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RESEARCH ARTICLE

Manufacturing Security Strategies for Personal Protective Equipment in Response to the COVID-19 Crisis: A Regional Emergency Manufacturing Consortium Design Based on Government Regulation

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ABSTRACT The outbreak of COVID-19 poses a great threat to human life. In the early days of the COVID-19outbreak, lockdown, quarantine, movement restrictions and personal protection became the main preventive measures, which caused a surge in demand for personal protective equipment (PPE). The PPE supply chain was disrupted by COVID-19, which resulted in a shortage of upstream raw materials, a lack of midstream manufacturing capacity and excessive downstream demand fluctuations. The panic buying and shortage of PPE have thrown the community into panic. In this context, the rapid restoration or construction of PPE manufacturing supply chain has become the main strategy to solve the COVID-19 crisis. Therefore, it is imperative to quickly restore or build new manufacturing supply chains of epidemic prevention supplies. In view of this, this research first proposes taking administrative regions as the basic unit, focusing on the manufacturing of epidemic prevention supplies in the supply chain, and using the mixed-integer optimization method to select partners with the the objectives of shortest manufacturing time, the highest reliability and the greatest core competitiveness, and establish for the first time a government-led system model of a regional emergency manufacturing consortium for epidemic prevention supplies, aiming to increase the regional PPE supply assurance capacity. Finally, the validity of the proposed model is demonstrated through case studies. The widespread adoption of this system model will not only solve the current crisis of short-supply of epidemic prevention supplies, but also make an important contribution to the scientific decision-making of the government in the event of similar crises in the future, which is a concrete manifestation of the overall national security.

INDEX TERMS COVID-19, manufacturing supply chain, personal protective equipment (PPE), public health emergency, regional emergency manufacturing consortium.

I. INTRODUCTION

The pandemic scale and socio-economic impact of COVID-19 are unprecedented in the 21st century. From 31 December 2019 to 24 March 2020, the COVID-19 crisis was first found in Wuhan, China and then spread rapidly across the globe [1], [2]. In March 2020, the International Health Organization defined COVID-19 as a pandemic given the severity of its risk [3]. The widespread outbreak of COVID-19 increases the number of deaths and health risks

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worldwide and caused billions of dollars of losses [4], [5], [6], [7]. Lockdown, quarantines, movement restrictions and self-protection have become the main preventive measures to slow down the spread of the epidemic [8]. Proactive preventive measures can be effective in slowing the spread of epidemics, whereas the lack of preventive measures can lead to uncontrolled pandemics. China was successful in limiting the number of new daily cases of infection to less than 100 within three months after the outbreak, as shown in Figure 1, thanks to active measures such as lockdown, quarantine, movement restrictions and self-protection. However, the preventive measures have severely impacted the logistics industry, thus disrupting global supply chains and hindering the growth of manufacturing [9]. 94% of Fortune 1000 companies were reportedly affected, and a survey of 10,000 small businesses showed that 96% were severely impacted by the crisis [10], [11]. The disruption of the PPE supply chain is highly concerning and poses a great challenge to the anti-epidemic. Rowan and Laffey [12] argue that well-managed supply chains of medical equipment are the material security for healthcare workers to fight against coronavirus pandemic. PPE are used primarily for patients and healthcare workers and for individuals during an epidemic. Therefore, the timely supply of PPE has become the key to winning the anti-epidemic war. For the disrupted supply chain by a global public health emergency(PHE) like COVID-19, there are many questions to ponder: What is the future development of our supply chain? How can manufacturing capacity be protected from unexpected uncertainties? What is the PPE supply assurance mechanism? What measures can the government take to ensure the emergency production of PPE?

Human development itself is a history of anti-epidemic war, from the great plague in Athens, the black death in Europe, smallpox in America, to cholera, influenza, Ebola, SARS, H7N9, and today's COVID-19, each of which has taken a heavy toll on humanity [13], which shows the inevitability and unpredictability of epidemics. Verikios [14] correlated epidemiological and economic models to capture the spread of regional populations to regional economies and found that COVID-19 may continue for longer and have a more severe economic impact than previous outbreaks. Many researchers analyzed and predicted a second wave of COVID-19 culminating in an autumn-winter epidemic, which turned out not to be the case [15], [16], [17]. As the virus mutated, triggering a new public health crisis, a wave of new daily cases worldwide culminated in January 2022 [2]. As seen in Figure 1, China saw a second wave of infections culminating in March 2022. The cumulative number of new cases worldwide reached 513 million and more than 6.26 million deaths as of April 30, 2022.

In response to the surge of PPE caused by the COVID-19 crisis, researchers have proposed many solutions including supply chain, manufacturing, and governmental perspectives. Regarding the supply chain perspective, it is generally agreed that the impact of uncertainties can be tackled by increasing the agility and resilience of the supply chain [18], [19], [20],

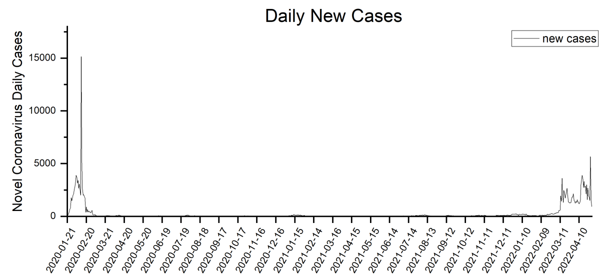


FIGURE 1. Daily new cases in china. (Data source: National health commission of the PRC, As of April 30, 2022.)

[21]. CAI Min [18] proposed to enhance the resilience of supply chain to help companies recover and cope with the current crisis based on the sustainability of the existing supply chain. Ivanov [22] analyzed and evaluated the survivability of supply chain in three dimensions: agility, resilience and sustainability, and proposed the concept of viable supply chain, aiming to help companies to recover and rebuild their supply chains during the COVID-19 crisis. In manufacturing perspective, the promotion and application of advanced manufacturing technologies such as cloud manufacturing, big data, and Internet of Things can reduce the impact of sudden supply chain disruptions [23], [24], [25]. Paul [23] considers a three-tier manufacturing supply chain recovery approach consisting of a single supplier, manufacturer and retailer in case of the uncertainties of demand fluctuations, manufacturing disruptions and raw material supply disruptions. Qi [25] suggests that new technologies can help companies quickly resume business operations. In the anti-epidemics war, the government plays an important role in the promulgation and implementation of policies, the deployment of social resources, the organisation and rescue of crises, and the pacification of people's emotions. The establishment of an epidemic prevention system involving the national government, local governments, regional cooperation and other organisations is conducive to improving the efficiency of emergency response plans [26], [27], [28]. The Chinese government has taken measures such as lockdown, quarantine, movement restrictions and self-protection to slowdown the spread of the epidemic, and has helped enterprises to resume work and production quickly with measures such as bank loan reductions, state tax exemptions, provision of subsidies, and conversion of enterprises to production [8]. Abolfotouh [26] studied public attitudes and behavioural responses to the COVID-19 disease pandemic in Saudi Arabia during an action limitation period, and found through a survey that government behaviour was the most critical measure in response to the COVID-19 crisis. Hale [28] collected information from over 180 national governments in response to the COVID-19 crisis, which provides a reference for both researchers and government decision making.

