H. Zhuge, Cyber-Physical-Social Intelligence on Human-Machine-Nature Symbiosis, Springer, 2020.

Chapter 10
Semantic Link Network for Understanding and Representing Reality in Cyber-Physical-Social Space – A Model for Managing COVID-19 Pandemic

Humans evolve with understanding reality and discovering, applying and developing knowledge. An approach to understanding reality is to observe and deal with unknown phenomena and then discover, interpret and verify the underlying principles and rules. Link and dimension are basic means for understanding and representing reality.

The natural ecosystem is a subsystem of the nature, which evolves symbiotic networks of various species and natural resources. Changing a symbiotic relation could influence the stability of the network, which provides a condition for one species to influence another species. The outbreaks of many pandemics in history are originated from interactions between humans and other species hosting various viruses. Understanding and maintaining various symbiotic relations between species is an important way to prevent and manage a pandemic.

A pandemic caused by a previously unknown virus reflects the unknown fields of reality to a certain extent. A pandemic evolving in a cyber-physical-social space can be modelled by a cyber-physical-social relational system consisting of a base network of various relations, various flows, and a superstructure that influences the evolution of the base network. Through modeling and analyzing a pandemic, the application of the model is demonstrated and particular rules and methods are unveiled.

10.1 Preliminary Understanding of Pandemic

Long-term evolution enables one kind of species (e.g. bat) to establish symbiotic relation with another kind of species (e.g. virus). Physical interaction between different species may lead to transmission of the symbiotic species (e.g. virus) between species. A special case is that one kind of animal interacts with another kind of animal will face the risk of being infected by the virus it carries. Infection can lead to invasion of virus into the cells of new host animals, where it reproduces itself on their organs.

Some animals can carry many viruses but not any virus can migrate from one species to another. Even within the same species, only when the virus in one individual satisfied some conditions (e.g. Koch's postulates) has the ability to infect others. If the immune system of the infected individual can conquer the virus, it will recover with antibody, otherwise it will be ill with a certain symptom or without obvious symptom, and can become critical and even death when the viruses heavily reproduces themselves to damage organs and the immune system reacts strongly so that the functions of organs are seriously hurt.

A pandemic is a wide propagation of virus through human-to-human, human-to-animal, animal-to-animal, animal-to-virus, and human-to-virus interactions in human society. The spread of a virus from one kind of animals to humans usually needs a help from an intermediate host where the virus can carry out variation. Some scientists regard bat as the possible origin of COVID-19, but the origin and intermediate hosts still remain to be uncovered (some researchers suspect that pangolin, mink and snake are possible intermediate hosts, and some even suspect that it was made by laboratories).

The following are some research problems on pandemic:

1. Trace the origin of pandemic including discovery of the intermediate host, which is essential for curbing the pandemic and prevent it from re-outbreak.
2. Find the propagation characteristics and control methods so that appropriate strategies can be adopted to curb the pandemic with the least cost.
3. Identify the virus, survey the clinical characteristics of the disease, suggest protection approaches and find the diagnosis methods.
4. Develop the vaccine and find the effective medicine.

Here the main concern is the second problem.

A pandemic network can be regarded as a governed self-organized network with propagation of virus. The state of the network is influenced by behaviours of individuals governed by laws and strategies made by the authority of society. An unknown virus can form a large-scale pandemic network, for example, the Black Death in fourteenth century in Europe, the outbreak of SARS during 2003-2012, MERS in Middle East during 2012 and the new coronavirus COVID-19 pandemic. Such a pandemic network has the following basic characteristics:

1. There is no vaccine and effective cure during pandemic.
2. One person can infect multiple persons but the toxicity of virus may be reduced through propagation. An intuitive explanation is that the nature of virus is to establish symbiotic relation with the new host for survival rather than to kill the host. The COVID-19 pandemic in Europe shows that the second wave took place with bigger infection number and lower death rate than that of the first wave.
3. The origin and intermediate hosts of the virus is unclear during pandemic.

4. The characteristics and structure of the propagation network are not completely known during pandemic.
5. The basic strategy for curbing a pandemic caused by an unknown virus is to cut the possible infection links.

COVID-19 has greatly influenced society and culture. More and more social activities such as physical teamwork and classroom study have been moved from physical space into cyberspace. Some traditional cultures like shaking hands and visiting friends' homes have been avoided. Pubs, restaurants and coffee shops need to innovate internal design to ensure personal spaces and develop online booking and delivery services. Public indoor spaces such as transportation vehicles and stations should be given more personal spaces by reducing human flow. People's work, study and daily life will be more and more in personalized spaces. The cost of personal space services will rise, which stimulates traditional enterprises that provide physical services for innovating new businesses.

Cyber-Physical-Social Space is a promising personal space that provides cyber, physical and social services.

10.2 Modelling Pandemic from Multiple Abstraction Levels

There is a long history of modelling pandemic. Compartmental models are based on classification of populations into different compartments with the assumption that individuals in the same compartment has the same characteristics (Kermack and McKendrick 1927). SIR Model consists of three compartments: Susceptible, Infectious and Recovered (or immune), changing their populations with time during general pandemic process. The SEIR model increases an Exposed compartment reflecting that the infected individuals have no infection ability during the latent period. These models can be used to predict the total populations of different groups of people and duration of pandemic (Bailey 1975; Hethcote 2000). Some researchers studied the propagation models during the outbreak of COVID-19. One research estimated that 75,815 individuals had been infected in Wuhan until 25/01/2020 with the assumption of reproductive number 2.68 (Wu et al. 2020), but the result is far from the official data (50,339) released and updated during pandemic.

Recognition of reality relies on observers' knowledge. So, it is understandable that both modelling and statistical data are not reality because models are based on simplification and statistic data are usually inaccurate due to technical factors (e.g. testing technique) and social factors (e.g. workers may not be able to approach reality or were busy in saving life during the outbreak of pandemic).

These mathematical models are based on simplification through omitting some particularities and assumptions that may not hold in real cases, especially the infection characteristics of the new virus are unclear (e.g. whether a patient has infection ability during latent period), human behaviours and strategies taken at different stages of pandemic. These models could be used for reference when making decisions on preparing and raising various resources according to incomplete information about reality.

Further, *the mathematic models neglect the structure of propagation network so they are limited in ability to solve the problems about the structure of the network*, for example the following two problems:

1. How to identify the potential next persons to be infected?
2. Where appropriate resources should be delivered?

Social network models and analytic approaches concern characteristics (e.g. degree distribution) and patterns (e.g. community discovery) of the structure of a society (Wasserman and Faust 1994; Newman 2004; Zhuge 2005; Liben-Nowel and Kleinberg 2007; Kossinets and Watts 2006; Zhuge and Zhang 2010). *These models can help solve some problems about the structure of the network*. For example, they can help identify the next persons to be infected, support deploying resources according to the weights (degree of infection) of communities on the pandemic network, and find and cut the key propagation paths (e.g., the link between communities).

However, *the social network models are too general to reflect the particularity of real applications involving the semantics of nodes, the semantics of links and rules on semantic links*. So they are limited in ability to answer such questions as:

1. Who were infected, and who will be probably infected?
2. Why was a person infected (in which way)?
3. Where was he/she infected?
4. Whether will his/her father or mother be probably infected?

Traditional pandemic networks and social networks can be regarded as macroscopic models, which neglect the diversity and complexity of society. A real pandemic network operates in a cyber-physical-social space where information is collected and transmitted, humans move and interact with each other and make decisions, and laws and strategies are applied to regulate human behaviours.

Semantic Link Network reflects a structure of an observed reality at a middle-abstraction level. It consists of a set of nodes, semantic links between nodes, and a semantic space that defines semantics on nodes and semantics on links (Zhuge 1998; 2003; 2004; 2005a,b; 2006b; 2007; 2009; 2010; 2011; 2012; 2016). It can be implemented on a centralized system or a decentralized system, e.g. on a peer-to-peer network (Zhuge and Li 2007).

The Semantic Link Network for social applications take the form of a social relational model, which consists of a base network and a superstructure including spaces of rules, laws, strategies and policies that influence the evolution of the base network. It can be used to model a pandemic from the following mutually interactive levels:

1. The base network models the structure of a pandemic network consisting of nodes (including individuals and organizations) and various relations between nodes. A base network can consist of multiple networks.

2. The superstructure includes various operations, a semantic space on nodes, links and rules as well as a space of strategies and policies.

An observed reality can be modelled by models of different abstraction levels as depicted in Figure 10.1. The microscopic level consists of data models that specify the data collected from the observed reality, e.g. images of the observed organs, test data and medical records of patients. The cyberinfrastructure level supports simulation of reality based on the models of different abstraction levels and interactions with users.

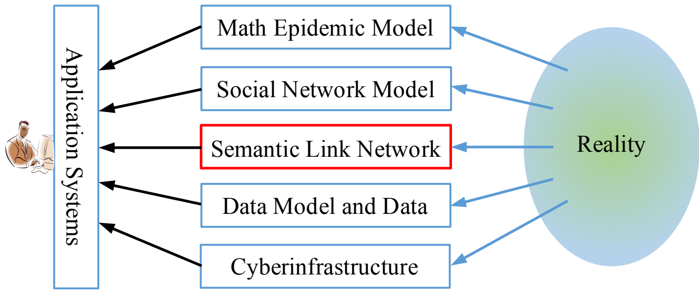


Fig. 10.1 Modelling the observed reality from multiple abstraction levels.

10.3 Semantic Link Network for Modeling Pandemic

Semantic Link Network for modelling pandemic has the following characteristics:

1. *Nodes represent active individuals or organizations*. An individual can be human or animal, both of which can carry virus. An individual has features (including *age*, *occupation*, *address*, *location*, …, etc.), states (including *healthy*, *contacted*, *suspected*, *infected*, *immunized* and *dead states*) and functions (for processing information and knowledge and performing behaviours). The location of a node can change with a certain daily pattern relevant to age and occupation. During serious pandemic, mobile communication operators can be authorized (by users, operators and laws) to obtain those features through mobile devices automatically with a certain level of privacy guarantee. An organization can be hospital, company and university that provides services for individuals with a certain social value.

2. *Semantic link represents various relations*, including *family relation* (*father-of*, *wife-of*, *mother-of*, *son-of*, …, etc.), *colleague relation*, *classmate relation*, *supervisor relation*, *business relation* and *physical distance*. Implicit links can be derived from relational reasoning on these relations.
3. *State of node depends on the state of the linked neighbour nodes and the semantic links*. One state can be transformed into another state with a certain probability as shown in Figure 10.2, which is extended from the state transformation of SARS (Zhuge 2005a). A transformation from one state into another state mainly depends on social relations, physical distance between them, characteristics of virus and rules of interactions. The following are characteristics of COVID-19: (1) the healthy state is transformed into the contacted state mainly through droplets or close contacts; (2) about 1-5% closely contacted people are transformed into the infected state (WHO 2020), and the rate of transforming the infected patient into the death state is 1.4% (Guan et al. 2020), which is closely relevant to age: the older the higher death rate (21.9% for those that are older than 80), relevant to gender (male: 4.7%, female: 2.8%) and occupations (the retired people is the highest) and (3) the average cure duration (from being hospitalized to death or recover) is about 12.8 days.
4. *Infection flow*, which can influence state transformation on the node that interacts directly or indirectly with the infected individual. Transformation from the "healthy" state into the "infected" state depends on the ways of being contacted.

Different viruses have different characteristics of infection. The main infection way of COVID-19 is droplets, which is closely related to the physical distance between nodes in the same space (e.g. when they lived in or travelled to the original region of pandemic, lived together with infected persons, or participated in the same event with the infected patients), the states of nodes and the relations between nodes (e.g. family relation conveys infection with a higher probability, 83% of infection happened in family during COVID-19 according to CDC of China). Transformation from the "contacted" state into the other states takes place after a certain latent period (1 day–24 days, the average latent period is 4 days) (Guan et al. 2020).

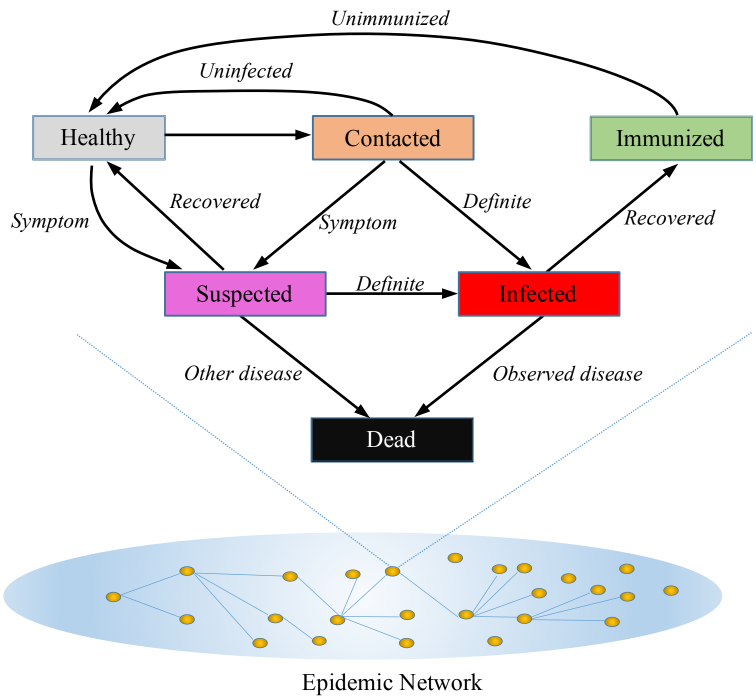


Fig. 10.2. State transformation network of a node on a pandemic network.

10.4 Predicting Next Infected Nodes

The extreme strategy for curbing a pandemic like COVID-19 is lockdown but this will heavily damage many aspects of society such as wellbeing and economy. Precisely predicting the next infected nodes is a way to minimize the damage. The prediction method is based on the availability of data on individuals, infection patterns and diagnose method.

10.4.1 *Problem and Assumption*

Predicting the next infected nodes is to identify the most probable nodes that will contact the current infected nodes so that appropriate warning can be sent to the nodes before actual contact rather than just identifying the contacted person.

Solving this problem concerns the base network and the superstructure of the pandemic network. Here focuses on the base network.

Different from the study of link detection on graph-based social network (Liben-Nowel and Kleinberg 2007), *a pandemic network evolves with emerging new nodes and transformation of the states of nodes according to some uncertain rules*. Although cyberspace is accumulating more and more data about people, we cannot assume that the neighbours of an infected node can be completely found because data may be incomplete and the mobility of people is high, especially for big cities. It is rational to have the following assumptions:

Assumptions:

1. An open set of data $D=(d_1, d_2, \ldots, d_n)$ is available for identifying nodes, where d_1, d_2, …, and d_n are dimensions (or databases) that specify the nodes. New nodes can be collected from cyberspace through various sensors (including mobile phones) or appended by people (professionals or citizen of the observed region). D records permanent residents and floating population. It changes with birth, death and rules of floating population because these data cannot be neglected in big countries (e.g., the normal rates of birth and death are about 1.295% and 0.709% respectively in China).
2. A disease is diagnosed through observing symptoms. Different symptoms can be observed from different dimensions (by using different devices such as clinical observation, nucleic acid reagent and CT). For COVID-19, about 87.9% of infected persons have fever (but only 43.8% of infected persons have fever at the early stage), 67% infected persons have cough, the accurate rate of nucleic acid reagent is 30%-50%, and the accurate rate of CT check-up is 76.4% (Guan et al. 2020). Some infected persons may have no symptom at the early stage of a new disease. Therefore, diagnosis comes with a certainty, and diagnosing from multiple dimensions generates a certainty determined by the certainties at all possible dimensions, denoted as $C(c(p, e_1), \ldots, c(p, e_n)) < 1$, where C is a function of the certainty of checking up person p by equipment e_k, $c(p, e_k)$, $k \in \{1, \ldots, n\}$.
3. The recovered nodes can be either immunized or unimmunized. For a new virus, it is usually unclear at the early stage of pandemic whether a recovered individual is immunized or not.

For a pandemic, it is reasonable to assume that the following data are available or can be constructed as a basic cyberinfrastructure:

1. Resident data d_1 records people of a city, d_1: (ID, *name*, *age*, *gender*, *occupation*, *family members, home address*), where *family members* = (ID: *relation* ∈ {*father*, *mother*, *son*, *daughter*}). The relations of family members can derive more family relations such as *spouse*, *sister* and *brother* relation.
2. Medical data d_2 records information about patients, including diagnosis and current status, d_2: (ID, *diagnose time*, *diagnose result*, *state*), where *diagnose result* is the name of illness, and *state* can be *healthy*, *suspect*, *infected*, *recovered* and *dead*.

3. Public transportation data d_3 records information of travellers, d_3: (ID, *destination, from, type of transportation, start time, arrival time*).
4. Risk levels of occupation are known. Some occupations such as doctors and inspectors of airport have a higher risk of being infected because they need to frequently interact with people.
5. Risk levels of social relations (semantic links between people) are known. Different social relations have different risks of being infected. For COVID-19, a node is easier to be infected through family relation.
6. Data about people in other public close space can be collected by their mobile phones or processed in the same way as the transportation vehicle.

The following is *a solution to identifying possible neighbours* (considering physical space) of an infected person X on a pandemic network.

1. Find real-time physical neighbours of X during the latent period by calculating the distance between people (through location sensors like mobile phones). If the distance between a node n and X is less than a safe distance (2 meters recommended by WHO), n is regarded as a neighbour of X and identified as 'contacted'. It is reasonable because of the wide coverage of smart mobile phones in whole population (94% in Korea and 68% in China according to the survey of PewResearch Center in 2018).
2. Find all neighbours of X during the latent period by searching d_1 to identify the most important relations. The COVID-19 pandemic shows that persons with family relations have a higher probability of being infected than other relations because public spaces such as libraries, cinemas, theatres, restaurants, companies and schools were closed and key workers were protected by safe distance during pandemic (a survey shows that the most infected cases of medical workers in Wuhan city were at home and the infect case of those volunteers from other cities is zero because of good protection).
3. Find all neighbours of X during the latent period by searching d_3 to identify all persons who are in the same enclosed space such as train and bus.

10.4.2 *General Solution*

A typical pandemic network takes the form of a dynamic forest where nodes change states. Different viruses spread in different ways. COVID-19 spreads mainly through touch, droplets and aerosol (through cough in closed space).

A general solution to identifying the next infected node consists of the following steps:

1. Input: (1) an open set of initial infected nodes $I=\{(n_1, t_1), \ldots, (n_p, t_p)\}$, where n_k and t_k ($k \in \{1, \ldots, p\}$) represent the identity of the node and a probability of being infected respectively; (2) an open set of data D that records the features of nodes in a society (e.g. people in one city) and (3) degeneration rate (the infect ability of the virus decreases through an infect chain), which can be neglected if it is unknown like COVID-19.

