Threshold Effect of R&D Investment during Shock - Evidence from COVID-19

Hongbin Huang*

Abstract

This paper investigates the patterns in research and development (R&D) investment decisions among firms under a systematic shock. Through the application of an R&D competition model, this study examines which firms are more inclined to invest in R&D during the pandemic. The results reveal the existence of a threshold for firms entering the R&D competition and shed light on how R&D investment varies based on firm size. I utilized the Chinese pharmaceutical industry during the COVID-19 pandemic to conduct empirical research. I demonstrate that the increase in R&D investment ratio of large firms is greater than small to medium-sized firms. Furthermore, by employing the panel threshold model using firm size as the threshold variable, I also show that there is a threshold in R&D spending increase. By analyzing the R&D investment decisions of firms within the Chinese pharmaceutical industry during the COVID-19 crisis, this study contributes to the understanding of how firms' responses to systematic shocks depend on firm size and provides fresh empirical evidence.

Keywords

R&D investment, Covid outbreak, Panel threshold model

JEL Classification: O32, L25

*Research Institute of Economics and Management, Southwestern University of Finance and Economics, 555 Liutai Blvd East Section, Chengdu, 611130, Sichuan Province, China.

1 Introduction

Research and development (R&D) has been shown to significantly boost economic growth (Aghion & Howitt, 2008). R&D can not only enhance production efficiency and reduce costs but also address a multitude of problems. Therefore, investing in research and development can benefit society and increase overall welfare in the long run. However, it is not always efficient for all firms to allocate resources to R&D. Some firms may lack the necessary human capital and equipment for conducting research (Ballot et al., 2001), making their R&D investment less cost-effective. Moreover, due to the spillover effect, firms can benefit from the innovations of others (Griffith et al., 2006). Therefore, it is crucial to study R&D spending for different firms to maximize their efficiency.

Another motivation for this study is that numerous systematic shocks have historically had profound impacts on firms, shaping their innovative strategies and influencing their responses to unexpected events. For instance, the Clean Air Act Amendment of 1990 in the United States led to the establishment of a market for sulfur dioxide (SO2) permit trading, significantly affecting firms' cost reduction strategies (Melnick, 2010). Similarly, more recently, the outbreak of Covid-19 emerged as a global public health event with unprecedented consequences, affecting economic, social, and political landscapes worldwide.

The motivation for choosing the Covid-19 and pharmaceutical industry is that the the Covid-19 had tremendously impacted our life, and it influenced pharmaceutical industry largely. Pharmaceutical industry played a critical role in combating the Covid-19 pandemic, striving to develop safe and effective vaccines and drugs to control its spread (Yuan et al., 2022). The surge in global demand for Covid-19 vaccines prompted governments to increase their financial support for Covid-19-related research, leading pharmaceutical companies to intensify their investments in research and development (R&D). Notably, Pfizer, a prominent US pharmaceutical company, successfully conducted trials for an experimental Covid-19 vaccine on May 6, 2020, which later became widely utilized. Given the circumstances, it is reasonable to assume that companies in the pharmaceutical industry were motivated to bolster their R&D investment. Furthermore, the size of a company is expected to influence its R&D investment decisions. Hence, this global-scale event provides a great quasi-experiment for this study.

To explore this phenomenon, this paper employs a theoretical model to identify the threshold at which firms engage in R&D competition and reveals how R&D investment varies based on corporate innovation capability, which is closely associated with firm size. In the primary empirical analysis, I utilize corporate R&D investment data to investigate whether large firms within the pharmaceutical industry experienced significant increases in R&D investment following the Covid-19 outbreak. I also use the panel threshold model to demonstrate there exist a significant threshold effect in R&D investment after a systematic shock, and the threshold effect is weak before the shock.

This paper makes contributions in two main aspects. Firstly, this paper establishes a theoretical framework that identifies the threshold at which firms engage in R&D competition and demonstrates how the optimal allocation of resources for R&D varies based on firms' innovation capabilities and firm size. This study also provides an empirical study of R&D investment in the Chinese pharmaceutical industry during the pandemic to verify the result based on the theory.