Global supply chains are an important pillar of economic globalisation, and China manufacturing has become an important part of the global supply chain [29]. Global supply chains also have many management risks, which have been exposed in the epidemic [30], [31]. Clinton Free [32] discussed the potential drivers of supply chain vulnerability exposed by COVID-19 and considered the potential future direction of global supply. China has played a very important role in global supply chains, however, many companies dependent on China have suffered severe losses in the wake of the COVID-19, which has led them to rethink the reconfiguration of global supply chains [33], [34], [35]. Lin and Lanng [34] stated that global firms will diversify their supply chains in the future, instead of relying only on China. COVID-19 has accelerated the trend of US companies looking to realign supply chains closer to home in countries such as Mexico, while also diversifying them to reduce future exposure risk by relocating to ASEAN states like Vietnam, Indonesia, Thailand and Malaysia [35]. It is necessary to relocate the supply chain upstream to domestic markets for some essential and medical supplies to reduce the risk of supply chain disruptions caused by epidemics similar to COVID-19 [19]. Multinational companies will reconsider building production bases and supply networks in end markets and adopt a sensible strategy of regionalising parts of their supply chains, which is the new normal in the post-epidemic era [18]. Experience from the post COVID-19 outbreak has demonstrated that the resilience production capacity of PPE is extremely low in the absence of advance planning, making it challenging to guarantee the PPE needed under emergency situations. The previous studies have proposed solutions at a macro level, while less research has been done on how to quickly restore or build new PPE production capacity. Hence, this research proposes taking the administrative region as the basic manufacturing supply chain unit and establish a government-led PPE mass production manufacturing consortium to form a complete, safe and reliable regional PPE manufacturing supply chain, which can not only solve the current COVID-19 crisis, but also make an important contribution to assist the government in scientific decision-making in the event of similar crises in the future, and is a concrete manifestation of the overall national security.

The organisation of this study is as follows: Section I is an introduction, which describes the impact of the COVID-19 outbreak on the global economy and lives, and the responses. Section II presents the theoretical study and construction of the model, focusing on the theoretical basis of building a regional emergency manufacturing consortium(REMC). Section III presents the functional design and structural equation modelling of the REMC system. Section IV is a case application and Section V is a conclusion and outlook.

II. THEORETICAL RESEARCH AND CONSTRUCTION OF REMC MODEL

The REMC is a manufacturing model in the context of PHE and the disruption of global supply chains, and is organised by government departments for the purpose of organising regional resources to produce PPE without profit.

A. BUILDING PROCESS OF REMC

The REMC is a government-led effort to mobilise all available resources, such as enterprises and universities, to establish a manufacturing defence to meet the demand for PPE in response to PHE. As shown in Figure 2, the government plays a leading role in the REMC establishment process, which is a responsibility the government must undertake in emergency context. The building process of REMC are shown below.

Step 1: In the wake of an outbreak, when the manufacturing supply chain is disrupted, a surge in demand for PPE causes a severe short-supply and a shortage of manufacturing capacity, the government must take the initiative to summon specialists to discuss response strategies.

Step 2: According to the response plan, conduct sample research and telephone consultation with relevant enterprises within the jurisdiction and collect data.

Step 3: Analysis of the collected data. According to a pre-drafted evaluation index scheme, the focus is on analysing the core competitiveness of the enterprises, their cooperation with upstream and downstream enterprises, social reputation, etc. The candidate enterprises are classified and ranked by each tier of the manufacturing supply chain, and the candidate enterprises are combined to make a decision on the optimal combination according to the objectives pursued (e.g. shortest time, greatest reliability, strongest overall competitiveness).

Step 4: In order to coordinate the distribution of PPE to where it is most needed, the government needs to reach an agreement with the manufacturing consortium to acquire the product, i.e. the majority of the PPE produced goes to the government for distribution.

B. ENTERPRISE CORE COMPETENCE EVALUATION

Before the establishment of an REMC, it is necessary to first research the manufacturing resources in the region, including the types of enterprises, the number of enterprises, their core competencies and operational status.

1) CONSTRUCTION OF ENTERPRISE SAMPLING MODEL

In order to accurately and quickly select the research enterprises, the enterprises that meet the requirements can be selected from the business registration information as the initial overall sample. Different probabilities can be set through comprehensive factor evaluation due to the differences in scale, registered capital and geographical location. Nonprobability sampling and full sample unequal probability sampling are used to select research enterprises from the initial overall sample [36], which is implemented as follows.

Let the initial overall sample N be sorted to generate a new overall sample $\overline{N}$ with priority, and set the sampling probability of individuals in $\overline{N}$ as $\Phi_i = \frac{N-i+1}{M}$, $(i = 1, 2, \ldots, N)$, where $M = \frac{(N+1)N}{2}$, and an integer $\overline{M} = \lambda M$, $(\lambda \in N^+)$ can always be found, so that each $M_i = \Phi_i \overline{M}$ is an integer. The individual i is given M_i codes, and M_i is accumulated. Each sampling generates a random number within the $1 \sim \overline{M}$ range, and takes the corresponding individual as the selected

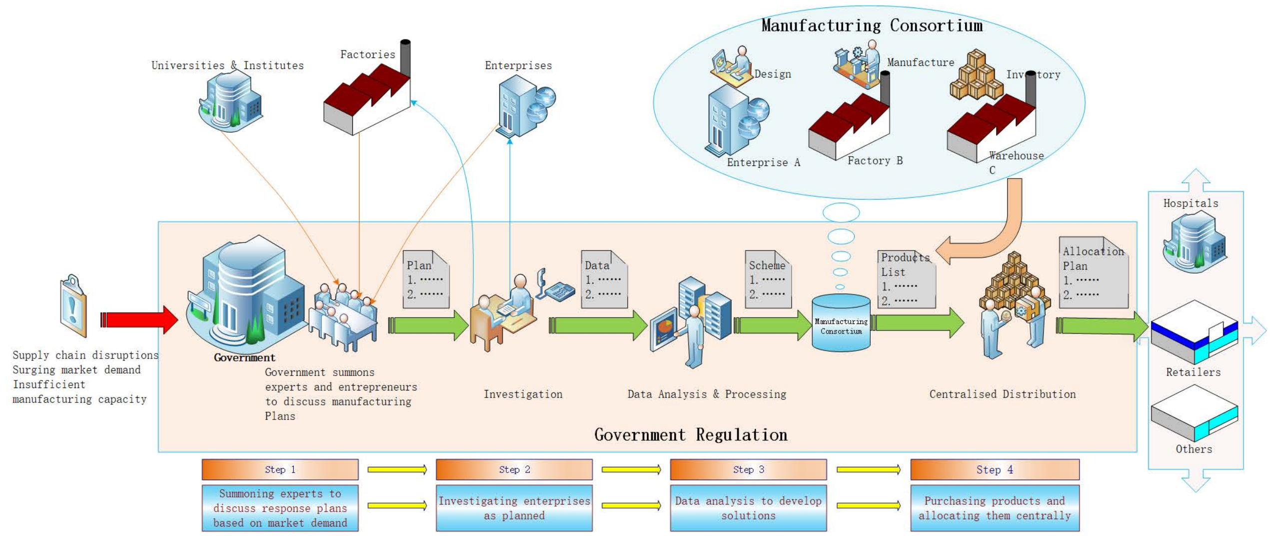


FIGURE 2. **Building process of REMC.**

sample, and repeats this process until the required number of n samples is obtained. λ should be larger to differentiate the individual probability.

