 4, the structural robustness of the initial network is 0.0245. Seen from Fig. 4, the black scatter curve fluctuates in a certain range when some nodes are attacked; however, the natural connectivity presents a downward trend with the wave band on the whole. The fluctuation reflects the randomness of node inactivation, and the upward or downward fluctuation depends on the node importance of random deletions.

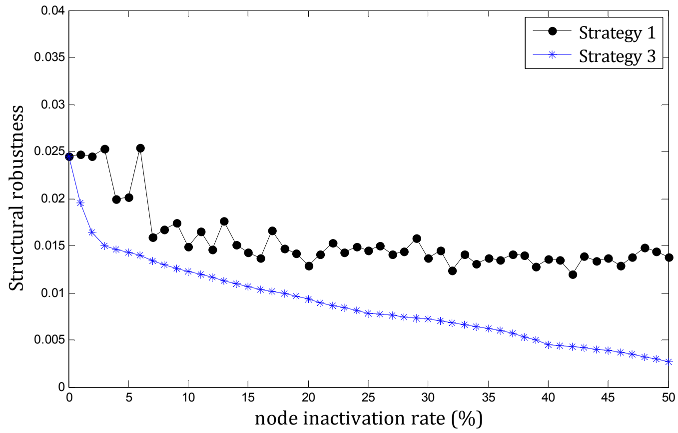

Fig. 4 Simulation results of structural robustness with strategy 1 and 3

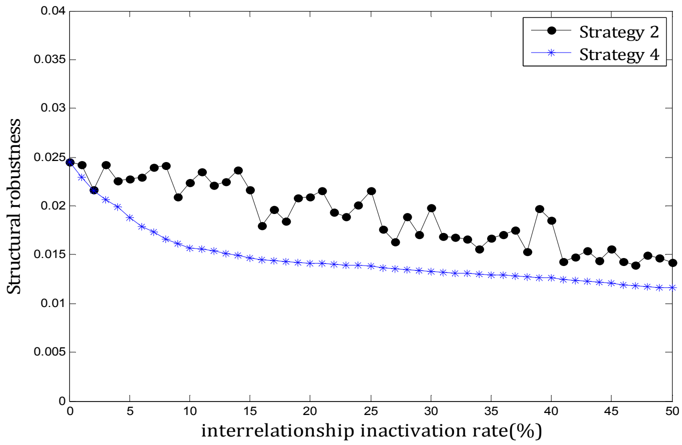

Fig. 5 Simulation results of structural robustness with strategy 2 and 4

In Strategy 1, when the node inactivation rate reached 8 %, the structural robustness had a reduction of 35.1 % than the initial state, and when the node inactivation rate reached 50 %, it only decreased by 43.67 %. These imply that MSS shows an obvious vulnerability to some core nodes, and may has a threshold for the occurrence of random cooperation interruptions in the interior of nodes, around where the structural robustness is very sensitive to node inactivation. Similarly in Strategy 3 and 4, the dramatic decline of structural robustness in the early stage with targeted cooperation interruptions also illustrates this phenomenon. What's different is that the threshold in the situation of random cooperation interruptions is different from that in the situation of targeted cooperation interruptions, which are just right for the correspondence to the two critical values of percolation theory under random failure and targeted failure. The phenomenon that the blue star curve was always below the black dot curve shows MSS has a certain resistance to random cooperation interruptions compared to targeted cooperation interruptions, and its structural robustness is slightly stronger.

5.2 Simulation of performance robustness

As you can see from Fig. 6 and Fig. 7, the performance robustness of MSS has a strong resistance to random cooperation interruptions. The reasons are chiefly as follows: one is due to the existence of a great many peripheral nodes, of which the inactivation may be beneficial to the improvement of network performance. This is consistent with many real networks, such as supply chain network and collaborative innovation network. The other is due to the tight partnerships between core manufacturers and major partners, who constitute a non-chain network structure like the relationship network formed by nodes 1-7 in Fig. 3. In particular, when the random factors lead to the interruptions within the node subsystem, MSS shows a more stable performance. The reason mainly lies in two aspects: 1) Random interruptions occur at the fringe nodes, which result in the deactivation of fringe nodes and improving the network efficiency. 2) Compared with targeted interruptions, random interruptions have little effect on the relation network consisting of core nodes with their high synergy. Although the interruptions of one or more interaction relations occur, the network efficiency shows a relatively stable trend on the whole as depicted in the black dot curve of Fig. 6.