2. Search D to identify the nodes (neighbours) that connect to each infected node through existing semantic links and the semantic links derived from reasoning on semantic links according to semantic linking rules (this provides a predictive ability for a pandemic network).
3. Calculate the infect probability $\chi(n_k)$ of each neighbour node of the current infected nodes n_1, …, and n_p, which is a function of the following factors as depicted in Figure 10.3:
   (1) *Certainty degree of diagnosis of each infected node*.
   (2) *Risk level of neighbour node*. Obtaining the risk level of the occupation of the node).
   (3) *Risk level of semantic links*. Obtaining the risk level of the semantic link (e.g. family relation is a high risk relation for COVID-19).
   (4) *State*. A node of suspect state has a certain probability of being transformed into the infected state. For COVID-19, a node with constant cough and fever has 43.8%-87.9% probability of being infected at different stages. A node of infected state has a certain probability of being transformed into the death state (i.e. death rate, for COVID-19, it is about 4% in Wuhan) and recover state (i.e. *recover rate* = *recover number* / *infect number*). A recovered node is immunized with a high probability.
   (5) *Physical distance*. The closer between two nodes in the same space, the higher the probability of being infected. As depicted in Figure 10.3, the probability of A being infected is greater than the probability of D being infected if $d(X, C) + d(C, D) > d(X, A)$.
   (6) *Time of interaction.* More time two nodes keep a close distance in the same space, the higher the probability of being infected one another (especially for COVID-19).
   (7) *Generation of infection. Infection ability of some virus decreases* along the infection chain until the virus establish symbiotic relations with the new host. COVID-19 pandemic shows the following rules on infected rates (the average number of persons that one infected person can infect) and death rates (i.e. *the death number* / *infected number*) of different regions: cities within China < Hubei province < Wuhan city. (Variation of COVID-19 took place in EU and American).
   (8) *Friend-of-friend propagation.* If two nodes share some common nodes (friends), one has a certain probability to infect the other in the future. The more common friends, the higher the probability (this is an instance of the social linking rules introduced in Chapter 3).
4. Identify each infected node's neighbour nodes with top k high infect probabilities as suspected nodes with the suspected time. Obtain the features of the suspected nodes.
5. Identify the suspected nodes as healthy nodes when they have shown no symptom within the latent period from the suspected time, otherwise identify the suspected nodes as infected nodes with a probability according to medical diagnosis methods. Obtain the features of the infected nodes.

6. Update the infected node set *I*, the recovered node set (with the immunized state and probability), and the dead node set.
7. Remove the dead nodes and its semantic links from the pandemic network.
8. Append new data to *D* and append newly found missed infected nodes to *I*.
9. Repeat from step 2 until all existing infected nodes have no neighbours in *D* when *D* keeps collecting new nodes and *I* keeps being updated with newly found missed infected nodes for a period of time (>2**latent period* according to epidemiology).
10. End with output *I*.

The above process considers the probability of infection, friend of friend relation and latent period. Figure 10.3 is a scenario of emerging infection on an evolving semantic link network:

1. Node *X* is identified as the contacted node if the distance between *X* and the infected node is shorter than a safe distance (2 m for COVID-19). Node *X* will be probably the next infected node if the distance between *X* and the infected node is longer than the safe distance and the semantic link between *X* and the infected node indicates a close contact relation (shorter than the safe distance) will be probably hold.
2. Node *A* and node *C* are potentially future contacted nodes before *X* is infected. The probability will be increased when *X* is infected.

Prediction of the potentially next infection node provides the basis for precise detection and isolation so that people can keep a safe distance while maximizing freedom. It can avoid enclosing infected people and healthy people in the same space, which increases the probability of cross-infection and mental problems.

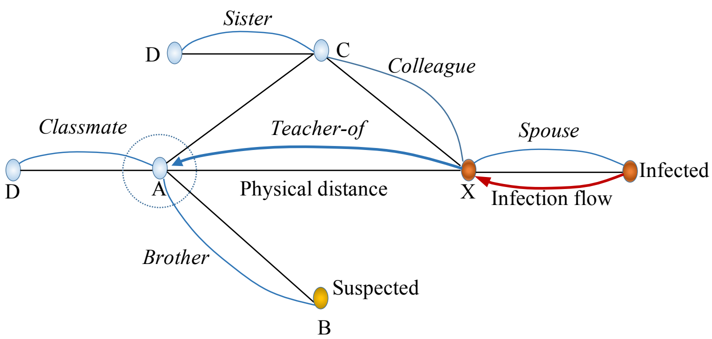


Fig. 10.3. Predicting the next infected nodes and risk nodes on a semantic link network of people.

10.4.3 *Infect Patterns*

It is important to identify the higher risk nodes that can be easily infected (according to the number of links coming from the infected nodes) and can infect more nodes (according to the number of outgoing links).

Figure 10.4 shows some infection patterns on pandemic network, where red, yellow, white and green colour indicate the infected, contacted, immunized and healthy nodes, and a link represents the integration of all possible types of social relations between two nodes. The doted circles enclose critical nodes, which have a higher probability of being infected and a higher probability of infecting other nodes. *Protecting the risk nodes can more efficiently prevent more nodes from being infected*.

The function for identifying the risk nodes depends on the following factors:

1. *The number of links of the current node*, the greater the higher risk. The following are two types of such nodes. Protecting them from being infected and reducing their links by limiting their social behaviours is an efficient way to control pandemic.
   a. *A node with many links* (called broadcaster), which has a higher probability of being infected and infecting many nodes. People of such occupations as teacher, doctor and aircrew belong to this type of node. The red node in Figure 10.5 (d) and (e) present an example of the broadcaster.
   b. *A node that connects multiple communities* (called social star). It can spread virus in multiple communities as shown in (a) and (b) of Figure 10.5. People of such occupations as various leaders, social worker and frequent travellers belong to this type of node.
2. *The physical distance to the infected node*. The closer the higher the risk. Nodes in the same social space such as transportation vehicle, restaurant, shop, school and theatre indicate a short social distance.
3. *The state of the node*. A node transforms its state with a certain probability when it is contacted by an infected node. An immunized node neither transforms state nor transmits virus while a healthy node can transform a healthy state into an infected state with a certain probability.
4. *The number of links to the immunized node*, the greater the lower the risk. A node with five links will be protected from being infected if the five linked nodes are immunized. A society will be herd immunized if a certain percentage (varies with disease, flu is about 33-44% and polio is about 80-86%) of its population are immunized. Immunizing broadcasters and social stars contributes more to immunizing a society than other nodes.

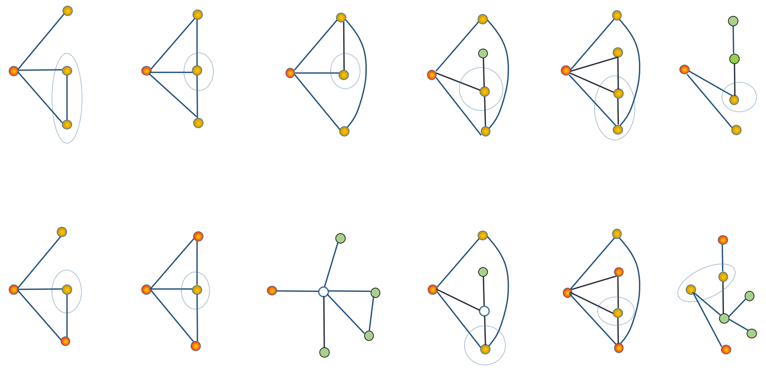


Fig. 10.4 Emerging infect patterns on a pandemic network.

Identifying the key link of infection is also a way to control the spread of virus. The link in red colour in (c) of Figure 10.5 bridges two communities. The link in red colour in (e) of Figure 10.5 bridges a community and a star node. It can be regarded as a special case of (a) when one of the two ends of the bridge link is regarded as a *social star*. Cutting the link can prevent spreading virus from one community to the other. For example, cutting the friend link can prevent nodes from meeting friends who may further infect families.

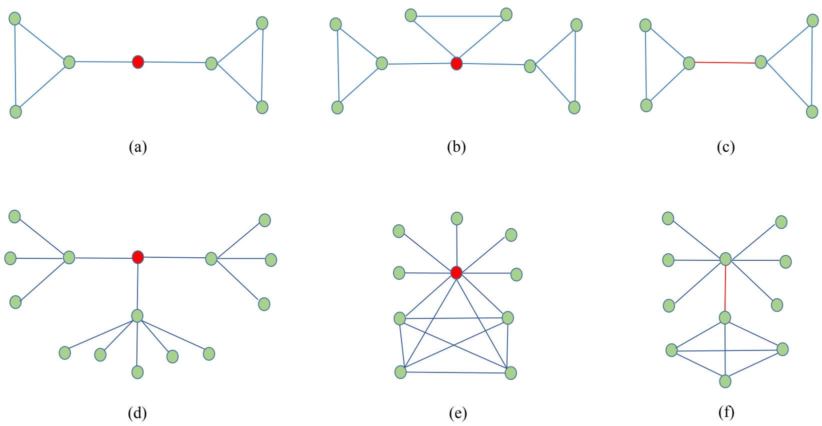


Fig. 10.5 Some important types of nodes and links on a pandemic network.

The worldwide experience of COVID-19 pandemic has built public a social distancing consciousness, which transforms traditional culture like handshake. Social distance was commonly regarded as a distance in physical space.

The following gives a definition for measuring social distance in a multi-dimensional space where Δt is the duration for keeping the distances.

Definition 10.4.1. *Social distance* is a distance in a multi-dimensional space that influences the state of individuals x and x' (nodes on pandemic network) with a certain probability, the shorter and longer time the higher probability: $distance_{social}(x, x', \Delta t)^2 = \sum_{s \in S} distance_s(x, x', \Delta t)^2$, where S is a set of dimensions including *physical dimension*, *semantic dimension*, *protection dimension* and *behaviour dimension* such that:

1. $distance_{physical}(x, x', \Delta t)$ maps the distance between x and x' in the physical space into a risk range [0, 1] when the *distance* < 2 *m* has been kept for a period of time Δt and a safe range [1, 2] when the *distance* ≥ 2 *m*.
2. $distance_{semantic}(x, x', \Delta t)$ maps semantic link/path between x and x' in semantic space into a risk range [0, 1) and a safe range [1, 2]. An order can be given on the set of semantic links according to the probability of keeping close contact, e.g., *family relation* < *friend relation* < *classmate relation* < *colleague relation*. A semantic link gets a value within the range according to the order.
3. $distance_{protection}(x, x', \Delta t)$ maps protection measures between x and x' into a risk range [0, 1) and a safe range [1, 2], the higher protection level the shorter. Protection measures are ordered according to the functions of protection measures, e.g., *wearing mask* < *washing hands* < *self-isolation* < *wearing protection suit*. A protection measure gets a value within the range according to the order.
4. $distance_{behaviour}(x, x', \Delta t)$ maps the behaviours of x and x' into a risk range [0, 1) and a safe range [1, 2]. Behaviours can be ordered according to the risk of being infected, e.g., *dinning with friends/family members* < *face-to-face talk* < *shaking hands* belong to the risk range. A behaviour gets its value within the range according to the order.

10.4.4 *Open Evolving Diagnosis*

Accurately diagnosing infected patients is an important medical step for detecting the next infected node. It is also the basis for timely treating infected patients. However, it is a challenge to accurately diagnose a new disease caused by a previously unknown virus especially at the early stage of a pandemic because time is needed to understand the disease. During the COVID-19 pandemic, the National Health Commission of China issued seven versions of Diagnosis Solution from 16/01/2020 to 04/03/2020, reflecting the development of recognition on the disease.

During COVID-19, clinical observation (including symptoms such as fever, cough, fatigue and difficulty of breath), CT and RT-PCR test were adopted as the main diagnosis method. Clinical observation is an easy approach to screening large-scale population. But on admission, only 43.8% of infected persons have fever, 67.8% infected persons have cough, and 56.4% have common radiologic phenomenon (ground-glass opacity) on CT but those without radiographic or CT abnormality is about 17.9%, and 83.2% have lymphocytopenia (Guan et al. 2020). With the disease develops, about 88.7% of infected persons have fever.

Moreover, some infected persons have no symptom at the early stage, and there exist contradict cases between different methods (e.g. CT and RT-PCR test). Clinical observation cannot provide Etiological evidence like RT-PCR test but the accuracy of RT-PCR test is less than 50% at the initial stage of the pandemic COVID-19.

Combination of different diagnosis methods of low accuracy will lead to a lower accuracy. Many infected persons missed the chance of being early isolated and treated. This is one of the causes that leads to a high infection rate and a higher death rate in Wuhan city.

At the middle stage of COVID-19 pandemic in China, a method of combining epidemiological evidence (travelled to Wuhan or contacted people with clinical appearance from Wuhan within 14 days), clinical observation (including CT), and RT-PCR test was recommended by the 6^{th} version of the Diagnosis Solution for COVID-19 issued by the National Health Commission of China.

Combination of different methods of different accuracies can raise the accuracy of identifying a particular infected person, but it will miss many patients who only show symptom with one method or miss the right time of diagnosis because of waiting test (a RT-PCR test needs 3-8 hours at the initial stage of the pandemic in Wuhan) when screening a large-scale population.

People understand a new disease through research and practice along the development of pandemic. Infected persons develop disease with different symptoms, which can be classified into different stages. It is necessary to adopt an open evolving diagnosis paradigm as depicted in Figure 10.6.

The paradigm suggests that using different test methods sequentially at different stages rather than using different test methods in parallel at one stage because of the following judgments:

1. *There is only one best testing method at one stage of the development of disease*.
2. *Using different testing methods at one stage cannot increase the accuracy of existing testing methods. Integrating methods of different accuracies decreases the general accuracy*.
3. *Using multiple testing methods at one stage wastes medical resources and increase the probability of cross-infection in hospitals when people wait for testing*.

Further, the paradigm suggests that one best method should be adopted for each development stage of disease. With the development of research and practice, the existing methods can be improved through accumulating experience, and a more appropriate method can be developed through research and used to complement or replace the existing methods.

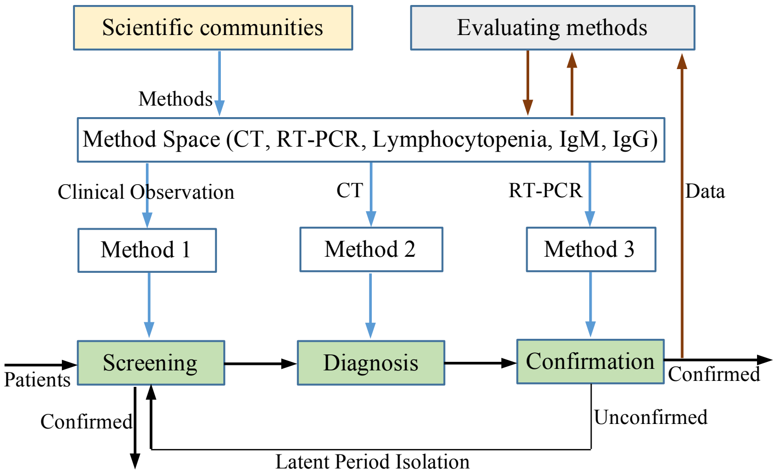


Fig.10.6 The paradigm for open temporal diagnosis.

Methods are evaluated according to the data obtained through practice to provide evidence for adopting methods. The diagnosis process forms a loop with unconfirmed patients going through screening and diagnosis after a period of time (e.g. a latent period), during which reality may change: the disease may develop symptoms, devices may change, the operation processes of testing may change, doctors with different experiences have time to take turn to participate in diagnosis, and knowledge on the disease develops.

The accuracy of a test method depends on the following factors:

1. *The nature of the disease*. Different diseases need different testing methods. It is important to select an appropriate method to test a new disease.
2. *Characteristics of device*. Different devices are created according to different principles (e.g. physical or biological principles) reflect different dimensions of the nature of the disease. One dimension cannot be interpreted from another dimension.
3. *Quality of device*.
4. *Evolving symptom*. Different stages of disease can have different symptoms.
5. *Operation process*. The RT-PCR test shows different results on sputum (best), nose (medium) and throat, therefore test on sputum is recommended.
6. *Skill of interpreting the result*, especially for CT.

Repeating the check-up process after a latent period is an approach to overcoming the shortcomings of a method so that more infected patients can be identified more accurately because some infected patients (including those without symptom) will be recovered without any treatment or showing symptom. A patient can be confirmed healthy with a higher probability when no symptom appears through the second-round of checking up. At this stage, immunoglobulin test (including IgM and IgG) can play an important role because immune system needs about two weeks to generate enough antibody that can be tested.

The method space constantly selects new methods (including new test devices and epidemiological methods) through evaluation. After evaluation, a better method can be adopted to replace an existing method for clinical practice.

Epidemiological method should be incorporated into diagnosis method as infected people with no symptom (during or after latent period) may have infect ability. That is, existing devices may not be suitable for diagnosing those people, who actually can propagate virus (COVID-19).

A survey from China shows that the probability of being infected through closely contacting infected people with symptom is 6.15%, and the probability of being infected through closely contacting infected people with no symptom is 4.11%, showing no big difference between the two groups of people (Chen et al. 2020). Survey results may vary with the scale of sample and the method for diagnosis but calculating the social distance between people is a way to identify the next infect person.

Different social relations propagate virus with different probabilities and long-term relations propagate virus with a higher probability, for example family relation (transmission probability is about 17.54%, and family members that live together is about 18.07%) and friend relation (transmission probability is about 15.69%). Temporal relation is mainly formed through sharing space (transmission probability: roommate is about 13.26%; using the same vehicle is about 11.91%; meeting/dinning/playing card is about 7.18%; cross-infection in hospital is about 1.94%; and supermarket is about 0.56%). The infect probabilities vary with countries due to such factors as policy and culture but it is reasonable to assume that people interact more frequently through long-term relation for infectious disease like COVID-19 have higher infect probability.

10.5 Reality, Information, Interest, Knowledge and Computing

10.5.1 *Implicit Link between Reality, Information and Community Interest*

A pandemic propagates in the natural physical space while people living in various communities in social space create and share information on pandemic in cyberspace. These spaces reflect pandemic with different principles.

Google Flu Trends is an effort to identify the link between reality and information. It used the words of searching flu to predict the propagation of flu. It was launched on 2008 but closed on 2014 (www.google.org/flutrends/about/).

With the development and widely use of mobile devices (mobile phone users has exceeded 82% population in China), more and more people use social media like Wechat through mobile phones, generating interactive information and reflecting characteristics of individuals and communities like those on Wechat. Popularity and persistency of a topic on social media reflect the severity and duration of a pandemic to a certain extent.

To unveil the link between reality and information, an experiment is carried out on Moments (communities of friends) and Official Accounts (public media) of Wechat (the most popular Chinese social media) during pandemic. The experiment collects information during pandemic from 17 communities of friends and 12 public media (Chinese Government, China News, Sina, People's Daily Online, ScienceNet, Xinhuanet, Xinhua News Agency, Guangming Online, Netease, ThePaper, Wuhan News and Hubei Daily) and then calculates the proportion of information on pandemic to the total information through pandemic. The curve in gray colour in Figure 10.7 represents the change of the proportion on Official Accounts, and the curve in orange colour represents the change of proportion on Moments. The curve in blue colour represents the infected cases published by Wuhan authority. It rises suddenly on 12/02/2020 due to the change of diagnosis criteria (taking clinical observation and epidemiology into account so that more suspected individuals can be monitored).

These curves indicate the following points:

1. Both the curve of Moments and the curve of Official Accounts increase rapidly when human-to-human infection was officially announced on 20/01/2020. This indicates that public (both ordinary communities and official organizations) are sensitive to infectious disease. *If real information is available on time, a community has innate ability to respond to possible damage.* So a strategy for managing pandemic is timely providing real information and relevant knowledge for people and giving them the right to decide social behaviours.
2. Official Accounts keep more sustained attention on pandemic than moments. Moments can keep about 50%, 60% and 70% of attention (on pandemic) for two weeks (22/01/2020-07/02/2020), two days and one day respectively. The pulse on 04/04/2020 should be related to the official announcement of lifting lockdown on 07/04/2020. This indicates that *the attention of ordinary communities is more easily fatigue*. Therefore, a strategy should be emphasized regularly otherwise it will fatigue people and people will turn to receive other interested information.
3. Both the curve of Official Account and the curve of Moments decline with the decline of the infected cases. The curve of Official Account declines slowly when the infect cases decline. It declines quickly after lifting lockdown of Wuhan city, but it still keeps the level of 0.4 (40%).
4. The curve of Moments decreases earlier and quicker than other two curves. It does not increase anymore when it reaches about 72%. This indicates that *communities have diverse interests and share more diverse information*.