2) CONSTRUCTION OF ENTERPRISE SPECIFIC CORE COMPETENCE(ESCC) MODEL

As the social division of labour continues to deepen and refine, more and more value-added links in the value chain are being created, and some enterprises are beginning to concentrate on their core business and gradually outsource their non-core business. Therefore, it seems rough to use the comprehensive competitiveness to represent the enterprise's capabilities. This article proposes using the enterprise dimension(ED) to detail the enterprise's comprehensive competitiveness as special core competitiveness so as to more clearly express the capability of the enterprise in each node of the supply chain.

Definition 1: ED are proposed based on the main processes of the research object (product) including design, production, logistics, testing and identification, sales and after-sales service involved in the whole product life cycle. The ED value indicates the strength of the ESCC in the form of a vector $ED = (a_1, a_2, \ldots, a_m)$, as shown in Figure 3. The ED value is obtained by normalising several indicators after a comprehensive evaluation. The larger the ED value, the stronger the ESCC, and vice versa.

3) ESTABLISHMENT OF AN EVALUATION INDEX SYSTEM FOR ED VALUES

Unlike the conventional enterprise competitiveness evaluation index system, the low rate of labour force resumption during the outbreak, especially for some enterprises with many migrant workers, has a significant impact on enterprise competitiveness [37]. Therefore, the labour force resumption rate is an essential indicator impacting the ESCC under the government mandated lockdowns and stay-at-home

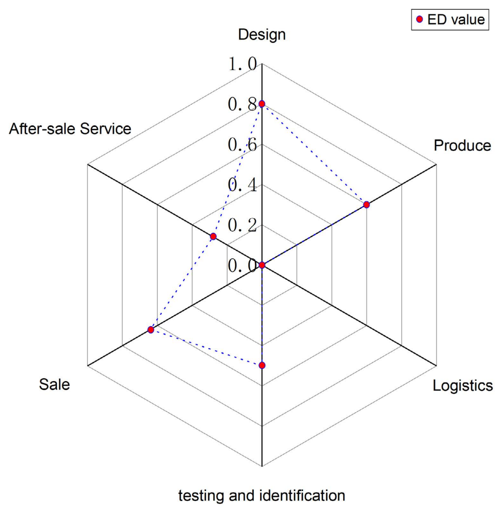


FIGURE 3. **ED value.**

restrictions. Ren [38] summarised the main indicators for evaluating a company's core competencies by extensive research and categorised the 32 criteria as Integration, Competence, Team building, Technology, Quality, Change, Partnership, Market, Education, and Welfare. Taking the R&D capability and production capacity of enterprises as an example, the evaluation index system was established after full consultation with experts and entrepreneurs, as shown in Table 1 [24], [37]. Typical multi-criteria decision-making methods include multi-objective planning methods such as classification, weighted point method, matrix method and objective programming [38]. Here, we propose using a combination of grey theory and the weighted point method to calculate ED values [39].

According to Table 1 and appropriate weights, the R&D capacity and production capacity of enterprises are expressed as follows:

$$\begin{cases} a_1 = \sum_{i=1}^{9} w_i \cdot k_i \cdot e_1^i, & k_{i=1,2} = k, \quad k_{i\neq1,2} = 1 \\ a_2 = \sum_{j=1}^{10} w_j \cdot k_j \cdot e_2^j, & k_{j=1,2} = k, \quad k_{j\neq1,2} = 1 \end{cases} \quad (1)$$

where w_i and w_j are the weights of the secondary target of R&D capability and production capacity respectively; k_i and k_j are the revision of the secondary target of R&D capability and product production capacity by the reliability level of labour resumption, when $k_i, k_j = 1$, the reliability level of labour resumption does not affect the secondary target.

e_1^i and e_2^j are the secondary target values of R&D capability and production capacity, respectively. They need to be normalised to eliminate the influence of different dimensions [40].

Therefore, an enterprise with m ESCC can be expressed as follows:

$$\begin{aligned} ED &= (a_1, a_2, \ldots, a_m) \\ &= (\sum_{j=1}^{n_1} w_1^j k_1^j e_1^j, \sum_{j=1}^{n_2} w_2^j k_2^j e_2^j, \ldots, \sum_{j=1}^{n_m} w_m^j k_m^j e_m^j) \end{aligned} \quad (2)$$

where $n_i \in (1, 2, \ldots, m)$ is the number of secondary targets of the core competitiveness of item i;

w_i^j and e_i^j are the weight of the j^{th} secondary target of the i^{th} ESCC and the normalised index value;

k_i^j are the correction coefficients of the reliability level of labour resumption.

C. REMC MEMBER SELECTION

Generally, in order to capture new market opportunities and reduce cost and risk, enterprises often choose to collaborate with other enterprises [39]. Cooperation between enterprises can enhance their competitiveness [38]. In selecting partners, many researchers mainly examine enterprise competence indicators, whereas ignoring the implicit factors that affect the overall effectiveness of the chain, such as the possibility of smooth cooperation between enterprises and the probability of successful cooperation with new partners [41], [42]. Therefore, the selection of REMC members should take full account of both the ESCC and the synergy efficiency among consortium members.

Definition 2: Given that the industrial chain length (i.e. ED) of PPE is m and the number of candidate enterprises participating in the industrial chain within the region is n. Let a_j^i represent the j^{th} specific core competitiveness index of enterprise i, so the dimension index of all participating enterprises in the industrial chain can be expressed as follows:

$$\begin{aligned} A^{n\times m} &= \{a_j^i, i = 1, 2, \ldots, n; j = 1, 2, \ldots, m\} \\ &= \begin{pmatrix} a_1^1 & a_2^1 & \cdots & a_m^1 \\ a_1^2 & a_2^2 & \cdots & a_m^2 \\ \vdots & \vdots & \ddots & \vdots \\ a_1^n & a_2^n & \cdots & a_m^n \end{pmatrix} \end{aligned} \quad (3)$$

Definition 3: Let r_{ij} be the smooth cooperation rate value(SCRV) between candidate enterprises in the manufacturing supply chain and R_{ij} be the set of SCRV, we then have

$$\begin{aligned} R_{ij} &= \{r_{ij}, i, j = 1, 2, \ldots, n\} \\ &= \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{pmatrix} \end{aligned} \quad (4)$$

where: $r_{ij} = r_{ji}, r_{ij}|_{i=j} = 1$.

As a quantitative indicator of the smoothness of cooperation between different enterprises, the SCRV is mainly reflected in the similarity of professional background, cooperation frequency, cooperation experience, cultural concept and management styles. Generally, the SCRV between the same company is greater than that between different companies. The higher the SCRV, the smoother the cooperation and the more reliable the completion of tasks. By the evaluation indexes in Table 2, the SCRV can be calculated by

$$r = \sum_{h\geq1} w_h \cdot b_h \quad (5)$$

D. SYSTEM PERFORMANCE EVALUATION

The PPE production problem in emergency context is a multi-objective problem, such as seeking the shortest production cycle time, acceptable product quality, a robust and reliable supply chain, and the capability for mass production. R.T. Marler [43] reviewed current concepts and methods for continuous nonlinear multi-objective optimisation and classified these methods into three categories: methods with a priori preference expressions, methods with a posteriori preference expressions and methods without preference expressions. He concludes that no single method is superior to the others and that the choice of a particular method depends on the information types, user preferences, solution requirements and the availability of the software provided by the problem. Here we focus on how to quickly make decisions on an REMC that performs well in production cycle time, manufacturing supply chain reliability and integrated competitiveness under emergency context, namely to build a manufacturing supply chain with the best system performance. For the sake of understanding, we combine Definition 2 and Definition 3 and use Figure 4 as an example for our later analysis.