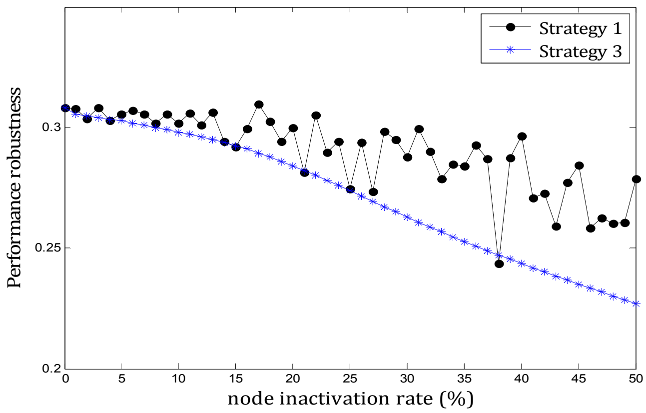

Fig. 6 Simulation results of performance robustness with strategy 1 and 3

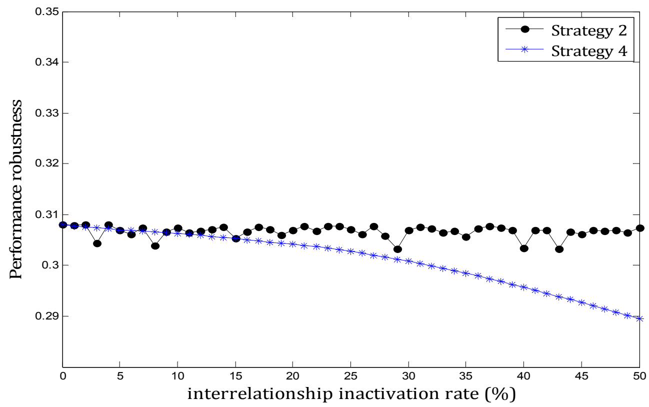

Fig. 7 Simulation results of performance robustness with strategy 2 and 4

From Fig. 6, we also find that the wave amplitude of the black dot curve is large at some time. For example, when the node inactivation rates are respectively 22 %, 39 % and 46 %, MSS' performance robustness severally had a reduction of 6.26 %, 15.18 %, 9.2 % than the previous state. This is because that the node inactivation rate of the simulation algorithm is based on the original network nodes every time instead of accumulating the node inactivation rate based on the previous network that has been attacked. Therefore, the randomness of node deletion may lead to the inactivation of some core nodes and even lead to the emergence of a sharp decline in performance robustness.

6. Conclusion

The downward fluctuation in the robustness of MSS caused by cooperation uncertainty will result in the degradation of service quality, the increase of service cost and the delay of service response time, so it's crucial for the company to guarantee the stability of internal and external cooperation relationships. Aiming at the problems that the loose coupling character of cooperation, we analyze the impact of cooperation uncertainty on the robustness of MSS. The findings show that: (1) natural connectivity and endurance can effectively measure the changes of structure and performance. (2) The structural robustness of MSS has an obvious vulnerability to the inactivation of core node subsystems, and also has a little stronger resistance to random cooperation interruption compared to targeted cooperation interruption. In addition, there should be a threshold respectively in the situation of random cooperation interruption and targeted cooperation interruption, which can be used as the judgement conditions for structure collapse. (3) The performance of MSS shows a stronger resistance to random cooperation interruptions, which verifies the importance of large scale presence of terminal enterprise, and of the synergy of core manufacturing enterprises and service providers. Accordingly, the performance robustness is more sensitive to the inactivation of nodes compared to the inactivation of interrelationships among nodes.

Therefore, the companies should first identify the critical paths of MSS, and then standardize the cooperation mechanism within and between core organizations, which can contribute the most to minimizing cooperation uncertainty. Besides, we can take the following measures to enhance the activity of network nodes, such like adjusting operation mode, strengthening informationization construction and building an emergency response mechanism. Simultaneously, managing customer relationship, establishing new collaborative relationships with those normative members, and searching for new partners with potentiality are also feasible to maintain the activity of nodes and edges of the critical paths. Compared to other measures, the governance of partnership and customer relationship can reduce the impact of cooperation uncertainty on the robustness with lower possible costs. The follow-up studies can be focused on the critical threshold in the situation of inactivation of interrelationship, robust operation optimization and service network planning.

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