5. The attention of communities can be an indicator for early predicting pandemic at initial state when no infect case appears as the turning point of pandemic appeared two weeks (just the same as the latent period) after the turning point of attention. This is rational because (1) information about disease is likely to be propagated within communities during the latent period of patients who may still stay at home before seeing doctor, and some of them can self-recover and (2) some patients were regarded as flu even when they see doctor. That is, *when the first patient is found, the pandemic may have already propagated for two weeks or even longer*. *Therefore, detecting information in communities can help the public health department of a country to make early preparation for a possible pandemic*.

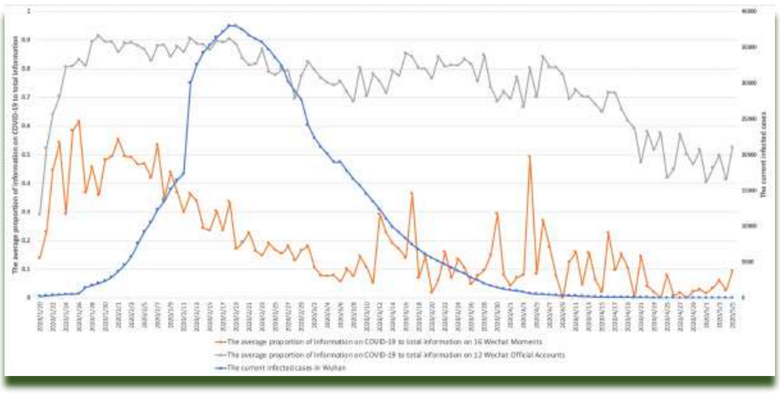


Fig. 10.7 Development of COVID-19 pandemic with the change of average proportion of information on the pandemic to total information on Moments and on Official Accounts of Wechat.

Due to the diversity of culture and interests, *people in different communities behave differently to respond the change of reality with different influences on the change*.

COVID-19 pandemic shows that different nationalities have prominent differences in government strategy, community behaviours and mortality.

The above discussion provides reasons for the following rules. Rule (1) is for suggesting warning of possible pandemic and guide including washing hands and social distancing. Rule (2) is for suggesting lockdown in the case that attention degree is greater than 30% and inter-community propagation of this information appears (assuming that behaviour of propagating information in different communities take place when people face serious situation). Rule (3) is for predicting the termination of a pandemic when the attention degree of Official Account is less than 70% and the average attention degrees of communities (Moments of Wechat) is less than 10% for a period of time (e.g. the latent period of the disease), where $O(k)$, $C(k) \in [0, 1]$ denote the attention degree of Official Account and moment (Community) respectively, and ICP (Inter-Community Propagation) =1 means that there exists inter-community propagation of disease information.

$$If \sum_{k\in[1,m]} \frac{C(k)}{m} > 0.3 \ then \ suggest\ warning\ and\ guide \tag{10.1}$$

$$If \sum_{k\in[1,m]} \frac{C(k)}{m} > 0.3 \ and\ ICP = 1 \ then \ suggest\ lockdown \tag{10.2}$$

$$If \sum_{k\in[1,m]} \frac{C(k)}{m} < 0.1 \ and\ \frac{O(k)}{m} < 0.7 \ then\ suggest\ lift\ lockdown \tag{10.3}$$

10.5.2 *Forming Knowledge Flow for Developing and Falsifying Knowledge*

A prominent change of reality especially a new pandemic provides new problems for scientific research. Facing challenges to life, it is necessary to publish research results rapidly so that governments, health workers, researchers and ordinary people can benefit from them. However, scientific research has a certain limitation due to such factors as time, effectiveness of sharing knowledge and the extent of understanding reality. Citation is a link that indicates a knowledge flow between authors, which develops and falsifies knowledge. A systematic knowledge is formed with the formation of knowledge flow network formed through completion, development, verification and application. This section is an application of the knowledge flow network introduced in chapter 5.

Publications on COVID-19 increased rapidly after it became a pandemic. Many works were done and published within a short time, reflecting the involvement of more researchers and their understandings of reality at a particular time. Some results were quickly falsified with the rapid development of pandemic and understanding as discussed in Appendix A.

A valuable knowledge can be constantly applied, compared, surveyed or introduced even though it completely solves a problem (e.g. a vaccine terminates a pandemic). A negative citation could stop a paper from being further cited. *Criticism is a kind of antibody of scientific community, which ensures healthy development of knowledge*.

Previous work for evaluating a scientific work are based on explicit citation. Although the value of a scientific work in an academic community is determined by many factors, the essential factors are on its influence on other works and the works that influence it:

1. *Essential authority*, which is based on the authority of the works it essentially cites and the authority of the works that essentially cite it. Explicit citation has been used for ranking papers but implicit citation is neglected. Implicit citation exists especially in non-scientific articles. Constant publications evolve a network of knowledge flowing through explicit citation and implicit citation.
2. *Diversity*, which is based on the types of the works that cite it and it cites, the more the higher. A higher diversity indicates that it influences more research directions.
3. *Lasting*, which is based on the duration that it has been cited, reflecting its historical value on influencing the development of knowledge.
4. *Depth*, it has a long chain of being cited, indicating the depth of the knowledge being developed. The formation of a citation chain on a research direction indicates the formation of a knowledge flow (Zhuge 2006). Due to the limitation of time and resources, systematic knowledge is developed through a process of understanding and defining problem, creating method (or model) with assumption as well as proving, verifying and applying method, which is hard to be accomplished within one paper.
5. *Originality,* which can be reflected by the authority and diversity of the works it essentially cites and the lasting and depth that the work has been cited explicitly and implicitly.

Automatic discovery of essential influence through citation concerns the analysis of links between the core components on problem, assumption, method, verification and application of papers. For two papers *A* and *B*, if there is a probabilistic semantic link between the core representations (or core concepts) of the two papers and *A* was published before the submission of *B*, an implicit citation link can be established from *B* to *A* with a probability. A similar-to link can represent this relation (Zhuge 2012), the probability of the implicit citation is determined by the similarity degree between the core representations (components) of two papers. The degree of similarity can be regarded as a degree of contribution of *A* to forming *B*. The higher the degree of similarity the higher the contribution, even in the case of plagiarism. Implicit citation happens due to intentionally omission (e.g. page limit, hiding related work and citing the latest work only) or unintentional omission (limited time for literature review). Other semantic links (e.g. *B extends A*, *B improves A*, *B applies A*, and *B* verifies *A*) is also based on similarity between their core representations. *Recovering the implicit citation is significant for scientific evaluation*.

Formally, an implicit citation from paper *B* to paper *A* with probability p can be represented as $com(B) \text{ —}\alpha\rightarrow com(A)$ with $p > \eta \Rightarrow B \text{ —}\alpha\rightarrow A$ with p, where $\alpha \in$ *Semantic Links*, $com(x)$ *is a function for getting a representation (component) of a paper* $x \in \{A, B\}$, and p is the similarity between $com(A)$ and $com(B)$, which can be measured by $com(A) \cap com(B)$ / ($com(A) \cup com(B)$) if $com(A)$ and $com(B)$ are sets of words or phrases for representing the components; and η *is a predetermined number within* (0, 1), e.g. 0.3 (i.e., 30% similarity). A rough way to implement the function *com* is ranking sentences according to a certain importance measure and then selecting top-k sentences.

There can be multiple semantic links between papers. The essential authority of a paper x can be calculated as follows where $\lambda \in [0, 1]$, $\mu \in [0, 1]$ and $\lambda + \mu = 1$.

$authority(x) = \lambda \sum_y authority(y) + \mu \sum_z authority(z)$ for any paper y that x essentially cites and any paper z that essentially cites x.

The above points do not specifically consider the number of co-authors, which is a factor of increasing citation number because co-authors can further cite this work in their future work. As co-authors have a higher probability to continue developing the knowledge so the knowledge of the paper could be propagated through more branches. But this case can be reflected by citations from the following papers.

Considering the above aspects, the value of a paper can be measured as follows, where w_1, w_2, w_3, w_4, w_5, $authority(A)$, $diversity(A)$, $lasting(A)$, $depth(A) \in [0, 1]$, and $w_1+w_2+w_3+w_4+w_5=1$.

$value\ (A) = w_1 \cdot authority(A) + w_2 \cdot diversity(A) + w_3 \cdot lasting(A) + w_4 \cdot depth(A) + w_5 \cdot originality(\mathrm{A})$.

Knowledge flows through explicit citation link and implicit citation link. The following is an example of knowledge flow path, covering concept, model, theory and applications of a systematic knowledge. The parts in boldface are monographs, which summarize and develop previous research on the research direction.

(Zhuge 1998) → (Zhuge 2003) → (**Zhuge 2004**) → (Zhuge 2006) → (Zhuge 2007) → (Zhuge and Li 2007) → (Zhuge 2009) → (Zhuge 2010) → (Zhuge 2011) → (**Zhuge 2012**) → (Zhuge 2016) → (**Zhuge 2020**).

The formation of knowledge flow through citation is a way to develop and falsify knowledge. Mature theories such as Newtonian mechanics, Einstein's general theory of relativity and Marx's Capital initiate knowledge flow networks containing long knowledge flow paths from the source to new works, covering a long period of time. This is because scientific research carries out with knowledge, resources and time, most researchers only refer relevant research within recent ten years and their understandings of theories rely on reading recent works rather than reading the original works even though they cite them or use them without explicit citation. Survey, review and book play an important role in inheriting and developing knowledge.

Seven versions of Diagnosis and Treatment for COVID-19 were published by the National Health Committee of China through studying over 150 different clinical treatment methods during COVID-19 and adopting research results at different stages of the development of the pandemic. Different versions have high similarity, therefore there exist implicit citation link from one version to the previous version, where the implicit citation chain shows the development of knowledge flow on diagnosis of COVID-19 in China.

10.5.3 *Implicit Link between Reality*, *Strategy*, *Knowledge and Information*

A complex link exists between reality (e.g. pandemic), behaviour, strategy, information and science as depicted in Figure 10.8. Pandemic like COVID-19 is closely related to various human behaviours, influenced by information, knowledge and strategies made by authority including government and public health organizations (e.g. CDC).

Availability of real information is the basis for a community to take protective actions to respond damage. However, people have different abilities in finding real information and have different alertness of protection. Information on pandemic and society influences behaviour and strategy.

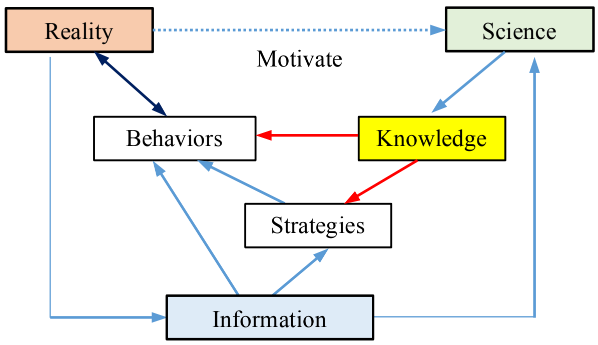


Fig. 10.8 Implicit link between behaviour, strategy, information, knowledge and science on pandemic.

Strategy can regulate social behaviours but a strategy could have different effects on different societies and influence different dimensions (e.g. on education and economy) of a society. A strategy should also consider such information as culture that influences behaviours, for example, people meet in church on Sunday in western countries. So a strategy will influence multiple dimensions of a society.

Scientific research discovers knowledge based on existing knowledge and information on pandemic with some conditions. Knowledge on a new disease provides evidence for authorities to make strategies and policies to influence behaviours including professional behaviours such as medical treatment and public behaviours, which in turn influence pandemic through improving diagnosis method and treatment method and reducing infection rate through adopting protection strategies (e.g. work and study from home and determining social distance). Without strategies based on scientific knowledge, behaviours will be self-organized and may face herd immune.

Facing a pandemic caused by a new virus, research has to carry out after the outbreak of pandemic. Without interference, about 86% population would be infected with a high infection rate. Scientific research races with the development of pandemic, the earlier the knowledge on pandemic is discovered, the earlier the appropriate medical methods can be adopted, and appropriate public strategies and policies can be made to curb pandemic. Different from general scientific research, the research on pandemic is time critical. *The influence of research on pandemic depends on the time of discovering knowledge and the problem that the knowledge can solve*. For example, discovery of infection path can help make the guidance of protection, and the adoption of treatment method can help increase the recovery rate, the invention of new medicine can cure disease earlier, and the development of vaccine can prevent healthy people from being infected.

Appropriate medical behaviours based on scientific knowledge at different times of pandemic play different roles in curbing pandemic. Early diagnosis can prevent healthy people from being infected.

Pandemic is reflected by populations of different groups of people with different states, e.g., $pandemic(t) = (infected(t), death(t), recovered(t))$, where t denotes the time of observation.

Pandemic can be regarded as a function of various behaviours and authorized strategies influenced by information, knowledge and time as follows.

$$pandemic(t+1) = \varphi(pandemic(t), behaviour(t)).$$
$$behaviour(t) = m(strategy(t), knowledge(t), information(t)).$$
$$strategy(t) = research(knowledge(t), information(t)).$$
$$knowledge(t) = research(knowledge(t-1), information(t)).$$

The next state of pandemic $pandemic(t+1)$ depends on the current pandemic represented as $pandemic(t)$ and current social behaviours represented as $behaviour(t)$, which depends on current strategy, information and knowledge ($t \geq 1$). When t=1, $information(1)$ represents the first case of human-to-human infection was found, $knowledge(0)$ represents no knowledge about the disease but knowledge about previous diseases are available, and $strategy(1)$ can be made according to information(1) and knowledge(0). The strategy needs to be adapted when knowledge about the disease is available. Function φ transforms the current pandemic into the next state with the change of the populations according to behaviour, and function m increases or reduces the number of populations with the change of strategy made according to current knowledge and information.

The following is a way to quantify the pandemic, where m maps a set of strategies into [0, 5], which reduces pandemic with a value within [0, 1] and increases pandemic with a value within [1, 5]:

$$pandemic(t+1) = pandemic(t) \times m(strategy(t), knowledge(t), information(t)).$$

For a new pandemic, no strategy is adopted at the beginning when there is no serious damage, therefore the pandemic will follow the SIR model. With the development of pandemic and understanding of reality, different strategies will be adopted to influence the pandemic.

Some strategies restrict social behaviours of different levels for restricting infection to different extents. For infectious disease like COVID-19, the following levels can be set within the region of pandemic:

1. Strategy Level 6 (the weakest strategy): Suggest individual self-protection behaviours (like washing hands) that do not greatly influence social behaviours.
2. Strategy Level 5: Announce travel warning and cancel large-scale public gathering events, including conference, meeting and exhibition.
3. Strategy Level 4: Close schools and universities, and reduce public transportations.
4. Strategy Level 3: Close public transportation.
5. Strategy Level 2: Close public spaces including pubs, restaurants and shops. People are requested to be self-isolation at home. Daily life is supported by online booking.
6. Strategy Level 1 (the strongest strategy): Cut off all physical interactions between people, e.g. isolating everyone in a separate room. It is the strongest strategy, which can help stop pandemic quickly but it will heavily influence society, including economy and social structures.

10.5.4 *Computing on Various Types of Information*

As a social being, people communicate in a cyberspace holding various information while interacting with each other (directly or through material flow) and with physical objects in physical space following social rules and physical laws. Various information can be classified into the following categories:

1. *Real information*. It reflects a fact that can be repeatedly verified by practice or derived from existing facts or knowledge. Knowing real information about pandemic enables people to make natural and timely reactions to reality, which can protect themselves through such ways as wearing mask, keeping social distance and reducing interactions between people during pandemic. However, sometimes it is difficult to know real information due to social factors, difference of measures and lack of knowledge about reality, especially for exploring the unknown parts of the world. For example, outbreak of a new pandemic is usually unknown at the beginning because of the latency period of disease and similar symptoms between diseases. Sometimes, real information is often neglected at the beginning of a pandemic. Social, economic and political factors can also distort real information.
2. *First-hand information*. It is usually unauthorized and may be inexact and superficial but it reflects reality to a certain extent or from a certain dimension. It mainly propagates in a peer-to-peer way within a small community first. Sometimes, it is regarded as a rumor. At the initial stage of the outbreak of

COVID-19 in Wuhan (about 01/01/2020), eight doctors found SARS-like disease when they check-up patients, unfortunately, this first-hand information was treated as a rumor. It was a critical time to control the pandemic in Wuhan.

3. *Incomplete information*. It reflects reality partially but often gives people an illusion of reality. During COVID-19 in Wuhan, people are told limited human-to-human infection so that they still participate in public gathering as usual, taking the risk of being infected. But incomplete information has a certain value.
4. *Statistic information*. It is about a method and data generated by using the method for processing data. For the same reality and aim, different statistic methods can generate different information, and methods are limited by inventor's cognition on reality and the results of using methods are influenced by the way of using the methods. For COVID-19 diagnosis, the infect number depends on the method of testing (the accuracy of testing is very low at the initial stage). So the infect number of different countries cannot be simply compared because they may use different methods.
5. *Fake information*. It does not reflect reality and can mislead judgment and behaviours of people. A fake information is generated with a certain motivation. It is propagated with different motivation and knowledge. It stops propagation with a high probability when passing through a node that receives a real information from other nodes.
6. *Emotion information*. It reflects different emotional states, involving pleasant, anxiety, unpleasant and boredom. Propagation of anxiety and unpleasant emotion could influence immune ability of a community so could lead to the rise of the probability of transforming contacted status into infected status. COVID-19 pandemic in Wuhan shows that the suspected persons are less than the infected persons but it becomes higher on the 22^{nd} day and the 23^{rd} day from the identification of the first patient. This concerns three factors: (1) more people with the symptom of flu went to hospital when anxiety and unpleasant information spread in society; (2) the latency of the disease is around 10 days (some infected people have no symptom) and (3) propagation of virus is prominent.
7. *Authority information*. It is issued by the authority of the superstructure of a society, including government or professional organization like CDC in some countries. Authority information is not equal to real information because the recognition of reality needs time but authority information is usually rational and influential in society. Timely announcing authority information helps people to recognize fake information and to complete and verify information. Regularly announcing authority information can also relieve public anxiety emotion. Experts' opinions can be regarded as a kind of authority information. Although different experts may have different opinions, and some experts may misunderstand reality at a particular stage of the evolution of an unknown thing like a new disease, open different opinions are helpful for public to know multiple dimensions of reality and current situation of recognition. Different development situations of COVID-19 in different countries

have shown the influence of different authority information, e.g. the opinion on herd immune and waring mask.

8. *Imagined information*. It is composed of things in mind generated from mental activities. Myth can be classified into this category.
9. *Legend information*. It is a story sometimes popularly regarded as a historical thing but may not be real.
10. *Rubbish information*. It is unhelpful, has no value and wastes time of receivers.
11. *Harmful information*. It may cause a certain harm to mental health or mislead behaviours of receivers.
12. *Mixed information*. It is usually formed by mixing two or more of the above information intentionally or unintentionally. It often leads to misunderstanding of information and requests people to extract real information from mix information. The mixture of fake information and other information enable fake information to be propagated, leading to different opinions about a thing.

As nodes in information flow networks, people receive information and knowledge, make judgment according to existing information and knowledge, and send information according to motivation and understanding of the input.

Different types of information influence behaviours of people with different knowledge, which further lead to different probabilities of being infected, therefore influence a pandemic.