Figure 4 illustrates the capability values of the candidate enterprises at each node of the supply chain. Where E_i denotes the i^{th} enterprise, t_i^j, a_i^j denote the time needed for enterprise E_i to complete the task assigned at node j in the supply chain and the specific core competency, respectively, $i \in \{1, 2, \ldots, n\}$and $j \in \{1, 2, \ldots, m\}$.

In general, the time to complete a task is expected to be a discrete random distribution function for members [44]. Let all values of discrete random variable T be $\{t_1, t_2, \ldots, t_n, \ldots\}$ and the probability of the event $\{T = t_i\}$ be $P\{T = t_i\} = p_i$,

TABLE 1. Evaluation index system of enterprise R&D capability and production capacity.

Primary target	Secondary target	Content details
R&D capacity a_1	R&D team $k_1 \cdot e_1^1$	The number of R&D personnel
	Product R&D cycle $k_2 \cdot e_1^2$	The time required for a successful product development/day
	Proportion of R&D personnel $k_3 \cdot e_1^3$	Number of R&D personnel/total number of technicians
	Proportion of professional titles of R&D personnel $k_4 \cdot e_1^4$	Proportion of personnel with technician or other intermediate title or above
	Personnel working experience $k_5 \cdot e_1^5$	Average years of R&D work
	Continuous learning ability $k_6 \cdot e_1^6$	Annual per capital cost of employees' relearning
	Proportion of R&D funds $k_7 \cdot e_1^7$	R&D capital investment/total enterprise income
	Annual average number of patents $k_8 \cdot e_1^8$	Average annual number of patents in recent 3 years
	Industry recognition $k_9 \cdot e_1^9$	Influence of enterprises in the industry
Production capacity a_2	Production cycle $k_1 \cdot e_2^1$	Time to complete a batch or a mould prototype/day
	Production team $k_2 \cdot e_2^2$	Number of production personnel
	Product quality reliability $k_3 \cdot e_2^3$	Product qualification rate
	Proportion of valuable production assets $k_4 \cdot e_2^4$	valuable equipment asset amount/total production equipment amount
	Current stock of raw materials $k_5 \cdot e_2^5$	Quantity of raw materials currently in stock
	Raw material replenishment capability $k_6 \cdot e_2^6$	Quantity of raw materials arriving per day
	Personnel working experience $k_7 \cdot e_2^7$	Average years engaged in production
	Continuous learning ability $k_8 \cdot e_2^8$	Annual per capital cost of employee relearning
	On time delivery rate $k_9 \cdot e_2^9$	Number of on time deliveries/total deliveries in the past year
	Production automation level $k_{10} \cdot e_2^{10}$	Fully automatic, semiautomatic, pure manual
Reliability level of labour force resumption: k = number of employees available to resume work/total number of employees		

TABLE 2. Evaluation index of SCRV.

Primary target	Weight	Secondary target	Content details
SCRV r	w_1	Annual cooperation frequency b_1	Annual average number of cooperation
	w_2	Cooperation success rate b_2	Annual average number of successful cooperation/annual average number of cooperation
	w_3	Distance b_3	The distance between enterprises can be divided into 0, 50, 100 and 200 km in accordance with grade
	w_4	Information sharing degree b_4	Degree of data information sharing between two enterprises
	w_5	Cooperation time b_5	The cooperation years between two enterprises
	…	…	…

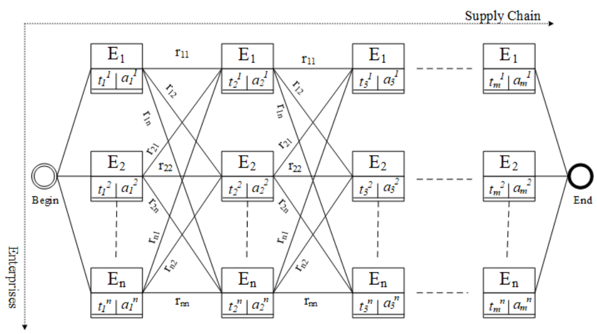


FIGURE 4. Diagram of the manufacturing consortium combination.

then the binary sequence table $\{(t_i, p_i) : i = 1, 2, \ldots\}$ reaches the probability law of T value, which is called the distribution column of T and meets the following conditions.

(1) $p_i \geq 0, i = 1, 2, \ldots;$

(2) $\sum_{i\geq 1} p_i = 1$. Its distribution function is

$$F(t) = P\{T \leq t\} = \sum_{t_i \leq t} p_i. \qquad (6)$$

1) SYSTEM PRODUCTION CYCLE

The system production cycle here refers to the total time by the REMC to complete a specified number of products. Under emergency context, finding a manufacturing supply chain that completes the task in the shortest possible time is the desired objective, which is a shortest-circuit problem [45]. For a linear industrial chain with m nodes and each node having a single enterprise, let a set of independent random variables $(T_1, T_2, \ldots, T_m)$ be the task completion time of each node in the chain, then we have $T_j = \{t_j^i, i = 1, 2, \ldots, n; j = 1, 2, \ldots, m\}$, Let $t_{j\_min}^i, t_{j\_max}^i$ be respectively the minimum and maximum time for enterprise E_i in completing the task at node j, namely $t_j^i \in [t_{j\_min}^i, t_{j\_max}^i]$. Let the system production cycle be S_m, the objective function of the system production cycle is

$$Min \quad S_m = \sum_{j=1}^{m} T_j = \sum_{j=1}^{m} t_j^i, \quad \forall i \in \{1, 2, \ldots, n\}. \qquad (7)$$

2) SYSTEM RELIABILITY MODEL

System reliability is mainly used to describe the total capacity of the system to complete its specified functions. Tillman F A [46] described certain models of system reliability, and the indicators and terms used in each model are different. Reliability is used to measure the probability of an enterprise or the REMC to complete a specific task under specific conditions and within a specified time. Its symbol is expressed as ζ.

According to (6) and its definition, let all the values taken by t_j^i be $\{t_{j\_1}^i, t_{j\_2}^i, \ldots, t_{j\_n}^i, \ldots\}$, let the probability of event $T_j = t_{j\_l}^i$ be $P\{T_j = t_{j\_l}^i\} = p_{j\_l}^i, l = 1, 2, \ldots,$ then the reliability of member E_i in completing task j within a specified time $t_{j\_set}^i$ can be expressed as

$$\zeta_j^i = P\{T_j \leq t_{j\_set}^i\} = \sum_{t_j \leq t_{j\_set}^i} p_{j\_l}^i. \qquad (8)$$

The probability mass function of the time to complete the total task of the system is the convolution of the probability mass function of the time to complete the subtasks of each member [47], therefore we have

$$P(S_m = s_m) = \sum_{k_j \in \bigcup_{i=1}^{n} t_j^i} P(T_1 = k_1) \times P(T_2 = k_2) \times \dots \times P(T_{m-1} = k_{m-1}) \times P(T_m = s_m - \sum_{j=1}^{m-1} k_j) = \sum_{k_j \in \bigcup_{i=1}^{n} t_j^i} \prod_{j=1}^{m} p_{j\_l}^i. \tag{9}$$

Its distribution function is

$$G(t) = P\{S_m \leq t\} = \sum_{s_{m_i} \leq t} P(S_m = s_{m_i}). \tag{10}$$

Therefore, the reliability of the system to complete the task within the specified time t_{s_set} can be expressed as

$$\zeta_s = P\{S_m \leq t_{s\_set}\} = \sum_{s_{m_i} \leq t_{s\_set}} P(S_m = s_{m_i}) = \sum_{s_{m_i} \leq t_{s\_set}} \sum_{k_j \in \bigcup_{i=1}^{n} t_j^i} \prod_{j=1}^{m} p_{j\_l}^i. \tag{11}$$

3) COMPETIVENESS OF REMC

The selection of members in the REMC requires not only a strong ESCC but also the collaborative ability with upstream and downstream enterprises, to ensure the completion of tasks with reliability and coherence.