Furthermore, the existing literature has only partially explored the relationship between the Covid-19 pandemic and enterprise R&D investment. By examining the response of enterprises in the pandemic's aftermath, valuable insights can be gained into the reactions of microeconomic entities (Shi & Li, 2022). This analysis holds practical significance and provides decision-making references for economic and social development in the post-epidemic era. Consequently, this study assesses the impact of the Covid-19 outbreak on enterprise R&D investment, revealing a substantial boost in R&D investment among large firms in the pharmaceutical sector. This research contributes to the existing literature and enhances our theoretical knowledge of the relationship between Covid-19 and R&D investment.

The remaining sections are organized as follows: Section 2 presents the literature review, Section 3 discusses the theoretical framework, Section 4 introduces the research design, and Section 5 presents the empirical results and analysis. Finally, Section 6 concludes the study with key implications and contributions.

2 Literature Review

A large body of literature has been focused on R&D and Growth (Aghion & Howitt, 2008). They are not only the key to firm success but also boost the entire global economy (Shefer & Frenkel, 2005). Numerous studies have explored R&D competition among firms (Aghion et al., 2005), although many of them have not placed significant emphasis on the impact of firm size. In the early stages of research, the focus was on understanding dynamic profit maximization in R&D competition among firms operating in the Cournot industry (Scherer, 1967). As the number of firms increases, each firm tends to reduce its R&D expenditures due to intensified competition, resulting in individual firms investing more in R&D than what would be socially optimal in a competitive market (Loury, 1979). Over time, firms may reduce their R&D spending or even exit the competition if they face uncertainty regarding the challenges associated with innovation. Additionally, as the number of participants in R&D competition rises, the intensity of competition typically increases (Malueg & Tsutsui, 1997). It is worth noting that the dynamics of R&D races differ between the private and public sectors. From a social welfare perspective, the R&D investments of public corporations often exhibit either excessive or insufficient levels, leading to inefficiencies (Ishibashi & Matsumura, 2006).

There are many studies on R&D competition between firms that do not emphasize the effect of firm size. In the early period, the dynamic profit maximizing in research and development competition between firms in the Cournot industry was studied (Scherer, 1967). As the number of firms increases, each firm will reduce the R&D spending on R&D competition, and each firm will invest more than the social optimum in R&D in a competitive market (Loury, 1979). When firms are unsure of the difficulties of innovation, as time elapses, firms tend to reduce R&D spending and even exit the R&D competition. Meanwhile, as the number of participants increases, the R&D competition will become more intense (Malueg & Tsutsui, 1997). The R&D race between the private and public sectors is also different. In view of social welfare, the R&D investments of public corporations are usually too large or too small, which would cause inefficiency (Ishibashi & Matsumura, 2006).

This research is also linked to studies on R&D races of different sizes. In the Bertrand industry, only a small number of firms with large sizes will participate in R&D competition, regardless of a high-cost project or a low-cost project (Quirmbach, 1993). Under a duopoly model, the larger firm tends to invest in R&D on cost-reducing while the small-sized firm tends to invest in innovating new products (Yin & Zuscovitch, 1998). Meanwhile, large firms tend to invest more than small firms, the R&D investment is determined by characteristics of firms such as size, location, and type of industry (Shefer & Frenkel, 2005). In addition, financing R&D expenditure is crucial for firms' innovation (Aghion & Tirole, 1994).Firm size may also influence the financial constraint, which will influence the R&D investment, and the firm size and innovation are non-linear (Fang et al., 2021). There are also some empirical studies on research and development competition of different sizes. For example, in the Internet technology industry, small firms are dependent on the knowledge and patents of large firms in the product market. The strategy of large firms might be cooperating with small firms and open innovation (Lim et al., 2010). This pattern is also found in the European manufacturing industry (Van Uden et al., 2017). It is also suggested that the productivity of firms' R&D is related to size and competition environment using 14 Latin American firm-level data (Waheed, 2011).