An individual (a node denoted as H in Figure 10.9) in a social relational system can be modelled by the following cyber-physical-social computing model:

1. Input:
   - Information of different types (arrows in blue colour) from other related nodes.
   - Knowledge (arrows in red colour) from other related nodes.
2. Computing according to information in the personal information base and knowledge in the personal knowledge base:
   - Evaluate input information and knowledge.
   - Select real information.
   - Complete incomplete information.
   - Reject fake information, rubbish information and harmful information.
   - Distinguish legend information and imagined information from other types of information.
   - Make a necessary summarization.
   - Put real information into the personal information base and then maintain the information base.
   - Put knowledge into the personal knowledge base and then maintain the knowledge base.
3. Output:
   - Recommend information and knowledge to different nodes through social relations according to a certain motivation. Different information

and knowledge will be sent through different social relations (e.g. send appropriate information and knowledge to children).

4. Action: Different actions are taken with a certain probability under different situations determined according to social motivation and input information and knowledge as well as existing information and knowledge:
   - *Situation* (*input*, *information, knowledge*, *motivation*):
     {($Action_1$, $probability_1$); …; ($Action_n$, $probability_n$)};
   - …...
   - *Situation* (*input*, *information, knowledge*, *motivation*):
     {($Action_{k1}$, $probability_{k1}$); …; ($Action_{kn}$, $probability_{kn}$)}.

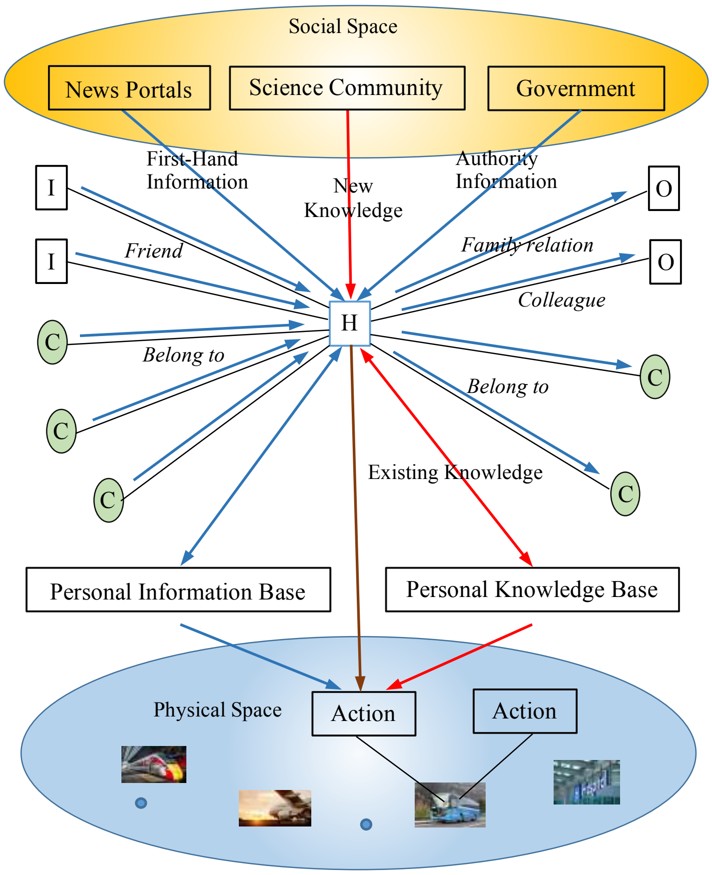


Fig. 10.9. Cyber-Physical-Social Computing Model.

Action concerns personal behaviour modelling. The application of pandemic management more concerns the spaces where a node has different probabilities to be infected, including “at home”, “work in company”, “in bus”, “in taxi”, “in train”, “in hospital”, “in train station”, “in theatre”, …, and “in market”.

When actions of two nodes lead to sharing a space such as home, bus and train, a neighbour link will be established through temporal distance detection. While scientists explore a pandemic from different levels to understand the natural symbiotic mechanism based on existing knowledge and methods, existing knowledge of similar pandemic helps people to take appropriate actions for reducing the probability of being infected, for example, the following knowledge for COVID-19, which has been tested through experiments:

1. COVID-19 has infection ability during latent period.
2. Close contact distance is within two meters.
3. Infection could pass through dense aerosol in a closed space.
4. Mask for medical operation can help prevent patients from infecting others through droplets and aerosol.

Common-sense knowledge of hygiene is suitable for a class of disease, for example: (1) place patient in a well-ventilated single room; (2) limit the number of caretakers of the patient; (3) let household members stay in a different room; (4) limit movement; (5) minimize shared space; (6) wash hands regularly and (7) wear mask.

With knowledge, individuals can actively protect themselves from being infected, for example, by reducing social interactions and keeping social distance. *A network with knowledge evolves with a different pattern from evolution of a network without knowledge*.

10.5.5 *Implicit Link between Patterns of Information Flow, Social Roles and Probability of Infection*

A social network consists of communities of different granularities, each of which has a specific function. A node can play different roles in different communities. Figure 10.10 depicts the patterns of sharing different types of information on a semantic link network. Various roles of nodes influence the health of a community differently, which therefore influences the probability of nodes being infected within the community.

Nodes within social network can be classified into the following types:

1. *Victim node*. The nodes who often receive fake information, unpleasant information and rubbish information will have depressed emotion which could influence immune system and mislead behaviours. Misleading behaviours will face a higher probability to be infected.
2. *Rubbish node*. It is a type of nodes who often generate rubbish information that wastes the time of receivers.

3. *Harmful node*. It is a type of nodes who often generate harmful information that negatively influences emotion of receiver or misleads behaviours of receiver.
4. *Authority node*. It is a type of nodes who often generate authority information that can widely influence behaviours of nodes. Leaders of government, heads of communities and experts can play this role.
5. *Responsible node*. It is a type of nodes who receive but do not propagate rubbish information and harmful information.
6. *Beneficiary node*. It is a type of nodes who often receive information from responsible nodes.

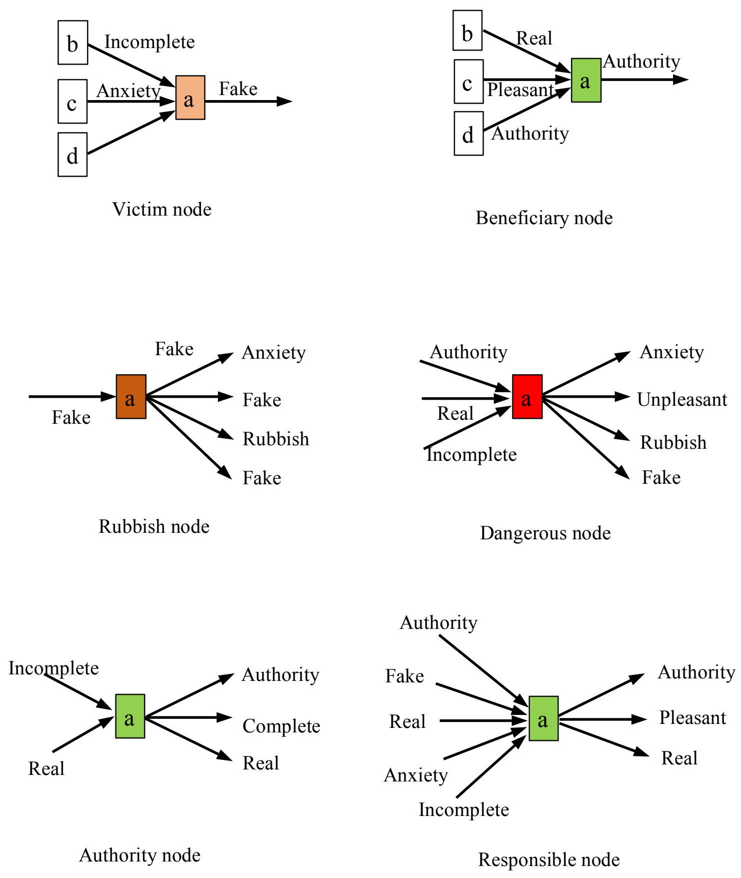


Fig. 10.10. Patterns of sharing different information and knowledge on a semantic link network.

Family is the most basic community. The nodes playing the role of father (or mother) in a family will only send real information, authority information and pleasant emotion to his (or her) child, while more types of information (including incomplete information and unpleasant information) may be shared between parents.

Links between social roles and the probability of infection can be found during COVID-19 pandemic: Children are not susceptible according to the director of CDC China (released on national press meeting on 22/01/2020). It was verified by a statistic study on 287 patients (from 9 months to 90 years old) showing that 68% of patients are 30-50 years old, and male is higher than female (Zhang et al. 2020). Another survey shows that the average age of infected patients is 47 years, and 41.9% of patients are female (Guan et al. 2020). The above phenomena have links to the following social behaviours: (1) children and old people have less active social roles to participate in social activities so they have less probability to be infected than working people and (2) male involved more social roles than female so leading to a higher probability to be infected.

Survey in the UK shows that death rate is relevant to nationality. Black ethnicity is about 1.9 times more than those of White ethnicity (https://www.ons.gov.uk). This is also relevant to social roles in the country.

The above discussion indicates an implicit semantic link between evolving things $A(x)$ and $B(y)$: $A(x)$ —i→ $B(y)$, where i is an influence such that $B(y)=i(A(x))$ for variants x and y on domains X and Y respectively, and a prominent change of $A(x)$ on X will lead to a prominent change of $B(y)$ on Y: $|A(x)-A(x')| > \lambda$ —i→ $|B(y) - B(y')| > \mu$, where λ is within $(0, max(A(x))-min(A(x)))$ and μ is within $(0, max(B(y))-min(B(y)))$. For example, a prominent change of strategy (e.g. normal to lockdown) leads to the prominent change of pandemic (e.g. infection rate from 3 to 1).

10.6 Understanding and Managing Pandemic in a Multi-Dimensional Space

Pandemic is a dimension of reality evolving in a multi-dimensional space, where one dimension can influence another dimension. For example, adopting different strategies has different influences on pandemic and economy. Establishing a multi-dimensional space of reality is an approach to recognizing and managing pandemic.

Generally, a multi-dimensional space can be represented as: $RS=(X_1, X_2, \ldots, X_n)$, where X_k ($k=1, \ldots, n$) denotes a dimension consisting of a set of classes $(C_{k1}, C_{k2}, \ldots, C_{ki})$. A dimension can also be understood as a subspace with specific rules and principles for specifying the evolving reality. The space can be further normalized for efficient operations such as locating a point or a subspace in the space according to some application constraints (Zhuge 2012, 2016; Zhuge and Xing 2012).

For pandemic applications, a space (*time, pandemic*, *science*, *strategy*, *economy*, *event*, *strategy*) can be defined to recognize the evolving reality as depicted in Figure 10.11.

1. *Time dimension*. All things in the evolving reality are uniformly mapped into a linear space that identifies their stages of evolution.
2. *Pandemic dimension*. It represents a space where people transmit virus through physical-social network and transforms their states of health. Populations of different groups of people with different states reflect a status of pandemic. A space (*pandemic*, *time*) reflects the evolution of a pandemic. The following is the evolution of the infected population during the early stage of COVID-19 pandemic: {<1, 01/12/2019>, <3,10/12/2019>, <27, 31/12/2019>, <44, 03/01/2020>, <59, 05/01/2020>, <62, 19/01/2020>, <198, 20/01/2020>, <444, 23/01/2020>, <1975, 25/01/2020>, <4515, 27/01/2020>, <1438, 02/02/2020>, <17205, 03/02/2020>, <20438, 04/02/2020>}. The pandemic dimension can be divided into three sub-dimensions: (1) *biological dimension*, symbiotic network of various species; (2) *statistic dimension*, which reflects pandemic by collecting and analysing data and (3) *model dimension*, which simulates reality through simplification and mathematic modelling like SIR model. Various models provide different approaches to comparing different pandemics and predicting the trend of pandemic.
3. *Science dimension*. It is an evolving space where scientists explore and unveil reality based on scientific paradigm. A *space* (*pandemic*, *science*, *time*) can reflect the influence of science on pandemic. For a new pandemic caused by a previously unknown virus, scientific research races with the development of the pandemic, for example, The New England Journal of Medicine published a paper on COVID-19 within 48 hours at the early stage of the pandemic. Knowledge on a new pandemic keeps being discovered through scientific research along the development of pandemic. The *science* dimension consists of sub-dimensions with specific principles and methods. For COVID-19 pandemic, the following dimension can be specified: *Science* = (*Biology*, *Medicine*, *Epidemiology*, *Pathology*):
    a. *Biology dimension, which* studies and identifies the virus through studying its physical structure, chemical process and molecular interactions, and then recognizes its characteristics, e.g. research unveiled that COVID-19 and SARS have 89.1% similarity at the early stage of pandemic, this provides an evidence for classifying the new virus into SARS category so that the experience on dealing with SARS can be used for reference. Constant investigation can check the possible variation of virus. As a sub-dimension of the biology dimension, immunology studies and develops vaccines. New discoveries increase knowledge (resources) of this dimension.
    b. *Medicine dimension,* which studies and determines the methods for diagnosis, prognosis, treatment and prevention of disease. Constantly study-

ing with the development of pandemic can adapt existing methods for treating current diseases. New methods increase resources (experience and methods) of this dimension.

c. *Pharmacy dimension,* which studies and finds (or selects) suitable medicines (including drugs and services) from the existing medicines to cure the current disease. New medicines increase medical resources of this dimension.

d. *Epidemiology dimension*, which studies the distribution, determinants and events about pandemic. Research unveils the characteristics of pandemic. For example, epidemiological information was found during COVID-19: the first case of human-to-human was found on 20/01/2020, 1.9% of infected patients contacted wild animal, 25.9% of infected patients did not travel to Wuhan or contacted people from Wuhan, and the death rate of infected patients is 1.4% in Guangzhou Province of China. New findings increase resources (facts) of this dimension, which provides an evidence for managing pandemic.

e. *Pathology dimension*, which studies the causes and effects of diseases. During COVID-19, deplaning 9 bodies shows a lot of slime in lung (done by Liang Liu's team in Tongji Hospital of Wuhan). It separates oxygen exchange in lung leading to respiratory failure. Due to pathological findings, drainage treatment was suggested in the 7^{th} version of Diagnosis and Treatment for COVID-19 released by the National Health Committee of China. With the development of research along this dimension, new findings increase the facts of this dimension, which provides an evidence for adapting treatment methods.

4. *Economic dimension*. It is an evolving space where materials or services flow through production and trade. It consists of three sectors with different percentage of total GDP in different countries: (1) Service (third) sector, which offers intangible goods and services, including retail, tourism, restaurant, banking, entertainment and hotel (it occupies different percentage of GDP in different countries, e.g. 54% of GDP in China). (2) Secondary sector, which produces goods, including various manufacturing industries (it occupies different percentage of GDP of different countries, e.g. 39% of GDP in China). (3) Primary (first) sector, which extracts raw materials from the nature, including agriculture, mining, forestry and fishing (it occupies about 7% of GDP in China). Different pandemics have different influences on these sectors. COVID-19 seriously influenced tourism, restaurant and hotel but online business and entertainment increased quickly. A serious infectious pandemic will greatly influence social activities and productions that need close contact between workers. Pandemic usually has little influence on the first sector. The healthy development of economy provides the basis for normal operations of the superstructure of a society.

5. *Event dimension*. It is an evolving space of various events that can be observed or verified by public. Events take place in cyberspace, physical space and social space, but they are usually presented in languages hold by cyberspace. Event dimension, economy dimension and time dimension can jointly

determine a sequence of events that influence economy, for example: Wuhan announced 27 infected patients on 31/12/2019, WHO announced PHEIC on 30/01/2020, and stock market of China dropped 8% on 03/02/2020. Events are generated constantly with the propagation of pandemic. The propagation of pandemic in other countries seriously influenced their stock markets: Italy's stock market dropped 4% on 24/02/2020 when Italy enclosed 11 towns. USA's stock market dropped 5 days from 24/02/2020, and then declined from 05/03/2020 to 23/03/2020 during which it experienced historically biggest drop (7.8%, 10%, 12.9%, 7%) on 09/03/2020, 12/03/2020, 16/03/2020 and 18/03/2020 respectively during exchange time.

6. *Strategy dimension*. It is an evolving empirical space of various possible strategies. Different strategies influence pandemic and economy to different extents. With the development of pandemic, strategies and effects of strategies are accumulated as experience, e.g. strategy of isolating Wuhan city and its effect provides an experience for other countries.

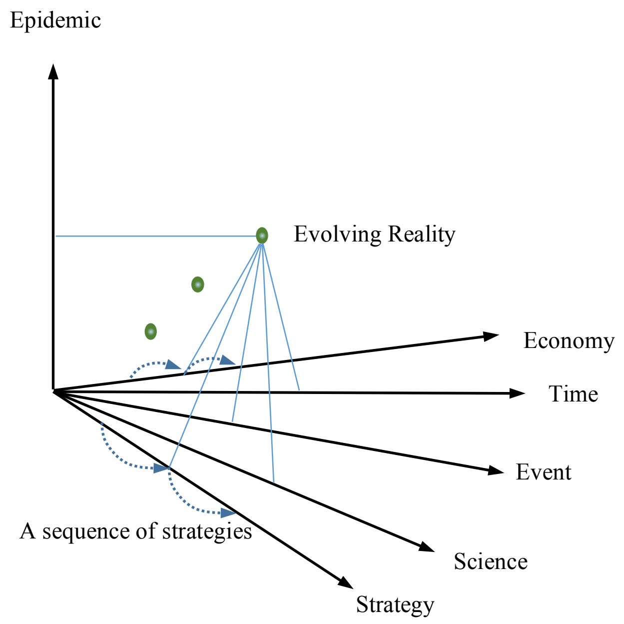


Fig. 10.11 A multi-dimensional space for recognizing evolving reality. Different dimensions have different representations and different methods. A prominent change at one dimension influences a prominent change at another dimension.

More dimensions like social dimension and wellbeing can be incorporated into the space. Social dimension reflects the states of the base network and superstructure of society, including political situation, e.g. COVID-19 influenced the support rate of the leaders of some countries such as USA and the UK. Strategies like social distancing and lockdown limit social behaviours, which influence wellbeing state of individuals. During COVID-19, social distancing can prominently reduce the infected number but it increases the risk of other diseases such as depression and heart disease. Lockdown strategy can increase the risk of other diseases that need emergent medical treatments.

Various subspaces can be constructed by selecting a subset of these dimensions. For example, space (*strategy*, *economy*, *pandemic*, *time*) can reflect the following influences: (1) Influence of a strategy on economy and pandemic at a particular time. The strategy of increasing production of producing oil on 09/03/2020 led to reduction of oil price, which formed pressure on the oil industry of USA as the price was lower than the cost of producing oil in USA. This in turn led to the decline of stock markets in the world (Dow Jones declined 7.79% on 09/03/2020). (2) Influence of a prominent state transition, e.g. adopting a sequence of strategies at one dimension on other dimensions. (3) Influence of pandemic on strategy. The situation of COVID-19 spreading in the world is a factor of influencing stock markets in the world.

The evolution of different dimensions with the change of coordinates and the increase of resources (including data, information and knowledge) reflects the development of understanding the evolving reality. The multi-dimensional space provides a coordinate system for exploring reality, for example:

- Mapping resources of one dimension onto another dimensions to see whether data, relations, rules and principles of one apply to the other.
- Discovering commonalities among facts, rules and principles between dimensions.
- Comparing differences between data, relations, rules and principles between dimensions.
- Unveiling influence between developments (changes) along different dimensions at different abstraction levels.

Discovering the implicit links between dimensions (e.g. the cause-effect link between pathological facts and treatment methods) enables the space to deeply reflect reality.

A conceptual mechanism of think lens was proposed to observe and understand reality through zooming from different dimensions at different abstraction levels of a resource space (Zhuge 2016).

Strategy can greatly influence economy. Electricity consumption and transportation are two of the key indicators that reflect the status of economy. Appendix B shows an implicit link between power and transportation influenced by pandemic.