The REMC competitiveness η is the comprehensive effectiveness of the ESCC and SCRV. According to definitions 2 and 3, η is equivalent to choosing a product process-based chain from $G = (A, R)$. Combined with the incomplete compensatory character of the weighted product, the competitiveness of the REMC can be expressed as [48]

$$\eta = a_1^{i_1} \cdot r_{i_1 i_2} \cdot a_2^{i_2} \cdot r_{i_2 i_3} \cdot a_3^{i_3} \cdot \dots \cdot a_{m-1}^{i_{m-1}} \cdot r_{i_{m-1} i_m} \cdot a_m^{i_m}, \tag{12}$$

where $i_1, i_2, \dots, i_m \in \{1, 2, \dots, n\}$.

Then the mathematical model for solving the optimal linear REMC competitiveness is

$$\max \eta = a_1^{i_1} \prod_{j=2}^{m} r_{i_{j-1} i_j} \cdot a_j^{i_j}, \tag{13}$$

where $i_1, i_2, \dots, i_m \in \{1, 2, \dots, n\}$.

III. FUNCTIONAL DESIGN AND STRUCTURAL EQUATION MODELLING OF REMC SYSTEM

In the face of PHE, a government-led emergency collaborative governance system is formed with timely enacting relevant policies, mobilising social forces, organising rescue, publishing news and calming people's emotions [26]. In terms of PPE security, the government should investigate the manufacturing resources, human resources, medical resources and public basic health facilities within the jurisdiction in advance and build a regional emergency manufacturing resource platform, including enterprises, medical system, public basic health system, scientific research institutions and other organisations using information technologies, such as big data, cloud manufacturing and Internet of Things, optimise the layout of the PPE supply chain, and form a complete, safe and reliable regional PPE manufacturing supply chain system to create a country-wide industry chain reserve base.

A. FUNCTIONAL DESIGN OF REMC SYSTEM

The REMC system is also a government-centred emergency management system that aims to provide scientific support for decision-making (Figure 5). According to the government's practical responsibilities in responding to PHE, the management system mainly includes the manufacturing resource classification, businesses functions, PPE regional industry chain construction and government functions.

Manufacturing resources classification: The government collects information from enterprises that have a certain scale in its jurisdiction on the basis of research, and classifies them into categories according to their main business scopes, such as design, production, logistics, inspection and testing, sales, storage type, etc.

Business functions: Business functions are the core part of this management system, mainly including enterprise capacity evaluation, industrial chain construction, information management and information sharing platform. The enterprises in the resource base are quantitatively evaluated through a certain evaluation system, and an industrial chain that meets the requirements is decided according to the industrial chain construction objectives and the optimisation algorithms that have been designed. Regular maintenance and data updates can ensure the authenticity of the information. Setting certain entry standards and dynamic assessment mechanisms can guarantee the competitiveness of the enterprises listed in the database. The information-sharing platform can drive the intensive use of various production resources.

Regional industry chain construction of PPE: The management system is currently oriented towards the supply chain construction of PPE, which can also be expanded in the future to include a range of products. There should be a complete and safe and reliable regional manufacturing supply chain for all PPE within the management system, i.e. when an PPE product is selected, the system automatically shows the relevant enterprises and the optimal supply chain combination solution can also be calculated upon request.

Government functions: This refers to the functions often involved in the application of the management system by the government in response to PHE, such as coordinating production, financial support, expert group formation, providing

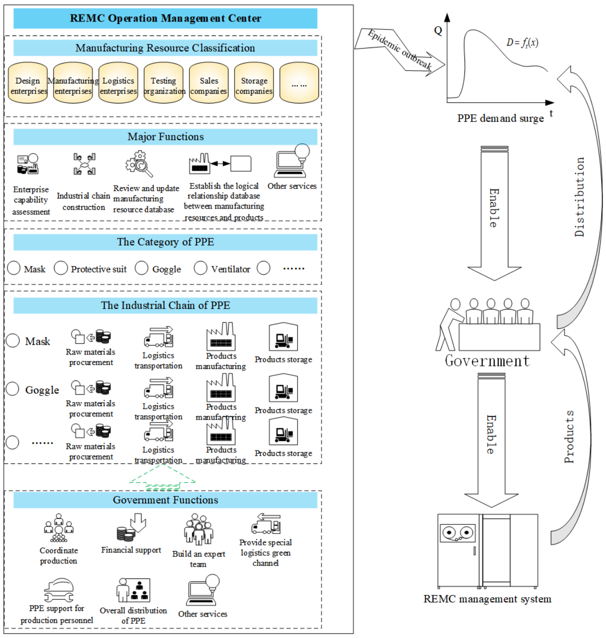


FIGURE 5. **REMC management system and key processes based on government regulation.**

green logistics channel, PPE co-ordination and distribution, and information publishing [26], [27], [28].

The sudden outbreak of PHE will cause abrupt changes in the PPE demand market, thus prompting the government to activate the management system for rational decision-making. In order to guarantee that PPE is allocated where it is most needed, the government needs to acquire a certain percentage of the products for integrated distribution to maintain a stable and harmonious social situation, as shown in Figure 5.

B. STRUCTURAL EQUATION MODELLING OF REMC SYSTEM

The REMC system is designed to rapidly integrate manufacturing resources in the region in case of a surge in demand for PPE caused by a PHE and a disruption to the existing PPE supply chain, to make a decision on the REMC solution that has the greatest system performance and to restore or create new production capacity in the PPE manufacturing supply chain so that market-demanded quantities of products or specified quantities of products can be produced in the shortest possible time. Therefore, a structural equation model for maximising the effectiveness of the REMC system is first developed with the optimisation objectives of time for task completion, reliability of task completion and system competitiveness.

1) MODELING ASSUMPTIONS

Considering the complexity of the model, the following assumptions are made.

(1) A given production volume is the target for the task, given the difficulty in predicting the market demand for the product.

(2) The time to complete the task at the supply chain nodes obtained from the research is authentic.

(3) The time or capacity to complete the task follows a certain random distribution.

(4) The cost of production is not taken into account and may be subsidised by the government.

(5) The logistics between supply chain nodes are not considered, and special passages are provided by the government.

The following symbols are introduced for narrative purposes.

(1) Superscript and subscript

I denotes the set of the number of enterprises in the system, $i \in I$;

J denotes the set of manufacturing supply chain nodes, $j \in J$;

i_j denotes the set of i's at node j, $i_j \in I$;

m denotes the number of enterprises in the system;

n denotes the number of manufacturing supply chain nodes.