This research is also related to R&D investment in the pharmaceutical industry. During the period 1995-2009, the total number of publications of large firms in the pharmaceutical industry presented a declining trend, and they also showed a tendency to outsource in Europe, and publications in developing countries are increasing (Rafols et al., 2014). R&D efficiency is also declining, and companies tend to reduce the portfolio and project risk and reduce R&D cost to improve R&D efficiency (Schuhmacher et al., 2016).

Finally, my research is linked to Covid-19's impact. Covid-19 caused a crisis for most companies, and firms are likely to postpone their investment and lay off their employees (Buchheim et al., 2020). However, small and medium-sized enterprises (SME) are likely to survive and become more profitable if they sustain and invest in research and development (Roper & Turner, 2020). Covid-19 also has a tremendous impact on the pharmaceutical industry, which will interrupt the supply chain. Due to supply shortages, some firms start to change into self-sufficiency companies (Ayati et al., 2020). Therefore, pharmaceutical companies might turn to invest R&D to become self-efficient. Meanwhile, the firms tend to cooperate with partners during the Covid-19 pandemic. Nearly one-third of vaccine products are developed through partnership, but this cooperation is mainly on material transfer instead of knowledge sharing (Druedahl et al., 2021).

3 Theoretical Framework

In a dynamic R&D competition, the optimal strategy for R&D remains constant (Malueg & Tsutsui, 1997). Therefore, this model focuses on a one-shot R&D investment decision among n firms with different sizes[1] denoted as S_i. Firm size is positively related to innovation capabilities, including patents, human capital (researchers' abilities), and facilities (Dakhli & De Clercq, 2004; Van Uden et al., 2017). Since R&D capability is difficult to measure

[1]Firm size is expressed in logarithm in the empirical study.

directly, it is closely positively correlated with firm size, I use size as a proxy to represent the company's R&D capability in empirical analysis. Since cooperation in R&D between firms is relatively rare, mainly involving material transfer rather than knowledge sharing (Druedahl et al., 2021), it is not considered in the model.

Furthermore, it is assumed that the first firm to successfully innovate and secure patents will monopolize the entire market, gaining all the profits denoted as R, while other firms gain nothing. Firms are assumed to be risk-neutral. To participate in the R&D competition, firms need to invest a fixed cost denoted as F, and once they decide to participate, each firm independently chooses the additional amount, m_i, to invest without knowledge of other firms' decisions. Each firm is also assumed to know the eventual return of innovation, R.

The time it takes for a firm to successfully innovate and create a product is assumed to follow an exponential distribution (Malueg & Tsutsui, 1997), represented as:

$$Pr(innovate\ before\ time\ t) = f(\lambda, t) = 1 - e^{-\lambda t} \tag{3.1}$$

When a firm is large in scale, its financial constraints are generally lower, leading to potentially lower interest rates when borrowing from banks or other financial institutions. Additionally, larger firms tend to exhibit higher R&D efficiency (Dakhli & De Clercq, 2004; Van Uden et al., 2017). Based on these findings, I assume that the parameter λ is correlated with both the total amount of money invested in R&D and the size of the firms, denoted by S_i. This relationship is represented by the following function:

$$\lambda = S_i m_i \tag{3.2}$$

Let the time when firm i innovates be X_i, and the time any other firms innovate be X_r[2]. Let the sum of λ except λ_i be λ_r. They are independent of each other, and their joint distribution is $f(x_i, x_r)$.

$$f(X_i, X_r) = \begin{cases} \lambda_i e^{-\lambda_i x_i} \lambda_r e^{-\lambda_r x_r}, x_i, x_r > 0 \\ 0, Otherwise \end{cases} \tag{3.3}$$

[2] X_r represents the time any other firms except firm i successfully innovated.