10.7 Identifying Key Dimensions

10.7.1 *Key Dimension, Key Deterministic Dimension and Key Dependent Dimension*

Reality can be viewed from many dimensions, which represent different abstractions on things (Zhuge 2012). Influence between dimensions may exist.

Generally, *a set of small number of dimensions that is the key concern of a community (or users of a system) is called key dimension set. A change at a key dimension prominently influences another set of dimensions called dependent dimensions. Another set of small number of dimensions that prominently influence the key dimension set is called deterministic dimension set.*

Identifying the key dimension set, its deterministic dimension set and its key dependent dimension set is important for people to understand the intrinsic links between different dimensions of reality so as to make appropriate decisions facing a large number of dimensions.

For managing a pandemic, the key dimension is pandemic, how to find the key deterministic dimensions that essentially influence pandemic is important for making and adjusting strategies to control pandemic, how to find the key dependent dimensions that are essentially influenced by pandemic is important for making strategies to prevent the dimensions from the influence.

The basic assumption of this problem is that there are various relations (semantic links) between dimensions of a space, and a change at one dimension will influence relevant dimensions to a certain extent.

As different relations could convey different influences, the solution is to find the most essential dimension set that influences or is influenced by the key dimension(s) through finding appropriate relations.

A multi-dimensional classification space called Resource Space Model was proposed for managing things from different dimensions (Zhuge 2008). Coordinates on a dimension or a sub-coordinates (subclasses) of a coordinate can have no order, i.e. changing the order does not influence other dimensions and operations on the space. A point in the space has a unique projection (coordinate) at every dimension.

Different from the original Resource Space Model (Zhuge 2008), in some applications, coordinates at a dimension have order (e.g. times and ranks) and the change of the order may influence the projections of a point at the other dimensions. The following definition specifies such a space with an ordered dimension.

Definition 10.7.1. An n-dimensional classification space $S=(X_1, X_2, \ldots, X_n)$ classifies things with n classification methods such that any point in the space can uniquely locate a coordinate at every dimension. A set of its dimensions can have ordered coordinates $X_k=(\{C_{k1}, C_{k2}, \ldots, C_{kn}\}, <)$ such that different coordinates at one of its dimensions correspond to different coordinates at another one of its dimensions $X_l=(\{C_{l1}, C_{l2}, \ldots, C_{lm}\}, <)$ such that (1) $C_{ki} < C_{kj}$ if $C_{ki} < C_{kq}$ and $C_{kq} <$

C_{kj}; (2) $C_{lo} < C_{lp}$ if $C_{lo} < C_{lr}$ and $C_{lr} < C_{lp}$ and (3) $C_{li} \neq C_{lj}$ if $C_{ko} \neq C_{kp}$, where i, q, $j \in [1, m]$, $o, r, p \in [1, n]$.

With the ordered dimension, the space can support range query, for example, locating a subspace according to the given ranges on dimensions:

Select Subspace s From S Where $C_{12} < X_1 < C_{14}$; …; $C_{n2} < X_2 < C_{n4}$.

The concepts of dependent dimension and key dependent dimension are defined as follows.

Definition 10.7.2. An n-dimensional classification space (X_1, X_2, …, X_n) classifies things with n classification methods, if X_i is a dimension that has a semantic link α to X_j, denoted as X_i—α→ X_j ($i, j \in [2, …, n]$) such that different coordinates at X_i correspond to different coordinates at X_j with semantic relation α, then X_i is a deterministic dimension of X_j, and X_j is the dependent dimension of X_i.

Definition 10.7.3. An n-dimensional classification space (X_1, X_2, …, X_n) classifies things with n classification methods, if (1) X_i and X_j are a deterministic dimension and a dependent dimension of the key dimension X_k respectively; (2) there does not exist a dimension X_p such that X_p—α→X_i—α→X_k and X_p—α→X_k, then X_i is the key deterministic dimension of the key dimension X_k and (3) there does not exist a dimension X_q such that X_k—α→X_j—α→X_q and X_k—α→X_q, then X_j is the key dependent dimension of the key dimension X_k, ($i, j, k, p, q \in [1, …, n]$).

For original Resource Space Model (Zhuge 2008), changing coordinate at one dimension may not influence another dimension. The above definition requests that different coordinates at the key deterministic dimension or key dependent dimension correspond to different coordinates at the key dimension (e.g. GDP), and the key deterministic dimension and the key dependent dimension are the most essential dimension that influences and is influenced by the key dimension. A semantic link can be *cause-effect* (denoted as —*ce*→), *influence* (denoted as ——→) and other types of semantic link (Zhuge 2012).

Some influences are positive (e.g. the higher GDP per person the higher the medical quality and access) while some are negative (e.g. the increase of oil consumption influences the decline of environmental quality). For qualitative analysis on influence, a positive influence link between two dimensions (X and Y) can be denoted as X—+→Y and a negative influence between two dimensions can be denoted as X—/→Y. The influence relation is transitive, i.e., X—+→Y, Y—+→Z⇒ X—+→Z, and X—/→Y, Y—/→Z⇒ X—/→Z, therefore an influence chain can be detected. A cause-effect link between two dimensions X and Y (denoted as X—*ce*→Y) is a stronger semantic link that strongly conveys influence.

The following question is how to identify the key deterministic dimension and the key dependent dimensions in a given space and its key dimension. The following is a solution:

1. Input dimensions, key dimension(s) and data managed by the space.

2. For each pair of dimensions, identify a semantic link between the two dimensions with a *probability = coordinates that hold a semantic link / total coordinates* according to the semantic link between corresponding coordinates at the dimensions.
3. Remove the semantic link if *probability* < β, a value predetermined according to application (e.g. 0.6< β <1).
4. Find the longest semantic link chains that convey influence from one dimension to the key dimension. The source dimension of the influence is the key deterministic dimension. There can be multiple key deterministic dimensions if there are multiple chains.
5. Find the longest semantic link chains that convey influence from the key dimension to the end dimension, which is the key dependent dimension. There can be multiple key dependent dimensions if there are multiple chains.
6. Output the key deterministic dimension and the key dependent dimension.

10.7.2 *Case Study on Identifying Key Deterministic Dimensions for COVID-19*

A case study for identifying the key deterministic dimension that influences the pandemic dimension is presented in Appendix C. It indicates that *economy*, *culture* and *medical capability* are three key deterministic dimensions that influence the key dimension (pandemic) and the effect of adopting a strategy.

Lockdown is effective in curbing a pandemic but it is restricted by economy because it will damage enterprises especially those related to travel, hotel and restaurant businesses, which will further lead to the rise of unemployment rate, therefore influence the stability of society. Science and economy play the fundamental role in developing medical capability, i.e. *science* $\longrightarrow$ *medical capability* $\longrightarrow$ *pandemic*. Therefore, *culture, science and economy are the key-dependent dimensions of the pandemic dimension*.

Actually, *there are implicit links between culture, science (and technology) and economy* as depicted in Figure 10.12, where the dotted arrows represent influence. A breakthrough in science can transform the development of economy in the long run, which can be envisioned in many economic transformations driven by scientific and technological innovation (e.g. steam power, electricity and computer). At another dimension, the development of economy significantly influences science as scientists and scientific research resources (including development of new devices) need financial support. A mutual influence link can be found between the development of science and the growth of economy of countries through comparing the competitive advantages.

Karl Marks argued that science and technology is a part of productive force. Some people even argued that science and technology is the primary productive force. But this argument cannot explain why some countries like Greece did not benefit from their advanced ancient science and technology.

History indicates that the development of modern science and technology rely on social conditions and demands. *The development of society provides better conditions and higher demands for the development of science and technology.*

The Black Death destroyed the base network and superstructure of societies in the middle Ages, which demands a new channel for carrying knowledge flow. Capitalist society provides better conditions for developing modern science and technology than feudal society, therefore provides a new condition for transforming sciences and technologies.

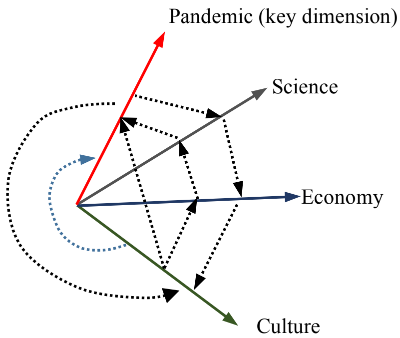


Fig. 10.12. Key dimension, key-deterministic dimensions and influence.

Transformational development of science is influenced by the ideological emancipation conceived in the soil of culture. From a macroscopic point of view, the culture renaissance transforms the knowledge flow from the stream of theology into the stream of science. It provides cultural basis for the generation of the first industrial revolution. The establishment and development of capitalist society provide material and thought basis for the first industrial revolution. The development of capitalist society driven by the first industrial revolution provides the thought, cultural and material basis for the second industrial revolution.

The above discussion reaches that culture, science and economy are dimensions that significantly influence pandemic. COVID-19 pandemic is influencing production relation, social relation and culture. Personalization and decentralization represent the trend of evolution of society and culture, which provide new demands for the development of economy as well as science and technology. The change of the base network will influence the superstructure of society in the long run. The coordinated development of science, economy and culture will play an important role in transforming science, economy and culture, which will pull the next industrial revolution.

The key dimension is determined by the main concern of a community or society, which varies at different stages of the evolution of society. At one stage culture can be the key dimension while at another stage science can be the key dimension.

Humans are the core of productive force because it is humans who create and develop culture, economy and science as spaces where humans can develop themselves in addition to physical space. Creating and developing these spaces can benefit humans but may also harm humans (e.g. smoking, economic crisis and atomic bomb). A good space could enhance health, mind or social relations but a bad space could harm human health, mind or social relations. A culture can also add economic and social values to materials. For example, Starbucks Coffee aims at creating the third space that provides a relax and reading atmosphere for customers in addition to home and office. Some people use coffee shops as studying spaces with free Internet access. It expands with attracting new customers and open new shops (through introducing new sales channels like take-away online ordering and strategies of cultivating market). It has opened 30,000 shops propagating nice coffee culture in the world since 1971. However, the space should evolve with the change of reality, especially meeting the challenge of COVID-19.

Humans have created culture, economy and science, which influence the development of humans who further develop culture, economy and science.

10.8 Representing Strategies and Laws in Multi-Dimensional Space

Managing a pandemic caused by a previously unknown virus by adopting various strategies to adjust the structure of society is an intelligent behaviour of understanding and exploring the unknown field. Observing phenomena especially abnormal phenomena from different dimensions is a method of exploration.

The superstructure of a society consists of interrelated spaces. State strategies and laws are spaces of the superstructure. Critical strategies like lockdown should be made according to laws. *Knowing the influence of strategies on pandemic enables the superstructure of a society to adopt rational strategies with evidence and analysis*. Different strategies need to be adopted with the development of knowledge on the evolving pandemic.

Strategies can be specified in a multi-dimensional strategy space, for example taking the following form where a point in the space represents a strategy or a set of strategies to be taken in response to the pandemic according to knowledge, condition, action and analysis at a time. Figure 10.13 depicts strategies in a multi-dimensional space.

(*Pandemic*, *Action*, *Knowledge*, *Condition*, *Analysis, Time*).

Linking coordinates at different dimensions forms an Event-Knowledge-Action-Factor-Analysis (EKACA) pattern, which determines a category of strategies for recommending actions when an event happens, the development of an event can be observed, relevant knowledge is available and conditions are satisfied.

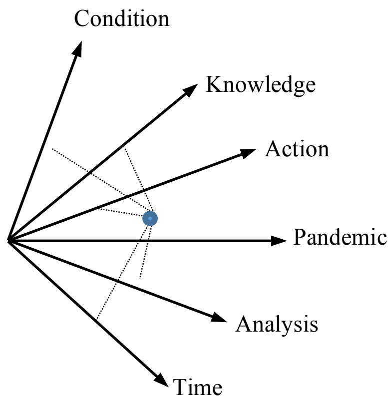


Fig 10.13 Strategies as points in a multi-dimensional space.

Law dimension is a constitution of the superstructure of a society, which can be specified in a multi-dimensional space for providing legal evidence for making strategies:

(*Pandemic*, *Action*, *Knowledge*, *Condition*, *Analysis*, *Legal provision*).

Establishing links between points in strategy space and points in law space enable strategies to be recommended with legal provisions.

The space of strategies and the space of laws can be integrated into one space as follows so that any action can be mapped onto a dimension of legal provision:

(*Pandemic*, *Action*, *Knowledge*, *Condition*, *Analysis*, *Time*, *Legal provision*).

Some instances for representing strategies and laws in the space are given with the background of COVID-19 pandemic in Wuhan, a city with over 11 million population and 3 million floating population in China, in Appendix D.

Representation of strategy space and law space in a Semantic Link Network as a social relational system enables it to provide intelligent services for decision makers so that decision can be made with evidences from multiple dimensions, e.g. linking a possible strategy to related laws, knowledge and conditions as well as strategies and effects. Laws are relatively stable while strategies evolve with the development of a pandemic, especially for a new pandemic. Knowledge and condition prominently evolves with the development of pandemic and scientific research.

The challenge is to automatically evolve the strategy space. A solution is to summarize the coordinates from scientific papers and government reports according to the given dimensions.

10.9 Challenges

Dealing previous unknown risks challenge existing culture, science and society.

10.9.1 *Managing Concurrent Networks in Cyber-Physical-Social Space*

It is a challenge to a society when it has to deal with two or more concurrent pandemics. In fact, flu spread seriously (www.cdc.edu/flu) when COVID-19 started to spread in USA. As variation may carry out during a pandemic, a new vaccine has to be developed when a new flu propagates. Actually, research unveiled that COVID-19 developed two types with different infect abilities (Tang et al. 2020). Some people were infected one type, some were infected the other type, and one was infected both types. Therefore, it is necessary to manage concurrent pandemics.

Figure 10.14 depicts the scenario of concurrent pandemics where arrows in red colour and arrows in blue colour represent the spreads of two diseases respectively.

A concurrent pandemic network has the following characteristics:

1. A node (individual) has more possible states and more transformations between states. Figure 10.15 shows transformation of states on a node with possible two diseases, where "1" and "2" represent disease 1 and disease 2.
2. A node can be infected by multiple viruses or different types of a virus.
3. A node recovered from one disease can be infected by another disease, i.e. a node can generate different antibodies for different viruses.
4. Two nodes can infect each other with different viruses or different variations of a virus.
5. A node has a higher probability of being infected by a virus in the concurrent transmission case. A node who is infected by two viruses faces a higher death rate because different viruses could attack different organs, which bring more difficulty to selecting medical methods.
6. Different diseases usually have different symptoms and therefore different diagnose methods, treatments and medicines are needed.
7. Different diseases usually have different infect paths, so different strategies for managing the diseases should be adopted.
8. It forms a higher psychological pressure that could influence public health and behaviours, and therefore it greatly influences social relations.
9. It has more groups of vulnerable people.

The above characteristics unveils the nature of a pandemic, which challenges science (e.g. monitoring variation of virus), the methods for diagnosis and treatment, the development of vaccine and selection of medicines, and therefore influence strategies for managing pandemics.

A pandemic network also operates with multiple types of networks:

- *Research networks*. Scientists study disease from multiple disciplines, find methods for curing disease and controlling pandemic, develop vaccine and select medicines. Knowledge flows through the network to develop understandings on reality. With scientific knowledge, methods and strategies for controlling pandemic can be made appropriately based on science.
- *Industrial symbiotic networks*. Various enterprises produce various material goods through material flows or services through human flow, information flow or knowledge flow. In additional to traditional manufacturers, hospitals can be regarded as an enterprise that provides medical services. Organizations like university can also be regarded as an enterprise that provides various services (e.g. education services).

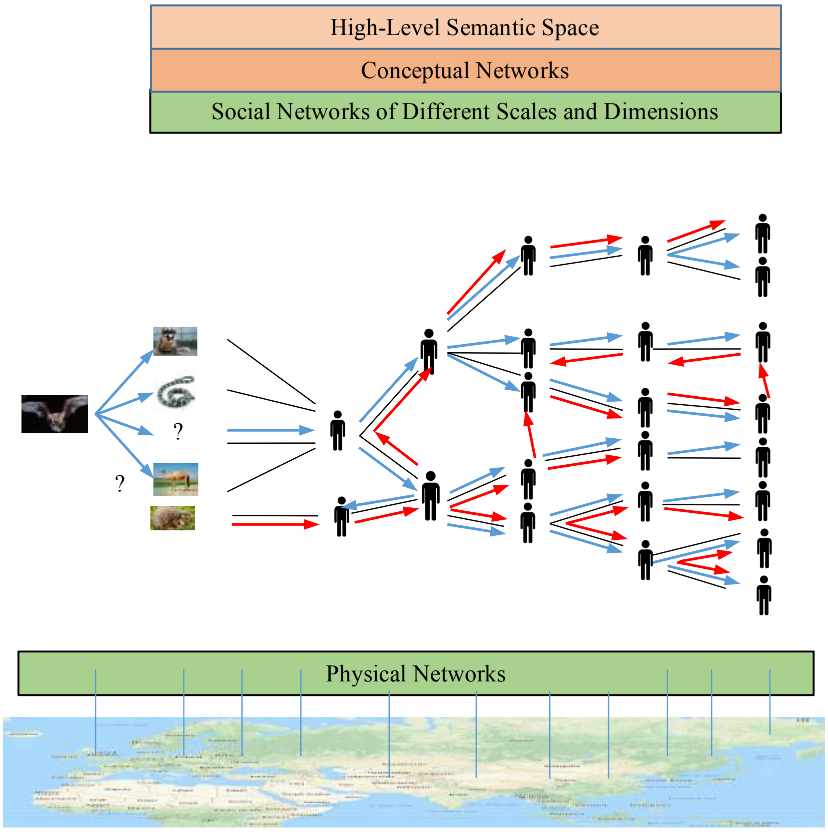


Fig. 10.14 A concurrent pandemic network, where black lines denote semantic links and arrows in blue colour and red colour denote the spread of two viruses.

An individual can play different roles in these networks. Doctors working for hospitals as nodes on pandemic network can be infected by family members when they play social roles in family. About 60% of infected medical workers in Wuhan were infected at home.

Nodes on a network can be centralized within one region or distributed in different regions. In a city, traditional medical resources especially experts and devices are centralized in big hospitals. Patients have to go to hospitals to see doctors for diagnosis and getting treatments in time. Therefore, patients and doctors have to face the risk of being infected when people gather in hospitals. Furthermore, when taking public transportation, other people on the same transportation also face the risk of being infected. Hospitals are nodes with heavy weights on the pandemic network. Distributing medical resources onto communities enables people to see doctors and get treatments within communities, which can reduce travel and the number of people gathered in one space.

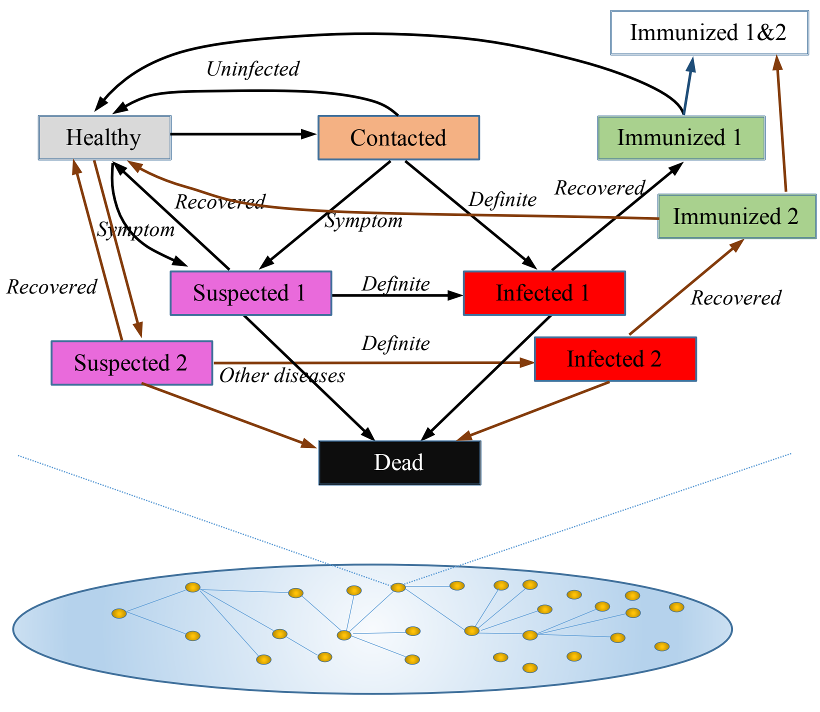


Fig. 10.15. State transformation of node on concurrent pandemic networks.