(2) Parameters

Q denotes the total amount of product demand (pieces);

S_m denotes the actual total time to complete all tasks, S_{m_min} denotes the theoretical minimum time to complete all tasks, and S_{m_set} denotes the upper bound time to complete all tasks.

ζ_s denotes the reliability of the system in completing tasks, ζ_{s_set} denotes the lower bound reliability of the system in completing tasks.

η denotes the core competency of the REMC system.

t_j^i denotes the time for enterprise E_i to complete the task at node j of the supply chain, $t_j^i \in \{t_{j\_1}^i, t_{j\_2}^i, \ldots, t_{j\_n}^i, \ldots\}$.

$t_{j\_min}^i$, $t_{j\_max}^i$ denotes the minimum and maximum values of t_j^i, respectively, therefore, $t_j^i \in \{t_{j\_min}^i, t_{j\_max}^i\}$.

$p_{j\_l}^i$ denotes the probability of the event $\{T_j = t_{j\_l}^i\}$.

a_j^i denotes the ESCC value of enterprise E_i at node j.

q_j^idenotes the productivity of enterprise E_i at node j.

$r_{i_{j-1}i_j}$ denotes the SCRV between the enterprise $E_{i_{j-1}}$ at node $j-1$ of the manufacturing supply chain and the enterprise E_{i_j} at the immediately following node j.

w_1, w_2, w_3 denote the weights of each sub-objective.

(3) Decision variables

$x_j^{i_j}$ is a 0-1 variable indicating whether the task at node j is performed by enterprise E_i;

u_j is a 0-1 variable indicating whether the task at node j produces products.

2) MODEL BUILDING

$$
\begin{aligned}
Max\,\mathcal{Z} &= \left(\frac{1}{t}, \zeta_s, \eta\right) \\
&= w_1 \frac{S_{m\_min}}{S_m} + w_2 \zeta_s + w_3 \eta \\
&= w_1 \frac{\min \sum_{j=1}^{m} t_{j\_min}^i}{\sum_{j=1}^{m} t_j^i} x_j^{i_j}
\end{aligned}
$$

$$+ w_2 \sum_{s_{m_i} \leq t_{s\_set}} \sum_{k_j \in \bigcup_{i=1}^{n} t_j^i} \prod_{j=1}^{m} p_{j\_l}^i \cdot x_j^{i_j}$$

$$+ w_3 x_1^{i_1} \cdot a_1^{i_1} \prod_{j=2}^{m} x_j^{i_j} \cdot r_{i_{j-1} i_j} \cdot a_j^{i_j} \quad (14)$$

$$\text{s.t.} \quad x_j^{i_j} = \begin{cases} 1, & yes \\ 0, & no \end{cases} \quad (14\text{-}1)$$

$$\sum_{i_j=1}^{n} x_j^{i_j} = 1 \quad (14\text{-}2)$$

$$S_m = \sum_{j=1}^{m} t_j^{i_j} \leq S_{m\_set} \quad (14\text{-}3)$$

$$t_{j\_min}^{i_j} \leq t_j^{i_j} \leq t_{j\_max} \quad (14\text{-}4)$$

$$u_j = \begin{cases} 1, & yes \\ 0, & no \end{cases} \quad (14\text{-}5)$$

$$\sum_{j=1}^{m} x_j^{i_j} \cdot q_j^{i_j} \cdot t_j^{i_j} \cdot u_j \geq Q \quad (14\text{-}6)$$

$$\zeta_s = P\{S_m \leq t_{s\_set}\} \geq \zeta_{s\_set} \quad (14\text{-}7)$$

$$j \in J, i_j, i \in I$$

The objective function Z (consortium efficiency) is a multi-objective function of the time t required for the REMC to complete the task, the reliability ζ_s to complete the task within the given time and the competitiveness η of the REMC, and the goal is to maximize the effectiveness of the REMC. Constraint (14-1) indicates whether enterprise E_i is selected at node j; constraint (14-2) indicates that each node has and only one enterprise to undertake; constraint (14-3) indicates that the system cannot take longer than the given time to complete the task; constraint (14-4) indicates the time range limit for different enterprises to complete the task at each node; constraint (14-5) indicates whether the j^{th} node produces products; constraint (14-6) indicates that the sum of the production volumes of all nodes producing products is not less than the given quantity; constraint (14-7) indicates that the REMC system reliability ζ_s must meet a required minimum acceptance level ζ_{s_set}.

3) MODEL SOLVING

From definition 2, there are totally n^m combination schemes of linear manufacturing supply chains. $a_j^i = 0$ indicates that the enterprise E_i is not engaged in the business of the node j in the manufacturing supply chain, then the η of all combination schemes containing $a_j^i = 0$ are 0. Let O_j be the number of $a_j^i = 0$ in node j of the manufacturing supply chain, then the total feasible manufacturing supply chain combination schemes is $N = \prod_{j=1}^{m}(n - O_j)$. Each combination scheme produces a result, so the REMC problem optimisation can be solved by MATLAB software using the traversal method, as shown in Figure 6.

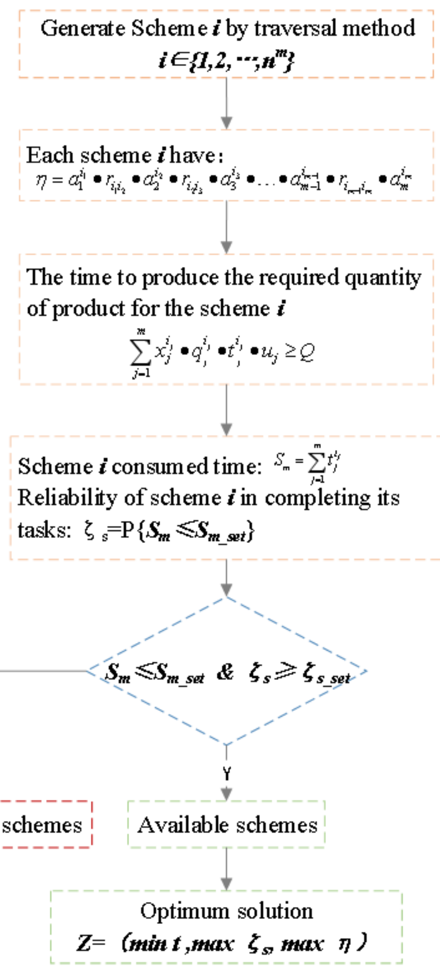


FIGURE 6. Solving process of REMC problem.

IV. CASE APPLICATION

In the wake of the COVID-19 outbreak, a serious shortage of PPE and tight supply are observed throughout the country. On January 31, 2020, the Department of Industry and Information Technology of Guizhou Province held an emergency meeting to mobilise some industrial enterprises in the city to jointly switch to produce PPE. Taking medical goggles as an example, no independent enterprise is engaged in the R&D and production of medical goggles in Guiyang. After a series of investigations, consultation and preparation, a medical goggle manufacturing consortium led by the government was established by Guizhou Haiyue Mould Co., Ltd., Guizhou University, Guizhou Provincial Institute of Standardisation, whose task is to produce 30,000 pairs of medical goggles in no more than 15 days if possible.