A homecare-support system based on mobile devices, GPS and the Internet enables patients to see doctors remotely from homes. Wearable devices like smart watches can collect some health data like blood pressure, but it is a challenge to explore light-weight client-side medical devices to collect sufficient body data to support diagnosis of more disease and the functions for managing and delivering medical services to homes of patients. This is a part of the strategy to break the link of infection.

A special case of concurrent pandemic is the variation of virus through transmission between communities. Different social relations and superstructures of different societies have different resistances to the transmission of virus, e.g. some countries like China adopted strict lockdown strategies while some countries like Sweden and the Netherlands adopted soft strategies (stricter strategies were adopted during the second wave but they are still looser than the strategies adopted by China). Virus of COVID-19 variated three types: type A widely transmitted in USA, type B variated from type A widely transmitted in eastern countries, and type C variated from type B widely transmitted in Europe (Forster et al. 2020). Lockdown strategy in eastern countries formed high resistance to virus transmission so type A and type C do not widely exist in eastern countries but type C also transmitted in USA due to free human flow between USA and Europe when the pandemic was outbreak in Asia. Variation leads to a difficulty that medical treatments, vaccines and strategies suitable for one society may not be suitable for another society.

10.9.2 *Intelligent Industrial Symbiotic Network*

Specialization is a way to promote the productivity of organization. Morden productions have developed into industrial symbiotic networks, where most nodes produce parts of end products. A node can supply parts to one demander or multiple demanders and have one supplier or multiple suppliers. The trade of parts occupied 70% of total value of global trade in 2018. An end-product like a cell phone usually needs parts from over hundreds of enterprises.

A pandemic will influence an industrial symbiotic network where nodes produce parts are influenced by the pandemic. A node represents a company that produce parts (or provide services) for other nodes. Material flow, information flow and knowledge flow pass through nodes for symbiosis (Shi and Li 2019). When a node stops production because of pandemic, it will influence the demander and even the whole network. Therefore, an industrial symbiotic network should be adaptive to the influence of crisis such as pandemic and earthquake.

A pandemic also increases demands on medical and protective products. The COVID-19 pandemic shows that the death rate of Wuhan (about 4%) is much higher than other cities like Shanghai (0.46%) until 04/02/2020. An authority explained on 04/02/2020 that it was mainly due to the low capacity of hospitals that can treat critical patients, which is about 10% of all patients according to CDC of China. How to increase the production of those products according to the changing demands at different stages of pandemic is the key to design an adaptive industrial symbiotic network.

Enterprises on a symbiotic network should be able to adapt (increase or decrease) production according to pandemic. As precisely predicting pandemic is hard and the cost for large-scale storage is high, an intelligent industrial symbiotic network is needed to quickly adapt production according to the change of production environment. It has the following characteristics:

- *Distributed supply*. Distributing an industrial symbiotic network onto different regions (or selecting nodes from different regions when building the network) is a strategy to make it adaptable to regional crisis. To prevent loss of supply during crisis, each node should have at least two suppliers distributed in different regions and at least two demanders distributed in different regions. When a risk takes place in one region that influences one of the two suppliers, the other supplier can still supply so that the symbiotic network can still operate. Considering the cost of supply (e.g., transportation), each node can have a strong supply link that supplies with the lowest cost in the normal case and a weak supply link that supplies during crisis with a relatively higher supply cost.
- *Information sharing*. Nodes can effectively share real, authority and first-hand information on pandemic and government strategies, which provide the basis for enterprises to adapt symbiotic network and arrange production according to the change of reality (including demands and productivity).
- *Predictive*. Nodes can predict the trend of pandemic at the initial stage of pandemic, and share prediction within the network so that the other nodes can make a plan to adapt production. They should be able to predict the change of demand when crisis takes place. Each node should be recommended to have a higher maximum production capacity than normal supply (e.g. double the normal supply) so that it can be easily to increase production when facing risk and hold a certain amount of storage according to the type of product. This will increase the cost of operating an enterprise but can prevent itself from being excluded from the symbiotic network during crisis that can last for several months like COVID-19.
- *Active*. Nodes can know the influence of pandemic and strategy on production or services. Nodes facing risk (within pandemic region) can start to produce and store products before production is seriously influenced (e.g. due to lockdown strategy). Nodes without risk (e.g. outside the pandemic region) can request the other supply nodes through the weak link to increase production before the supplier within the risk region uses up storages.
- *Knowledge-based*. An intelligent industrial symbiotic network can respond to a global risk like COVID-19 pandemic based on knowledge. It can learn knowledge about the risk from the state-of-the-art scientific research so that it can take measure to protect workers and reduce loss. The following measures can be adopted during COVID-19: (1) carry out antibody test and then allow workers with antibody to continue to operate production (this is based on testing antibody of the recovered people); (2) re-arrange workspace to keep so-

cial distance (2 m) between workers and (3) move a part of production (services) to homework. It is necessary to have a plan of work from home so that operation can be quickly shifted according to the plan when crisis takes place.

10.9.3 *Prominent Evolution of Social Relations*

A pandemic will form a prominent psychological influence on social interaction. Social distancing influences the traditional way to making friends and keeping close friendship and family relations. The following are some aspects of prominent influence on social relational network:

1. *Evolution of nodes*, including necessity (or weights), characteristics and functions. The necessity of some businesses such as restaurant, classroom teaching, face-to-face meetings and conferences will be decreased in daily life while the necessity of some businesses such as logistic services, online education and meeting and entertainment will be increased. Cyber images of humans (including robots) and organizations will increasingly participate in social interactions and reforming human beliefs with increasing virtual interactions. Independent work will be increased and accepted as it can be finished with less social interactions. Physically centralized teamwork will be reduced. Automatic production will be speeded up.
2. *Influence links*.
   - *Influence friend relation*. Meeting friends will be reduced, so opportunity to know new friends in person will be reduced, therefore traditional close friend relations (maintained through physical interactions) will be reduced. Friendship is influenced by different responses to the risk and different views on various information on risk. On the other hand, weak links will be increased therefore nodes have more chances to interact with each other. An instance is that students have more chances to ask questions during online teaching.
   - *Influence trust*. Trust between people will be reduced and need to be rebuilt due to less physical interactions. Useless, rubbish and fake information will increase, therefore misunderstanding on reality and misunderstanding each other will increase.
   - *Influence family relation*. Family relations will be dispersed as they transmit infection with higher probability than other relations. Relatives will avoid visiting homes. Pandemic is changing social characteristics of humans because traditional social behaviours such as shaking hand, meeting and dinning together become a characteristic of natural selection from pandemic.
3. *Migration*. Decrease of physical interactions will lead to increase of interactions in cyberspace. This will increase the influence of cyberspace on the evolution cyber-physical society (Zhuge 2012). As the consequence, the value of cyberspace will be increased as a network effect.

Facing the prominent evolution of social relation, *a challenge issue is to find rules on the new social relations*, which can derive new relations.

10.10 Summary

Semantic Link Network is a semantic relational system for understanding and representing various social relations and self-organization characteristic of society. Dimension is a basic abstraction means for understanding and representing reality. Incorporating multi-dimensional abstractions into the Semantic Link Network forms a more powerful semantic relational system for understanding and representing the observed reality and managing things in reality.

A pandemic can be viewed as a dimension that reflects the dynamic nature of reality. It obtains higher attention (weight) when a new pandemic is outbreak. A pandemic caused by a new virus provides a new lesson for humans to understand reality and explore the unknown fields. It also provides an opportunity for innovating methods for dealing with unknown threats through cooperative multi-disciplinary research concerning virology, pathology, medicine, epidemiology, public health, intelligent industrial ecosystem and smart cities.

An SLN-based Social Relational System models a pandemic with an evolving complex base network (consisting of human individuals, various things, social relations and public space), and an intelligent cyber-physical-social superstructure (consisting of strategies, laws, sciences and various social organizations). The superstructure and the base network interact with each other to operate and evolve the system. It can be a semantic framework for developing smarter cities or countries that support intelligent management of various crises.

Different from previous semantic web techniques, the SLN is a social relational system with the following advantages for modelling and managing things:

1. *It can help predict and manage the evolution of observed reality* (*e.g. a pandemic*) *with awareness of the base network* (*e.g. transmission network*). In application of managing pandemic, this can be done by precisely identifying potential next infected nodes on social network and adopting appropriate strategies with analysis.
2. *It can provide evidence-based decision support*. A strategy can be made with evidences and analysis from multiple dimensions.
3. *It can model, manage and evaluate a complex social system through modelling both the base social network and the superstructure*, *sharing information, knowledge and materials on the base social network* and enabling interactions between the base network and the superstructure.
4. *It provides multi-dimensional abstraction mechanism for modelling and analysing observed reality.*

Discovering various symbiotic networks is the basis for managing pandemic as a dimension of reality through identifying the key nodes, cutting the key infection link and adapting different symbiotic networks in society.

Efficiently managing new risks requests a cyber-physical society with innovating cyberspace (including systems for effectively managing crisis, sharing information and knowledge, cooperative scientific research, automatic production, e-commerce, e-entertainment, …, etc.), the physical space that supports daily life, work, education and public services, and social space that holds politics, economy and culture. Discovering the key dependent dimensions that influence pandemic is the basis for making an appropriate strategy.

10.11 Appendix A: Implicit Link between Evolving Reality and Developing Knowledge

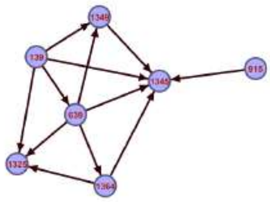
An implicit link between prominent evolution of reality and the development of knowledge generated through scientific research can be observed from tracing pandemic and scientific publications.

Figure 10.16 shows the number of papers on COVID-19 published in four major medical journals (The New England Journal of Medicine, The Lancet, Journal of the American Medical Association and British Medical Journal) per week during the pandemic in Wuhan. The number increases rapidly from the week by 19/01/2020 to the week by 16/02/2020, during which the number of the infected number increased from 62 on 19/01/2020 to 37152 on 17/02/2020 (newly infected number is 1600 on the day, which is 90 less than previous day). Curve (a) increases faster than curve (b) during the first week (indicating the leadership of the journals), and then both curves increase rapidly until the week by 16/02/2020, while curve (b) increases rapidly to 110 during the week by 23/02/2020. The turning points of the increase rate of curve (a) and curve (b) developed during the week by 16/02/2020 (reached 30 papers) and during the week by 23/02/2020 (reached 110 papers) respectively. They are close to the turning point of the infected cases in Wuhan (on 18/02/2020). After reaching the high point, the number of journal papers keeps the level until 08/03/2020 when the infected number is 49948 with new daily-increase 36 in Wuhan city (most cities have zero new case in China). Outside China, the pandemic developed rapidly in Asia, Europe and America. Italy announced isolation of 14 provinces on 08/03/2020 and then isolation of the whole country on 09/03/2020. This strategy drew public attention, which led to the rise in Moments and Official Account in WeChat as shown in Figure 10.7.

The global situation prolongs research interests on COVID-19, therefore curve (a) and curve (b) keeps going at the high level after the increase rate reaches the peak. The curve of the right part of (a) rises again from 15/03/2020 to the peak on 29/03/2020 and the curve of the right part of (b) rises constantly when pandemic developed rapidly in Europe (lockdown of Italy was on 10/03/2020, and lockdown of the UK was on 23/03/2020).

(a) The number of papers on COVID-19 in four major journals during pandemic.

(b)The number of papers on COVID-19 in MedRxiv and BioRxiv.



(c) Citation network on 735 papers on COVID-19 in the four journals.

(d) Citation network of 1888 papers published during 1995-2018 in AI journal.

Fig. 10.16 Comparison among patterns of evolving knowledge in different fields.

The citation network shown in Fig. 10.16 (c) shows a small citation network on new papers as most papers are published without referring other papers on COVID-19 pandemic during the first period (three months) of the pandemic. *This indicates that understanding of this pandemic is still shallow*, *and this is one of the causes that it became a global pandemic and the outbreak of the second waves in some countries*. Timely notifying researchers of the published work is an important scientific service for effectively developing knowledge flow on a rapidly changing reality.

During pandemic, discoveries were published quickly than normal so that researchers can quickly share knowledge. However, some discoveries were falsified quickly because of lack of evidence and in-depth understanding of the quickly evolving reality — the pandemic in society.

Figure 10.16(d) depicts a dense citation network of papers published in Artificial Intelligence journal during 1995-2018. Cleary, it contains more citation chains to verify, confirm or falsify knowledge.

10.12 Appendix B: Implicit Link between Power Consumption, Transportation and Pandemic

This section takes China as a case of study. Power plants in China mainly consume coal, so coal assumption is a key indicator of economy. It has a special holiday economy: most people return to hometown for celebrating Chinese New Year (CNY in short) on 25/01/2020. About 3 billion people travel by long-distance public transportation for spending one-week holiday. The primary sector (e.g. coal consumption) and secondary sector (e.g. power generation) of economy decline but the third industry (e.g. travel) increases during this week (people will stay at home together with family members on the eve so travel drops sharply on the first day of the new year). Figure 10.17 compares the change of 2019's and 2020's coal consumption (data from statistic department of China) and migration index (data from Baidu), which indicate the following points:

1. The consumption of coal was largely in line with the migration index during COVID-19 in China (the pulses of 2019's migration index were formed on holidays). The consumption of coal drops quickly during the weeks of 2019's CNY and 2020's CNY, but the curve of 2020 kept operating at the low level for about one month during lockdown strategy was adopted and the consumption of coal rose when the strategy was loosed after 36 days from Chinese New Year when the newly infected number greatly reduced outside of Wuhan city and two weeks after the peak of the infected number of Wuhan city, which is just the latent period of COVID-19.
2. The coal assumption rose quicker than transportation because the inter-city transportation recovered slower than intra-city transportation.

3. Transportation keeps running at the low level until 94 days after CNY (Wuhan city experienced 76-day lockdown since it was locked down on 23/01/2020). This also indicates that social activities and economy take a latent period (about 2-3 weeks) to recover.
4. The difference between two years' curves reflects the cost of isolation strategy, reflecting the influence of lockdown strategy on economy. The change of coal consumption also coincides with the change of carbon emission.

The environmental dimension can be also included to reflect the influence on behaviours on natural environment. Coordinating the environmental dimension, economic dimension, social dimension and strategy dimension can unveil the influence of strategies on other dimensions. For example, the lockdown strategies during COVID-19 in some countries prominently reduced the demands of coal and oil, which leads to the greatest reduction of carbon emission since World War II.

The reduced demand of power also greatly pushed down the oil price and the stock price of transportation companies.

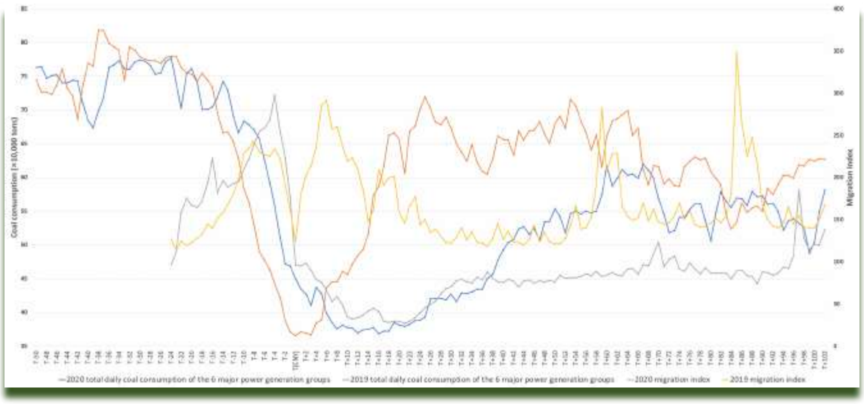


Fig. 10.17 Consumption of coal and migration index during COVID-19 in China.

10.13 Appendix C: Deterministic Dimensions of Pandemic

Strategies are made by intelligent individuals or organizations to reach a relatively long-term aim based on knowledge and understanding of reality. It is the basis for an intelligent system to know the deterministic dimension of a key dimension that its users concern. This section is to demonstrate the approach to finding the deterministic dimensions of a key dimension (pandemic) through survey based on analysis on multiple dimensions on reality. It is not only significant for recognizing the pandemic but also provides the basis for studying automatic discovery of deterministic dimensions.

Strategies of a country are made by the superstructure of a society to influence its base social network, and the change of the structure and evolution rules of the base social network can also influence the superstructure. For managing a pandemic, different strategies should be made according to the information on reality evolving in a multi-dimensional space and knowledge (including existing knowledge and knowledge learnt from the evolution of a pandemic). Adopting different strategies from light interference to strong interference at the strategy dimension influences other dimensions differently.

Lockdown is a strategy of strong interference, which can quickly curb pandemic in the short term by ensuring physical distance but it will negatively influence wellbeing, demand, supply, finance (including stock market) and labour market, which further negatively influences industrial symbiotic networks.

A soft strategy (e.g. washing hands) will not greatly influence other dimensions (especially economy) but the infect number would keep increasing if the transmission path is unknown. So scientific research is the basis of adopting soft strategy. The increase rate can be reduced if the deterministic dimensions can be found on time so that appropriate measures can be taken, e.g. warning can be issued and knowledge of self-protection can be announced.

Strategies can be chained for dealing with changing reality. A strategy can be adapted according to unforeseen change of reality and knowledge learnt from research and practice. At the initial stages of COVID-19 pandemic, China adopted a strict lockdown strategy facing an unknown disease. With the development of the pandemic, the infected number and mortality rate increased rapidly in Asia, Europe and USA, the UK made a plan to response to the pandemic by linking four strategies: *Contain* (detect early cases and close contacts) → *Delay* (slow the spread) → *Research* → *Mitigate* (provide the best care). It turned to adopt a lockdown strategy at the second stage (delay) facing the pressure of rapidly increasing morality number.

Some countries like Sweden insisted on adopting a soft strategy when most countries adopted lockdown strategy. Comparing the influences of different strategies adopted by different countries in a multi-dimensional space is a way to deeply analyse strategies.

Different strategies can be described and compared in a space of multiple dimensions *S* = (*country*, *pandemic*, *healthcare*, *economy*, *society*, *culture, strategy, analysis*), where each dimension consists of coordinates and a coordinate can be a tree structure of coordinates.

The following are points with mapping images of China, some representative countries in EU and USA at the country dimension of the space reflecting the socioeconomic reality to a certain extent during pandemic COVID-19. The influence of different dimensions on the pandemic is analysed. As data change with the development of pandemic, detailed analysis needs to be carried out after the pandemic is completely terminated (the epidemic is still developing in the world when this book is submitted). Research on Resource Space Model provides a way to automatically generate the contents of points according to given data (texts) and dimensions (Zhuge 2008).