In the production cycle of medical goggles, we focus on three aspects of the R&D of the mould, the production of the mould and the production of the product. The logistics are not considered here because of the special passageway

TABLE 3. Statistics of the R&D capability and production capacity of candidate enterprises.

Enterprise name	Mould R&D cycle time/day	Mould production cycle time/day	medical goggle production capacity/(100 pieces/shift)
E1	3–5	3–5	-
E2	5–7	5–7	28–32
E3	2–3	4–5	-
E4	-	-	36–40
E5	2–4	4–6	24–28
E6	3–4	-	-
E7	-	-	40–44
E8	2–3	5–6	26–30
E9	3–5	3–5	30–34
E10	4–6	-	32–36

TABLE 4. ESCC of candidate enterprises.

Enterprise name	Mould R&D capability a_1	Mould production capacity a_2	Medical goggle production capacity a_3
E_1	0.528	0.494	0
E_2	0.331	0.436	0.778
E_3	0.651	0.449	0
E_4	0	0	0.730
E_5	0.690	0.588	0.638
E_6	0.687	0	0
E_7	0	0	0.801
E_8	0.768	0.525	0.708
E_9	0.472	0.481	0.848
E_{10}	0.408	0	0.714

TABLE 5. SCRV between candidate enterprises.

r_{ij}	r_1	r_2	r_3	r_4	r_5	r_6	r_7	r_8	r_9	r_{10}
r_1	1	0.68	0.52	0.61	0.64	0.63	0.72	0.73	0.52	0.71
r_2		1	0.54	0.86	0.89	0.60	0.73	0.84	0.54	0.54
r_3			1	0.68	0.70	0.51	0.56	0.74	0.56	0.62
r_4				1	0.83	0.74	0.59	0.55	0.60	0.85
r_5					1	0.87	0.51	0.69	0.68	0.61
r_6						1	0.82	0.57	0.70	0.55
r_7							1	0.55	0.84	0.77
r_8								1	0.88	0.62
r_9									1	0.83
r_{10}										1

provided by the government. After a rapid sampling survey, 10 enterprises are selected as candidate enterprises, and the data are collected according to Table 1. The R&D capability and production capacity are shown in Table 3. The ESCC of each candidate enterprise calculated by (2) is shown in Table 4. By (5), the SCRV between candidate enterprises is shown in Table 5.

A. ESTABLISHMENT OF MATHEMATICAL MODEL

The REMC of PPE (medical goggles) in case of PHE will pursue the objectives of short completion time, high reliability and high overall core competitiveness. Based on (14), Table 3 and Table 4, the mathematical model for the maximum overall efficiency of the linear REMC is developed as follows:

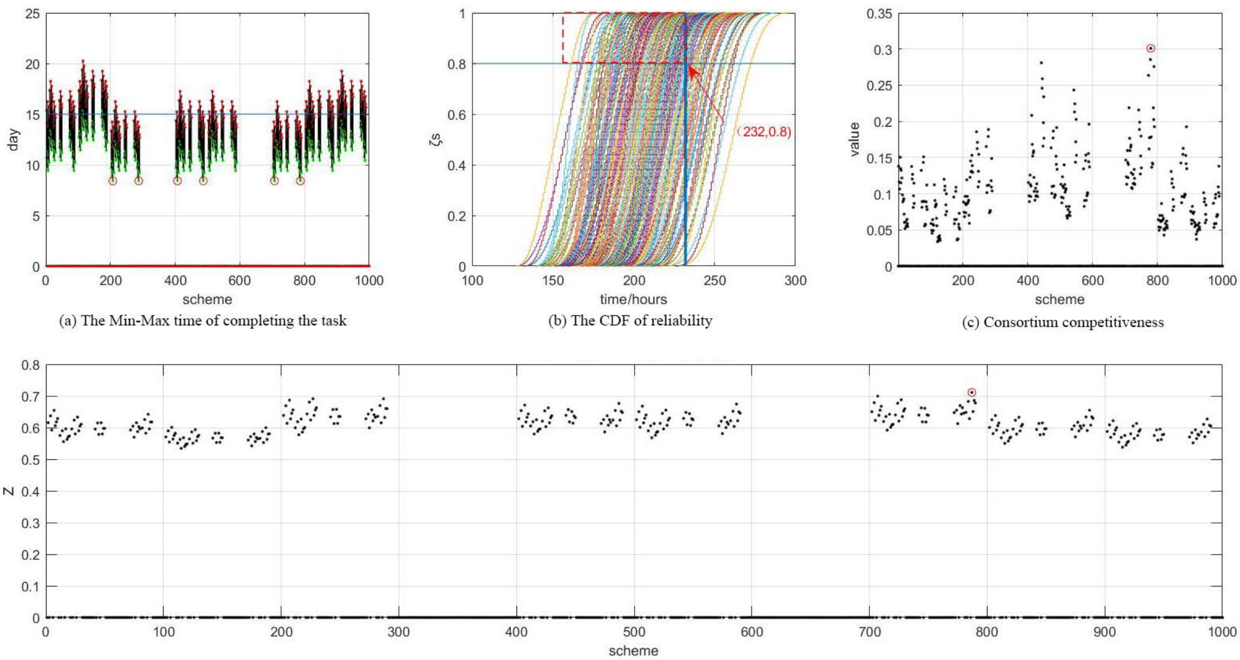
$$
\begin{aligned}
Max\,\mathcal{Z} &= w_1 \frac{S_{m\_min}}{S_m} + w_2 \zeta_s + w_3 \eta \\
&= 0.5 \frac{\min \sum_{j=1}^{3} t^i_{j\_min}}{\sum_{j=1}^{3} t^i_j} x^{i_j}_j \\
&\quad + 0.3 \sum_{s_{m_i} \leq 15} \sum_{k_j \in \bigcup_{i=1}^{n} t^i_j} \prod_{j=1}^{3} p^i_{j\_l} \cdot x^{i_j}_j \\
&\quad + 0.2 x^{i_1}_1 \cdot a^{i_1}_1 \prod_{j=2}^{3} x^{i_j}_j \cdot r_{i_{j-1} i_j} \cdot a^{i_j}_j
\end{aligned}
$$

$$
\begin{aligned}
\text{s.t.} \quad & x^{i_j}_j = \begin{cases} 1, & yes \\ 0, & no \end{cases} \\
& \sum_{i_j=1}^{10} x^{i_j}_j = 1 \\
& S_m = \sum_{j=1}^{3} t^{i_j}_j \leq 15 \\
& 2 \leq t^{i_1}_1 \leq 7 \\
& 3 \leq t^{i_2}_2 \leq 7 \\
& 6.8 \leq t^{i_3}_3 \leq 12.5 \\
& \sum_{j=1}^{3} x^{i_j}_j \cdot q^{i_j}_j \cdot t^{i_j}_j \cdot u_j \geq 30000 \\
& u_1, u_2 = 0 \\
& \zeta_s = P\{S_m \leq 15\} \geq 0.8 \\
& i, i_j \in \{1, 2, \ldots, 10\}, \quad j \in \{1, 2, 3\} \qquad (15)
\end{aligned}
$$

where w_1, w_2, and w_3 are the objective priority factors. The first sub-objective is the task completion time, which is preferred to the minimum time in the problem, so the conversion to the maximum value here is expressed using its reciprocal with the minimum completion time score, which can be limited to a range of values between $[S_{m\_min}/S_{m\_max}, 1]$. The second sub-objective is reliability, which is subject to a certain random probability distribution and takes values in [0,1]. The third sub-objective is system competitiveness, which is determined by the nodal enterprises of the manufacturing chain and their cooperative relationships which have been normalised in the calculation of the ESCC and CSRV. As shown in Table 4 and Table 5, the range of values is also between [0,1].