- **Point 1:**
  - *Country*: China.
  - *Pandemic*:
    - *Response time*. It found the first case on 01/12/2020, and then adopted strict lockdown strategy on 22/01/2020. It took 52 days to reach the decision. It lifted lockdown on 07/04/2020 but some social activities are still limited according to the situation of different cities.
    - *Mortality*. The mortality number reached 4645 and population is 1.4 billion until 17/05/2020. Its mortality per million population is about 3.32.
  - *Healthcare*: Its 2009's HAQ (Healthcare Access and Quality Index) is No.48, the most quickly improved country (according to report in Lancent 2009).
  - *Economy*:
    - *GDP*. Its 2019's GDP is about 14010 billion USD (the growth rate is 6.1%). The GDP of the first quarter declined about 6.8% according to the report from the Sate Statistic Department of China on 17/04/2020, and consumption reduced 23.7%.
    - *Economic strategy*. To pull economy, China invested 38917 billion USD into the construction of infrastructure.
    - *Problem*. After lifting lockdown, the general recovery rate of industry is 84% until 15/04/2020 but demands were reduced and more and more orders were cancelled with the development of the pandemic in other countries. Then, its economy recovered constantly.
  - *Society*:
    - *Governance*. It takes a tree structure where the root has long chains to leaves: central government – province – city – district – street, or central government – province – county – town – village.
    - Unemployment rate. It increased from 3.62% by the end of 2019 to 6.2% in February of 2020. About 21.93 million people lost jobs in the first two months of 2020, but this situation changed with the recovery of economy.
    - *Population*. It is about 1.4 billion. The population density is 143 /km^2. The central area is about 200 / km^2 (Hubei Province is 325/km^2, and Wuhan city is 1282/km^2). The east area is 400 / km^2. The population of Han nationality occupies 91.5% of the whole country's population. About 12.6% population is above 65 years old (in 2019).
    - *Education*. Higher education is not free but very cheap. The number of university student is about 37 million who study in big classrooms, share canteens and live in student dormitories.

- *Culture*: Moral, moderation and nature are words indicating its root in agriculture with family, patience, diligent and polite characteristics.
  - *Habit*. People are used to dining with sharing food and travel during Spring Festival to meet family members and friends, which enhance family relation and friendship but also increase the probability of transmission of virus. Traditional Chinese Medicine helps reduce symptom in addition to modern medical treatments.
  - *Saving*. 2018's saving rate is 44.7%.
  - *Living*. Most people in cities live in tall apartment with lifts. Public transportations are main vehicles of daily life. Shops open every day and for long time (9:00-22:00). This increases the probability of transmission and provides necessity for wearing mask in public indoor spaces.
- *Strategy*:
  - *Lockdown*:
    - *Reasons*: (1) Dense population and frequent public gathering activities of universities make it necessary to close them with priority; (2) outbreak of pandemic was mainly in the big cities with high density of population and people mainly rely on public transportation in daily life; (3) its culture makes people more easily expose to infection; (4) its culture is in line with its superstructure, which gives the government the power to schedule medical and living resources within the country to support lockdown strategy; (5) facing previous unknown disease, adopting lockdown strategy provides more time for scientists to study the disease and (6) high saving rate supports a longer term lock down strategy than other countries.
    - *Effect*:
      - *Positive aspect*: It curbs pandemic quickly. Wuhan city used 76 days to lift the lockdown strategy when no new infection had not been found for 14 days.
      - *Negative aspect*: (1) staying home will damage the health of people, lead to psychology issues (e.g., anxiety and depression), and increase interactions between family members; (2) patients with other diseases cannot get timely treatment; (3) economy will be damaged and (4) unemployment rate rises. With time increases, the negative effects rise.
    - *Unlock*: Unlock strategy consists of a chain of strategies: (1) New infect number becomes zero and then keeps zero for 14 days → (2) Unlock districts from the 15^{th} day but the roads between districts were still locked until new infect number keep zero for the 2^{nd} 14 days → (3) Unlock the whole Wuhan city from the 29^{th} day but the ways between Wuhan and other cities was still locked until new infection number keeps zero for the 3^{rd} 14 days → (4) Unlock the ways (airway, railway and motorway) between Wuhan and other cities from the 43^{rd} days.

- *Analysis*. Considering healthcare, social, economic and cultural characteristics, strict lockdown strategy is necessary and feasible when outbreak took place. For controlling pandemic, it is better to respond quicker but it takes time to recognize the new virus. For the same reason, the unlock strategy is prudent. One option is to adjust strategy when the benefit curve is developing toward the negative curve growing with time. For example, public transportations within city and shops relevant to daily life can be opened with social distancing regulations earlier.

- **Point 2**
  - *Country*: UK.
  - *Pandemic*:
    - *Response time*. It adopted a soft strategy (introducing self-protection knowledge like often wash hands) when the first case was found in the country on 23/01/2020. The government adopted lockdown strategy on 23/03/2020 (6 days after France), but this strategy is not as strict as China. The decision took 60 days after the first case was found (8 more days than China).
    - *Mortality*. The mortality number reached 34716 until 17/05/2020 and reached 41592 on 02/09/2020. Its population is 66.65 million. The mortality per million population is 624.
  - *Healthcare*. Its 2009's HAQ (Healthcare Access and Quality Index) is No. 23 (Lancent 2009).
  - *Economy*.
    - *GDP*. Its 2009's GDP is 2830 billion USD (growth 1.4%). The second quarter's GDP declined 20.4%.
    - *Economic strategy*. The government released the follow-up strategy to save economy: waive 12-month tax for seriously influenced enterprises like restaurants, supplied 330 billion loan to enterprises, and reduced the interest rate of bank from 0.75% to 0.1%. An unemployed people can get 80% salary for three months. This provides economic condition for adopting lockdown strategy.
  - *Society*.
    - *Governance*. The social system is constitutional monarchy and structure is flat. It is used to establishing social consensus before decision. Most government departments have a chief scientific advisor to provide scientific advice. The Government Chief Scientific Adviser (GCSA) is responsible for providing scientific advice to the Prime Minister and Members of cabinet and advising scientific policy as well as ensuring and improving the quality and use of scientific evidence. This setting helps government to make strategies with scientific evidence.

- *Unemployment rate*. The unemployment rate was 3.93% in Dec of 2020, it was 4% during Dec of 2020 to Feb of 2020, and it reached 10% (estimated).
- *Population*. Population is 66.65 million, among which 86% are white people and 14% are minority people, 81.5% lived in an urban location and 18.5% lived in a rural location. The density of population is 260 / km^2 and most people live in the great London area. About 18.4% population is above 65 years old (in 2018).
- Education is not free. It has 0.45 million international students (this increases the risk of transmission between countries).

o *Culture*. Science, philosophy and discipline indicate its marine culture rendered by brave and cooperative behaviours.

- *Habit*. People like social and teamwork. Many young people are used to get together in Pubs. Over 98% minority people prefer to live in city especially London. It is understandable that avoiding danger is more important than limiting freedom caused by strategies made by government.
- *Saving*. 2019's saving rate is 15.1%.
- *Living*. Shops in big cities open on Saturday and Sunday (10:00-16:00). Many people lived in houses and apartments are usually not tall (many apartments have 3-4 levels).

o *Strategy*.

- *Strategy*. Soft strategy → Lockdown → Lift with social distance.
- *Effect*. Infection number was significantly reduced after lockdown.
- *Optional strategy*. The herd immune strategy is to protect vulnerable people (old people and sick people who were advised to stay home), ensure normal operation of NHS and keep operating economy with the conditions of no effective medicine and unavailable vaccine. But this strategy takes effect only when over 60% of whole population is affected. This idea has root in British culture and faces humanitarian risk. A report from Imperial College argued that 0.51 million people would loss life (0.25 million will loss life even if lock down strategy can be adopted). Over 600 scientists object herd immune strategy. A different opinion argued that herd immune takes effect when 10%-20% of population is affected. An evidence is that 712 people were infected among 3711 people on board the cruise of Diamond Prince but it adopted isolation strategy on 04/02/2020 when one infect case was found, indicating that the final infected case is the result of interference.

o *Analysis:*

- *Influence of culture*. Statistic data show that about 70% of sacrificed medical workers are minority. This can be explained from their culture and the fact that over 98% minority people live in big cities like London with higher density of population. It indicates that culture is a factor of influencing pandemic.
- *Testing method*. As the UK only tested the critical patients in hospitals (people with mild symptom were suggested to stay home), people were

experiencing herd with a certain social distance. This is one of the causes of the outbreak of the second wave.

- **Point 3**
  - *Country*: Italy.
  - *Pandemic*.
    - *Response time*. It found the first cases on 30/01/2020 and the first mortality case on 22/02/2020. The government announced 6-month national emergency and cancels flights from and to China on the following day. Outbreak of pandemic in Italy was on 22/02/2020. The government enclosed 11 provinces on 24/02/2020, enclosed 14 provinces on 08/03/2020, and then lockdown the whole country on 10/03/2020. It used 39 days to reach the lockdown strategy from the first two local cases were found.
    - *Mortality*. Its mortality reached 31908 until 17/05/2020, and reached 35491 on 02/09/2020. Its population is 60.4 million. The mortality per million population is 588.
  - *Healthcare*. The Healthcare Access and Quality Index is No. 9 (Lancent 2009).
  - *Economy*. Its 2019's GDP was 2000 billion (growth 0.3%). The first quarter declined about 5% and the second quarter declined 12%.
  - *Society*. Its population is 60.36 million. The density is 203/ km^2. About 23% population is above 65 years old. Unemployment rate was 7.3% in April, 8.5% in May, 9.3 in June and 9.7% in July.
  - *Culture*. Truth, personality and freedom of thought indicate the spirit of culture renaissance, represented by arts and sciences.
    - *Habit*. People are hospitality and open, and like to make friend and talk to others (this increases the probability of being infected).
    - *Saving*. 2019's saving rate is 22.6%.
    - *Living*. People prefer to live close to family members (this increases the probability of being infected).
  - Strategy: It quickly adopted regional lockdown strategy.
  - *Analysis*. People are not willing to stay home nor to ware mask in public indoor space. This increases the probability of being infected. This is relevant to its culture. It is worth noticing that a Chinese community with about 50,000 population in Prato city has no infection case. This provides an evidence that culture is the determinate a factor on pandemic.

- **Point 4**
  - *Country*: Germany.
  - *Pandemic*.
    - *Response time*. It found the first local infect case on 27/01/2020 and then found the first mortality case on 09/03/2020. It closed schools and most public facilities and cancelled flights from and to China on 17/03/2020. The Premier called for reducing public activities, stopping visiting and

travelling and keeping social distance on 18/03/2020. Berlin and 15 states lockdown on that day. It spent about 50 days to reach an actual lockdown strategy from the first infect case (it actually did not fully lockdown the whole country).

    - *Mortality*. It reached a mortality number 7988 on 17/05/2020, and reached 9320 on 02/09/2020. Population is 83.02 million. The mortality per million population was 112.3.
  - *Healthcare*. Its 2009's HAQ (Healthcare Access and Quality Index) was No.18 (Lancent, 2009).
  - *Economy*. It's 2009's GDP is 38500 USD (growth 0.6%). It declined 2% in the first quarter and declined 9.7% in the second quarter.
  - *Society*. The density of population is 228/km^2. Unemployment rate was 3.2% at the end of 2019 and it constantly rose up to 4.4% by the end of July in 2020. About 21.4% population is above 65 years old (in 2018).
  - *Culture*. Philosophy, science, art and efficiency are words that indicate its culture.
    - *Habit*. Most shops are closed after 6:30 pm and on whole Sunday, which helps reduce transmission of virus in public indoor space.
    - *Saving*. 2019's saving rate is 26.4%.
    - *Living*. Clean, discipline, separate dinning and quiet environment helps control pandemic.
  - *Strategy*. It adopted a limited lockdown strategy (people can still go to work, see doctor, buy food and outdoor sport with social distance). On the other hand, it provides 756 billion Euro financial support for enterprises.
  - *Analysis*. Professor Christian Drosten argued that 2/3 population will be infected and the strategy is to distribute the infect number onto different times to keep health care system operate normally, which plays an important role in saving life. Experts in Germany argued that wearing mask and testing body temperature are unnecessary. Waring mask in public space became compulsory at the end of April.

- **Point 5**
  - *Country*: France
  - *Pandemic*.
    - *Response time*. It found the first local case on 25/02/2020. It took 21 days to adopt lockdown strategy on 17/03/2020 (7 days after the lockdown of Italy).
    - The mortality number is 28111 until 17/05/2020, and reached 30666 on 02/09/2020. Population is 67 million. Mortality per million population is 457.7.
  - *Healthcare*. Its 2009's HAQ (Healthcare Access and Quality Index) is No. 20 (Lancent, 2009).
  - *Economy*. Its 2009's GDP is 2778 billion USD (growth 1.3%). It declined 5.9% in Jan and 13.8% in July 2020.

- *Society*. Density of population is 119/km^2. Unemployment rate is 8.1%. About 20% people is 65 years old (in 2018).
- *Culture*: Freedom, equality and love are words indicating its culture represented by art, philosophy, science and social movement.
  - *Habit*: Food and pub are words indicating habit. Most shops are closed on Saturday and almost all shops are closed on Sunday.
  - *Saving*: 2017's saving rate is 14.2%.
  - *Living*: Family is usually small and simple.
- Strategy. It adopted a limited lockdown strategy on 17/03/2020 (people can go to unavoidable work, buy living materials, see doctor, take care of children and individual sport).
- *Analysis*. The government reached the lockdown strategy quicker than Italy, Germany and UK. Its saving rate is close to the UK but much lower than Germany and Italy, so it cannot support lockdown strategy for a long term.

- **Point 6**
  - *Country*: Sweden
  - *Pandemic*.
    - It found the first local case on 09/03/2020. It only bans gathering of 50 or more people and suggests young people reduce social activity and old people to stay home.
    - Mortality. The mortality number reached 3698 until 17/05/2020, and reached 5813 on 02/09/2020. Population is 10.23 million. The mortality per million population is 568.
  - *Healthcare*. Its 2009's HAQ (Healthcare Access and Quality Index) is No. 8 (Lancent, 2009).
  - *Economy*. Its 2018's GDP is 556.1 billion USD. It declined 8.3% by the end of July.
  - *Society*. Population is about 19 million. Density of population is 24.7/km^2. Unemployment rate on Dec 2019 is 7.7% and it rose to about 9% by the end of July. About 20% population is above 65 years old (in 2017). Government's decision relies on the suggestion from the independently operated department of public health. Shops open on weekends.
  - *Culture*. Fairness and equality represented with polite, harmony, independent and neutral behaviours.
    - *Habit*. People tend to think of giving neighbour an individual space, therefore they don't like to chat with each other in public areas.
    - *Saving*. It 2019's saving rate is 29.6%.
    - *Living*. Consensus and collectivism is a criterion of daily life and work.
  - *Strategy*: It does not adopt a full lockdown strategy.
  - *Analysis*. The decision of not adopting lockdown strategy is relevant to behaviours rooted in its culture. People are used to keeping social distance, work from home and trust scientists. The domestic travel decreased

drastically during pandemic, which is an effect of timely sharing epidemic information.

- **Point 7**
  - *Country*: USA
  - *Pandemic*.
    - *Response time*. It adopted a series of strategies: It started to test the temperature of people travelled from Wuhan at three airports (San Francisco, New York and Los Angeles) on 17/01/2020. The first infect case was found on 19/01/2020 (Holshue 2020). Following the lockdown of Wuhan city in China on 22/01/2020, it evacuated American diplomats and citizens from Wuhan on 27/01/2020, raised the warning of traveling to China to the highest level on 29/01/2020, and banned travel from and to China on 31/01/2020. It may be a critical time to adopt stricter strategies (e.g., limit travel between USA and EU) when 9976 cases were found in 21 countries on 30/01/2020, especially considering people can freely travel between majority of EU countries and USA. The infected number increased to 1629 until 13/03/2020 when it announced national emergency. On 11/03/2020, it announced travel ban from Europe when the pandemic develops rapidly in Italy. On 16/03/2020, it announced a new instruction to social distance. On 19/03/2020, California adopted lockdown strategy, and then followed by New York and other states. Entering April about 95% of American's population were under some form of lockdown. It used more than two months to reach an actual lockdown strategy.
    - *Mortality*. The mortality reached 91061 until 17/05/2020, and it reached 188900 on 02/09/2020. Its population is 328.2 million. Mortality per million population is 575.56.
  - *Healthcare*. Its 2009's HAQ (Healthcare Access and Quality Index) is No. 29 (Lancent, 2009).
  - *Economy*. Its 2019's GDP is 21700 billion USD (growth rate 2.3%). Its 2020's GDP declined 31.7% by the end of July. According to Moody's Analytics, the lockdown strategy influences the areas that generate 96% of this country's GDP, and its daily economic outcome reduces 29%. It released 2000 billion USD to stimulate economy. A family can get 2400 USD if its annual income is lower than 150 K.
  - *Society*. Density of population is 35.7/km^2. Unemployment rate is 3.5% (Feb 2020) and it rose to 14.7% in April and then improved to 10.2%. Population over 65 years old is 15.4% (in 2017). Shops open everyday.
  - *Culture*. Independence, freedom, innovation and entrepreneurship are words indicating its multiculturalism.
    - *Habit.* Like fast food (e.g. hamburger and coke).
    - Saving. Its 2018's saving rate is 17.3%.
    - *Living.* Family first.

- *Strategy*. Its states adopted lockdown strategy independently.
- *Analysis*. The decision process considers the balance among pandemic, economy and politics. It took a long time to reach a lockdown strategy.

Based on the above representations of points, countries can be ordered at different dimensions.

- Pandemic (Mortality per million population): UK (624) > Italy (588) > USA(575.6) > Sweden (568) > France(457.7) > Germany (112) > China (3.3).
- *Healthcare Quality and Assess*: Sweden (8) > Italy (9) > Germany (18) > France (20) > UK (23) > USA (29) > China (48). This criterion does not significantly influence the pandemic in general.
- Economy (GDP): USA (21700) > China (14010) > Germany (3850) > UK(2830) > France(2778) > Italy(2000) > Sweden(556). Although it does not completely match the pandemic, GDP is more significantly influence the pandemic than the healthcare quality and assess. It is the economic basis of adopting the lockdown strategy and determines the duration of lockdown.
- Unemployment rate: Before pandemic: USA (10.2%) > UK (10%) > Italy (9.7%) > Sweden (9%) > France (8.1%) > China (3.62%) > Germany (3.2%).
- Response time (to Lockdown): France (21) > Italy (39) > China (52) > Germany (50) > UK (60) > USA (60+) > Sweden (No lockdown). We can see that the response time does not significantly influence the pandemic.
- Density of population: UK (260) > Germany (228) > Italy (203) > China (144) > France (119) > USA (35.7) > Sweden (24.7). It is not in line with the mortality number per million of the countries. Referring to the zero mortality number of Macau, the highest density of population in the world, we can reach that the density of population is not the deterministic dimension that influence pandemic.
- Population over 65 years old: Italy (23%) > Germany (21.4%) > France (20%) > Sweden (20%) > UK (18.4%) > USA (15.4%) > China (12.6%). It is inconsistent with the mortality per million of countries although the highest one Italy has the highest mortality rate and the lowest one China has the lowest mortality rate. If EU is regarded as a country (comparative to USA), it is in line with the mortality per million population: China (3.3) > USA (168.9) > EU (276.3). Therefore, age can be regarded as a partially deterministic dimension of pandemic.
- Saving rate: China (44.7%) > Sweden (29.6%) > Germany (26.4%) > Italy (22.6%) > USA (17.3%) > UK (15.1%) > France (14.2%). We can see that the saving rate is inconsistent with the pandemic. Saving rate reflects a certain extent of economic freedom. A country with 20% saving rate has 2.4 months' freedom from work for a year, i.e. lockdown for 2.4 months should not lead to financial difficulty. Saving rate and the unemployment rate is a condition for adopting lockdown strategy.
- Culture: Different communities with different cultures have different mortality rates because of the following two typical facts: (1) nationality is closely related to the mortality rate according to statistic data in the UK and (2) Chi-

nese community in Italy has zero infection number. In addition, cultures of different countries can be evaluated by their attitudes on a set of strategies, e.g. wearing mask, lockdown and social distance. The attitudes of people in different countries can be evaluated by marking the set of strategies such that the higher the total mark (e.g. *mask* + *lockdown* + *social distance*) the heavier influence on curbing the pandemic, e.g. China (*mask*=10, *lockdown*=10, *social distance*=10) > Germany (mask=1, lockdown=9, social distance=9) > France (mask=1, lockdown=8, social distance=8) > USA (mask=1, lockdown=7, social distance=7) > Sweden (mask=0, lockdown=0, social distance=10) > UK (mask=1, lockdown=8, social distance=8) > Italy (mask=1, lockdown=7, social distance=7).

The space can include more dimensions that may also influence pandemic. The number of ICU beds in different countries represents the capacity of a country in saving critical patients. The order of the ICU number per 100k population in 2012 was: Germany>USA>France>China>UK (Murthy and Wunsch 2012). But this number is dynamic and can be increased during pandemic. Further, China's mortality number is much less than USA and France, therefore the ICU beds is not the deterministic factor of influencing the mortality number in general. This indicates that *it is more important to take measures to prevent transformation from mild state into critical state than increasing the number of ICU beds in general*. However, increasing ICU beds is necessary when the number of critical patients becomes more than the number of ICU beds.

A key issue is to automatically generate the contents of points in the multi-dimensional space according to the given specifications of points and a set of texts on the pandemic, e.g. automatically generating slots X_1, …, and X_{10} of the point with the following dimensions (some have only dimensions and some have coordinates at dimensions).

Country: USA
Pandemic: (*Response time*: X_1, *Nationality*: X_2)
Healthcare: X_3
Economy: X_4
Society: X_5
Culture: (*Habit*: X_6, *Saving*: X_7, *Living*: X_8)
Strategy: X_9
Analysis: X_{10}.

Solution concerns the early discussed steps in this chapter.

10.14 Appendix D: Representations of Strategies and Laws

The superstructure of Semantic Link Network contains a strategy space and a law space for modelling a society. The following are some instances for representing strategies as categories. They provide knowledge, evidence and analysis for adopting strategies. An "Action" of one strategy can be linked to the "Event" of another strategy so that a chain of strategy can be formed.

Strategy 1. Category: Response to pandemic

Event:

- A disease case is detected.
- The virus that causes the disease (pathogen) is found.
- One case or more cases of human-to-human infection is detected.
- One case or more cases of death is occurred.

Knowledge:

- Link between the new virus and the existing virus.
- Strategies adopted during pandemic caused by the linked type of virus.
- Category of existing virus and the infection path.

Action:

CDC (Centers for Disease Control and Prevention):

- Identify infection ability according to existing category of virus with link to existing category on disease.
- Report event with knowledge and suggestion to the department of health.
- Organize survey and research on disease (including origin, infection path and vaccine) to obtain new knowledge.
- Collect data, evaluate the situation and predict the trend.
- Provide consulting service for public about the pandemic, including guidelines of protection.

Local Government:

- Announce the disease according to relevant laws (link to legal provisions).
- Advise people with mild symptoms or critical symptoms to stay at home or go to hospitals (or call hospitals) for medical check-up.
- Announce regulation to isolate the infected patients in hospital for medical treatment according to law.
- Plan logistic for hospitals.

Hospital:

- Determine treatment process.
- Select appropriate medicine for the disease.

Factor:

- *Stage of pandemic*. Strategies are more effective at the initiation stage of pandemic when the number of infected people is small.
- *Capacity of hospital and estimated number of patients*. The capacity includes devices, resources and conditions specific to the disease. It is more necessary for critical patients.
- *Accuracy of the existing diagnosis measure*. If it is too low, diagnosis may mislead treatment and lead to cross-infection in hospital. During the initial stage of outbreak of COVID-19, the nucleic acid reagent was recommended as the gold standard of diagnosis.

Analysis:

Advantages:

- Patients can be diagnosed through medical check-up.
- Patients can get supportive treatment although there may not have effective medicine to cure the disease.
- Hospitals have professional facilities to isolate the infected patients and protect others.

Disadvantages:

- Patients with different diseases could infect each other in hospitals, so hospitals may become a new source of infection.
- Shortage of experts and resources during the outbreak of a pandemic, especially in big cities.

Influence:

- *On social relation*: It will reduce the number of neighbors of infected nodes because of isolation. It will increase material flow to hospitals, which will become centers for processing incoming people with symptom and then outputting the dead and recovered people. It is a strategy to issue a certificate to the recovered people (with antibody) so that they can work and move as normal.
- *On pandemic*: The evolution of pandemic will be separated into two branches: One is outside of hospital, which expands with the spread of the disease from the initial stage, it keeps stable when the speed of diagnosis catches up and keeps the same as the speed of transmission, and then declines with more and more people were isolated in hospitals and more and more people recovered. The other is inside hospital, which expands with more patients are admitted, it keeps stable when the recovered patients keep the same level as the new patients, and then declines when more patients are recovered and new patients reduce.
- *On psychology*. Patients will feel lonely and nervous when they are isolated in hospitals. Anxious emotion could depress immune system.

Instances:

- This strategy was taken by the municipal government of Wuhan during the outbreak of COVID-19. The consequence is that too many people went to hospitals so that hospitals are overloaded at the initial stage. The death rate of Wuhan is much higher than other cities in China, which indicates the probability of cross-infection and lack resources in hospitals. With the development of the pandemic, the municipal government decided to rapidly build a central hospital for hosting about 2000 patients with high standard facilities. It opened on 03/02/2020, which is more than one month from official announcement of the pandemic (21/12/2019). However, this is still not enough for hosting increasing patients in Wuhan city (5142 on 03/02/2020). Wuhan city requisitioned hotels for hosting patients on 02/02/2020, but hotels need time to be equipped with medical facilities, which is more important for critical patients. Isolation strategy, policy for encouraging people to go to hospital, and outbreak of suspected people formed a big pressure on hospitals. Over 3062 hospital staffs were infected in Hubei province, among which 23 people died in Hubei Province (account for 59% in China) according to WHO' press release on 24/02/2020. The development of the pandemic in the world shows that the strategy is successful.

- Link to more instances.

Strategy 2. *Advice people to stay at home for self-isolation*.

Event: It is the same as strategy 1.
Knowledge: It is the same as strategy 1.
Action:

CDC: It is the same as strategy 1.

Government:

- Announce the disease according to the law on public health.
- Advise people with symptoms (cough and fever) to isolate themselves at home, and arrange critical patients to go to hospitals for medical check-up and isolation.
- Announce regulation to isolate the infected patients at home.
- Plan logistic (ensuring local store or delivering services) for community hospitals and homes.

Hospital:

- Determine treatment process.
- Select appropriate medicine for the disease.
- Prepare medical service for homes.
- Distribute medical resources to community hospitals.

Factors:

- Available logistic ability to dispatch resources (including daily life resources and medical resources) for homes.
- Existing medical resources (including doctors and facilities) of community hospitals.
- Available remote medical diagnosis and advice.

Analysis:

Advantages:

- It can avoid cross-infection in central hospitals during outbreak of pandemic.
- It can isolate infection within homes.

Disadvantage:

- It can lead to infection between family members, especially for small homes.
- Patients lack medical support at home, especially for critical patients.

Influence:

- On social relation: Infection will be restricted to homes.
- On pandemic: Evolution of pandemic will focus on family relations.
- On mental health: Living with family members helps mental health of patients if strict protection can be adopted by family members.

Instance:

- During outbreak of COVID-19 in China, other cities including big cities with population over 21 million such as Beijing and Shanghai adopt this strategy. Until 16/20/2020, their death rates were 1% and 0.3% respectively, which were much lower than that of Wuhan (3.1%). The lower death rate partially lies in the small number of critical patients, relatively richer medical resources in central hospitals and precaution measures.
- WHO announced a series of technical guidance for dealing with COVID-19 (2019-nCoV), including risk communications, infection prevention and control, and home care for suspected patients (on 20/01/2020). CDC of USA also announced a guidance on 26/01/2020.
- *Link to more instances*.

Reducing interactions between people is an essential way to control the spread of an infectious virus, especially when there is no effective medicine to conquer the virus. Different strategies and policies influence behaviours of nodes differently, which further influence the links between nodes.

Strategies should be adopted according to the strategies of the development of the pandemic. At the early stage of pandemic when the number of patients is small, it would be better to advise patients to go to hospital with better medical facilities and experts so that the disease can be treated, studied and controlled quickly. At the middle stage of the development of the disease when patients increase rapidly, it would be better to advise the critical patients to go to hospital for professional treatment in hospital while other patients could be treated at home to avoid cross-infection if home is big enough (otherwise, they should be treated in hospital if capacity of hospital is enough or can be extended to meet the need). At the final stage when patients decrease, patients should be checked up in hospitals to ensure that they are really recovered.

Strategy 3. *Isolation* (lockdown)

Event: It is the same as strategy 1.
Knowledge: It is the same as strategy 1.
Action:

CDC: It is the same as strategy 1.

Government:

- Announce the disease according to the law (link to law space).
- Stop operation of all transportations.
- Advise people with symptoms to self-isolate at home and arrange critical patients to go to hospitals for medical check-up and isolation.
- Announce regulation to isolate infected patients at home.
- Plan logistic for community hospitals and homes.

Hospital:

- Determine treatments.
- Select appropriate medicines for the disease.

- Prepare medical service for homes.
- Distribute medical resources to community hospitals.

Factors:

- Logistic ability to dispatch resources (including daily life resources and medical resources) to homes.
- Medical resources (including doctors, nurses and facilities) of community hospitals.
- Availability of remote medical diagnosis and advice.

Analysis:

Advantages:

Different extents of isolation can be adopted according to the pandemic situation. Total isolation refers to the isolation of the communities of all granularities, including city, district, street, building, house and home.

- It can prevent pandemic propagation from one community (e.g. city) to other communities (e.g. cities) when lockdown carries out at the early stage of pandemic.
- It can restrict pandemic within the whole society if other communities can also be isolated and the lockdown period is longer than the maximum latent period. For an unknown pandemic, the maximum latent period is known when pandemic develops. So a full isolation can restrict the infected person without symptom and with a long latent period within home.

Disadvantages:

- It damages economy of society (e.g. city or country).
- It damages industry, especially SMEs (Small and Middle Enterprises, especially for hotels, restaurants and pubs) and industrial ecology.
- It influences social relations between people and the way of communication.

Influence:

- *Social dimension*: Infection will be restricted to community. Social relations tend to develop toward decentralized and loosely coupled patterns because theatres, cinemas, restaurants and pubs will be closed. The way of communication and lifestyle need innovation. The structures of workspace and home need to consider a safe social distance (2 m), e.g. personalized space, larger dining table and ventilation.
- *Cyber dimension*: It moves socioeconomic activities to online. Therefore, the development of e-commerce, e-government, e-learning, e-science, robots and automatic intelligent manufacturing will be accelerated. It also provides new requirements for designing and implementing smart cities that can meet new challenges especially the outbreak of new pandemic.
- *Pandemic dimension*: The pandemic network will be dispersed into communities of different granularities. Protecting family members from infecting each other is the key to the success of adopting lockdown strategy.
- *Psychological dimension*:
    - People will feel lonely and anxiety.

    - Family issues will increase (it was reported that divorce rate increased in some countries).
    - Risk of family members will increase, especially for those people who live in small homes.
    - People will be afraid of face-to-face communication.
    - Residents may choose to leave the city to be isolated.
- *Optimization*: Scheduling medical resources and living resources challenges the operation of the city when economic activities stop.
- *Daily life*: Daily life will be transformed into more personalized style. Social media will be innovated to provide more advanced functions to support communication.

Instances:

- *Strategy of isolation*: The Wuhan city was isolated by stopping all transportations to the external world on 23/01/2020 and then stopped internal public transportation, and finally all business activities were closed. On 10/02/2020, all resident districts were closed and patients were only allowed to go to hospitals within the same district.
- *Subsequent strategy*. During the development of the pandemic, the central government of China sent doctors of other cities to Wuhan city to support the newly built hospitals. The advantage is that the capacities and facilities of hospitals can be enhanced according to the changing situation but this needs efficiently forming the capability of a medical team including facilities and logistics.
- *Fatality Rate*. In general, different diseases have different fatality rate: flu is about 0.1%, SARS is about 9.04% (WHO) and COVID-19 is about 2-4%. For the same disease, different strategies influence the fatality rate differently. The effect of initial lockdown strategy in China is that the death rate of Wuhan is much higher than other cities. From the first patient was identified on 08/12/2019 to 04/02/2020, the infected number is 6384 and dead number is 313, i.e. the fatal rate is 4.9%. In contrast, Beijing: 0.44%; Shanghai: 0.46%; Tianjin: 0; Guangdong: 0 and Zhejiang: 0. When lockdown was lifted in China on 07/04/2020, the fatal rate of Wuhan is 5.1%, in contrast, Beijing: 1.4%; Shanghai: 1.3%; Tianjing: 1.7%; and Guangdong: 0.52%. The big difference of fatal rates indicates that protecting hospitals from overwhelming is important to reducing fatal rate when adopting lockdown strategies. When it develops into a global pandemic, protecting NHS (National Health Services) became a prior strategy of the UK for dealing with COVID-19 pandemic.
- *Optional strategy*. Link to further comparison.
- *Historical experience*. During the outbreak of SARS, no city was totally lockdown, the total number of death is 774 in the world (different diseases have different death rates).
- *Surrounding environment*. Considering the pandemic in smaller cities surround Wuhan city such as cities Xiao Gan, Huang Guang and Sui Zhou, which has less medical resources, the lockdown strategy will block the

critical patients to see doctors in bigger hospitals in Wuhan, the capital city of Hubei province.

- Link to more instances.
- *Economy dimension*:
    - *Regional economy*: Wuhan city is an important industrial base of central China. Most industries produce parts for global industrious ecosystems of products. Optimization of supply chain requests minimized storage. This makes a fragile industrial ecosystem because once an enterprise stops production for one day the whole ecosystem will be influenced. Stopping production for a longer period of time (e.g. one month) may lead to reorganization of an industrial ecosystem, consequently some enterprises may be excluded. According to 2019's Government Report of Wuhan Municipal Government, the avenue of three supporting industries (optoelectronic information, automobile and parts, biomedicine and medical instruments) is 500 billion Yuan, the avenue of software and information technology is over 210 billion Yuan, and the avenue of finance and business is over 100 billion Yuan. A lockdown strategy will influence regional industries and influence global industrial ecosystem.
    - *Economy of country*.
        - *General activeness*. Compared to the previous year, transportation reduced to 20%, car sale reduced to 78.5%, electricity generation reduced to 60%, and employment requirement reduced to 65% until 11/02/2020. It is estimated that total consumption of country was reduced 1380 billion Yuan.
        - *Negative impact*. More than 30% of small and middle enterprises felt that their cash can only support their enterprises to survive for 1 month, and over 80% of them can only survive for 3 months.
        - *Positive impact*. Some enterprises such as manufacturers of medical resources and companies that provide online services will directly benefit from the pandemic. A serious pandemic forces people to adjust traditional style of life and proposes new requirements, which provides new business chances.
    - *Enterprise strategy*: Pandemic also provide time to adjust or promote enterprise strategies.
        - Reduce cost.
        - Predict new requirements.
        - Develop new product.
        - Practice new work model (ensure social distance between workers).
- *Recommendation*
    - Smallest-first, i.e. lockdown carries out from the smallest communities to larger communities with the development of pandemic. It has the following advantages:
        - Precisely isolate infected people or suspect people to reduce cross-infection in public space.

        - Minimize negative influence on daily life of healthy people. Most people are healthy at the early stage of pandemic. During the development of pandemic, people will reduce unnecessary interactions, which can effectively reduce transmission of disease.
        - Minimize negative influence on economy through the process of dealing with pandemic. At the same time, real-time pandemic information should be provided for public to take protection measures.
- *Evaluation*
    - *Summarization of analysis*. Lockdown takes effect at the initial stage on small communities such as families, resident area or organizations. Strict lockdown of a big city or a country will damage economy but it also gives time to thinking about the future form of society.
    - *Post-adoption evaluation*. The effect of adopting isolation can provide experience and evidence for making future strategies.

Strategy 4. *Dynamic precise isolation*.

Event: It is the same as strategy 1.
Knowledge: It is the same as strategy 1.
Action:
CDC: It is the same as strategy 1.
Government:

- Announce the disease according to the law on public health.
- Authorize the right to CDC so that it can obtain location and health information (including body temperature) of patients. Crowd sourcing strategy can be used to get information about patients.
- Reduce public events.
- Inform people of keeping social distance (2 m for COVID-19).

Hospital:

- Determine treatment.
- Select appropriate medicines for the disease.
- Prepare medical services for homes.
- Provide remote medical services.

Factors:

- Available remote medical diagnosis and advice.

Options:

- Isolate the infected persons and the suspected person through testing process.
- Isolate the infected persons and the directly contacted persons for observation.
- Isolate the infected persons, the directly contacted persons and the persons who directly contact the contacted persons. Assume an infected person has 3 contacted persons on average, Wuhan city needs to isolate 234,696 persons for 19,558 infected persons on 12/02/2020, this is clearly beyond

the capacity of hospitals within Wuhan city. So it is important to identify the direct close-contact person.

- Isolate the infected persons, the direct-contact persons and the persons who directly contact the direct-contact persons.

Analysis:

Advantages:

- Influence on socioeconomic activities can be reduced because healthy people can work with some protection measures.
- The death rate could be reduced according to the analysis on strategy 3.

Disadvantage:

- The infected number could increase due to the increased probability of interaction in vehicle and workplace but the probability can be reduced when protection measures are taken.

Influence:

- On social relation: Infection will be restricted onto individuals or small communities.
- On pandemic: Evolution of pandemic will focus on social relations between individuals.
- On psychology: It has little influence on patient's psychology.

Instances: Link to instances.

The following is an instance for representing legal provisions of China on pandemic.

Legal Provision: Category: Pandemic
Event: Outbreak of infectious disease of category A, B or C.
Knowledge:

- On virus: Category of existing virus.
- On law: Law of China on Preventing Infectious Disease.

Action:

Local Government:

- Report to and get approval from a higher level authority.
- Act after getting approval from the higher-level authority:
  - Limit market, theatre and public gathering activities or lockdown.
  - Lockdown social organizations including factories, stores and schools.
  - Isolate infected origins such as drinking water, food and relevant materials.
  - Control or kill infected animals.
  - Close infected area or the area that will lead to infection.

Higher-Level Government:

- Receive the report from the local government.
- Approve/reject the report from the local government.

Condition:

- Stage of pandemic.

Analysis:

Advantages: Decisions can be made prudently.

Disadvantages: It takes time to go through the process from report to approval.

Influence: Lockdown a big city will influence society from multiple dimensions: *pandemic*, *economy*, *psychology* and *daily life*.

Instance: The municipal government of Wuhan made the following regulations after several hours of official announcement of the outbreak of COVID-19:

- Warning: everybody must wear mask in public area on 22/01/2020.
- Stop operation of public transportations on 23/01/2020.

The outbreak of the second wave in EU and USA indicates that the strategies of China provide a valuable case for study. Incorporating strategy space and law space into the superstructure enables a Social Relation System to provide optional strategies and analyses for decision makers before making a decision and to interpret decision.

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