B. PROBLEM SOLVING

The problem is a multi-objective decision-making problem, and its solution method is systematically discussed by Hwang and Masud [49]. In this problem, time is the first main objective, followed by reliability and the competitiveness of the consortium. Considering the opinions of the research team, its priority coefficient is set as: $w_1 = 0.5$, $w_2 = 0.3$, $w_3 = 0.2$. We assume that it obeys uniform distribution within the estimation range because part of the data of enterprise R&D capability and production capacity is based on enterprise experience and is an estimation range, and no data can be used as the analysis basis [44]. All original data need to be normalised to remove the dimensions of different targets [40].



(a) The Min-Max time of completing the task (b) The CDF of reliability (c) Consortium competitiveness

(d) The feasible REMC performance

FIGURE 7. Problem solving results.

The results of solving for each sub-objective and the total objective by MATLAB are shown in Figure 7.

Figure 7 (a) shows the minimum and maximum time for different effective schemes to complete tasks. The effective scheme here refers to that the ESCC in each process of the consortium is not 0. Figure 7 (b) shows the reliability of different effective schemes to complete tasks within a certain time range. The x-axis is the time (unit: hour), and the y-axis is the cumulative probability. Under the constraints of time (15 days) and consortium system reliability (≥ 0.8), the effective feasible solution is located within the red dotted box. Figure 7 (c) shows the consortium competitiveness of different effective schemes. Figure 7 (d) shows the consortium performance of different effective schemes.

C. RESULTS ANALYSIS

As shown in Figure 7, multiple optimal solutions are found in each sub-objective, but the schemes corresponding to each optimal solution are also different, showing that a certain conflict is found between the sub-objectives. The multi-objective optimal solution to this problem is the 787^{th} scheme, and the consortium performance is 0.711. The corresponding scheme is $E_8 - E_9 - E_7$, that is, the mould design is undertaken by enterprise E_8, the mould production is undertaken by enterprise E_9, and the product production is undertaken by enterprise E_7. After inverse normalisation, the feasible schemes are sorted, as shown in Figure 8, and the top 10 schemes are shown in Table 6.

By the actual production situation, the consortium members work overtime or two shifts frequently to complete the task as soon as possible. To improve the calculation accuracy, we convert time from days to hours for calculation, that is, the mould R&D time is converted as 12h per day, and the mould production and product production are converted as 16h per day. Combined with the data in Table 3, the maximum time will not exceed 232h when 15 days are converted to hours.

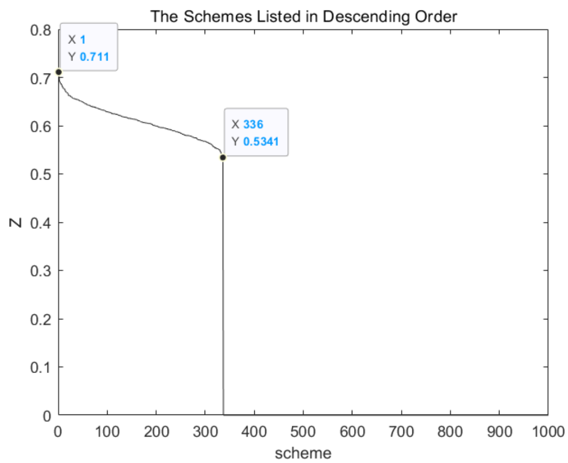


FIGURE 8. Feasible scheme after sorting.

TABLE 6. Top 10 feasible schemes.

Ranking	Schemes	Z	Time/h	Reliability	Consortium efficiency
1	$E_8 - E_9 - E_7$	0.7110	175	0.9996	0.2187
2	$E_8 - E_1 - E_7$	0.6992	171	0.9864	0.1597
3	$E_3 - E_3 - E_7$	0.6910	173	0.9925	0.1311
4	$E_3 - E_9 - E_7$	0.6909	171	0.9864	0.1180
5	$E_8 - E_3 - E_7$	0.6877	173	0.9925	0.1145
6	$E_3 - E_1 - E_7$	0.6866	171	0.9864	0.0964
7	$E_8 - E_9 - E_9$	0.6854	190	0.9869	0.2757
8	$E_8 - E_9 - E_4$	0.6823	177	0.9837	0.1424
9	$E_3 - E_3 - E_4$	0.6804	179	0.9887	0.1451
10	$E_8 - E_1 - E_4$	0.6785	177	0.9837	0.1233

Therefore, the schemes in Table 6 can provide the government with a scientific basis for organising production.

V. CONCLUSION AND OUTLOOKS

Under the condition of PHE, taking COVID-19 as an example, the existing manufacturing supply chain is paralysed in a short period due to uncertainties such as low labour resumption and logistical disruptions, which makes it difficult to respond quickly to market demand for PPE. Multiple initiatives to enhance the stability and competitiveness of manufacturing supply chains and maintain the security of manufacturing supply chains are important elements of the overall national security. In view of this, we researches how to quickly restore or create new manufacturing capacity for PPE under the context of PHE, and builds an REMC system model based on government regulation for the first time, which forms a relatively complete, safe and reliable regional supply chain system for the manufacturing of PPE, and is a concrete action for the overall national security. This research presents a detailed analysis of the REMC establishment process, establishes an enterprise core competitiveness evaluation system, designs the functions of the REMC system and constructs a structural equation model of system performance. Finally, the practicality of the research content and the validity of the method are verified by using the construction of a goggle manufacturing consortium in Guiyang, China, as an example, which fills the gap in the field of rapid resumption of manufacturing supply chains to improve the capacity in case of uncertainties such as low labour resumption and disrupted logistics when facing PHE.

In summary, in the case of PHE, labour resumption is derived as one of the important factors affecting manufacturing capacity. The selection of REMC members requires not only strong special core competencies but also factors such as smooth cooperation with upstream and downstream members, reliability in completing tasks on time and system reliability. The government should actively explore the resource potential of local enterprises to build an REMC that is unaffected by factors, such as lockdown and movement restrictions, and form a regional emergency manufacturing mechanism of 'emergency response in emergency and peacetime service', which is a concrete action for the overall national security. The widespread adoption of the REMC model will form a robust PPE supply guarantee and is a complement to the current global supply chain manufacturing model, which is the main emergency manufacturing model to deal with PHE in the future.

The significance of this research is that it proposes a PPE manufacturing assurance strategy in response to the COVID-19 crisis, demonstrates the feasibility of PPE REMC through case studies, and hopes to draw the attention of government to construct REMC in the field of public health and safety in the future. However, in this case, a certain one-sidedness in data collection and processing is observed because of the small number of relevant enterprises in the selected region. We aim that the proposed model can be demonstrated again in the region with a large number of samples. This research mainly studies the series scheme of manufacturing consortium and ignores the hybrid scheme, which will be the focus of the future research.

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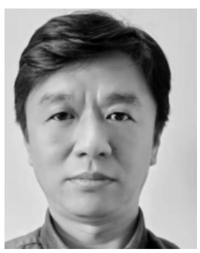

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