Then the probability that the firm i will innovate the product before all other firms is:

$$\begin{aligned} Pr(X_i < X_r) &= \iint\limits_{0<X_i<X_r} f(x,y)\,dx\,dy \\ &= \frac{\lambda_i}{\sum_{i=k}^{n} \lambda_k} \end{aligned} \tag{3.4}$$

Therefore, the expected return of each firm can be calculated, the results are represented below.

$$E(Profit_i) = R\frac{S_i m_i}{\sum_{k=1}^{n} S_k m_k} - m_i - F \tag{3.5}$$

Then firms need to decide how much money they need to invest, and the optimum money for firm i needs the flowing four requirements:

$$\begin{cases} m_i > 0 \\ \frac{\partial E[\pi]}{\partial m_i} = 0 \\ E[\pi(m_i)] > 0 \\ \frac{\partial^2 E[\pi]}{\partial m_i^2} < 0 \end{cases} \tag{3.6}$$

$\pi(m_i)$ is the profit of firm i investing m_i amount of money to R&D.

To calculate the optimum R&D investment for n firms with different sizes, I take the first-order derivative for each firm's expected profit function[3]:

This results in the following equation system that needs to be solved:

$$\begin{cases} SUM = \sum_{k=1}^{n} S_k m_k \\ \frac{\partial E_1}{\partial m_1} = \frac{RS_1 SUM - RS_1^2 m_1}{SUM^2} - 1 = 0 \\ \frac{\partial E_2}{\partial m_2} = \frac{RS_2 SUM - RS_2^2 m_2}{SUM^2} - 1 = 0 \\ \vdots \\ \frac{\partial E_n}{\partial m_n} = \frac{RS_n SUM - RS_1^2 m_n}{SUM^2} - 1 = 0 \end{cases} \tag{3.7}$$

[3]When m_i is larger than 0, the second-order derivative of E is negative, indicating a concave relationship. As a result, the maximum value of E is attained when the first-order derivative is equal to 0.

The generalized solution for the equation system is[4]:

$$m_k = \frac{R(n-1)[\sum_{i=1}^{n} \frac{1}{S_i} - \frac{n-1}{S_k}]}{S_k(\sum_{i=1}^{n} \frac{1}{S_i})^2} \tag{3.8}$$

Then, replace the result m_k to the profit function (3.5):

$$E(Profit_i) = R[1 - \frac{(n-1)(2\sum_{k=1}^{n} \frac{1}{S_k} + \frac{n-1}{S_i})}{S_i(\sum_{k=1}^{n} \frac{1}{S_k})^2}] - F \tag{3.9}$$

It should be noted that there are several m_i values that might be smaller than zero, and even when m_i is larger than 0, $E(profit_i)$ might still smaller than zero. This indicates that these firms will not participate in the R&D competition. In such cases, the firm with the smallest size should be excluded from the equation system (6.1), and the solution should be recalculated until the optimal investment in R&D and expect return for every firm is larger than 0.

Given the complexity of the results presented in equations (6.7) and (3.9), I have visually summarized the findings in Figure 1, which illustrates the outcomes of the simulation. Notably, Figure 1 reveals an observable pattern: there are two distinct shifts in the optimal R&D investment and one notable shift in expected return. The first jump (occurring at a firm size of 1.77) in the optimal investment is primarily influenced by the fixed cost. Below this threshold, Firm 3 would incur losses if it invests in R&D, but above the threshold, it significantly increases R&D spending (much higher than the fixed cost F). The second jump (occurring when firm size exceeds 2.41) in the optimal investment and the first jump in expected return are both attributed to the exit of Firm 1. Due to its relatively small size, continuing R&D investment would lead to losses for Firm 1. Consequently, the graph suggests that the threshold is highly dependent on the fixed cost and the sizes of other firms, and it might exist at multiple points.

Meanwhile, Figure 2 demonstrates that the expected success time decreases with the increasing size of Firm 3. However, notable jumps or slumps occur around specific thresholds: when Firm 3's size exceeds 1.77, all firms choose to invest, resulting in a significant decrease in success time; and when Firm 3's size surpasses 2.41, Firm 1 decides to exit the R&D competition, leading to a substantial increase in success time. This figure suggests that an

[4]The steps of calculation is presented in Appendix B

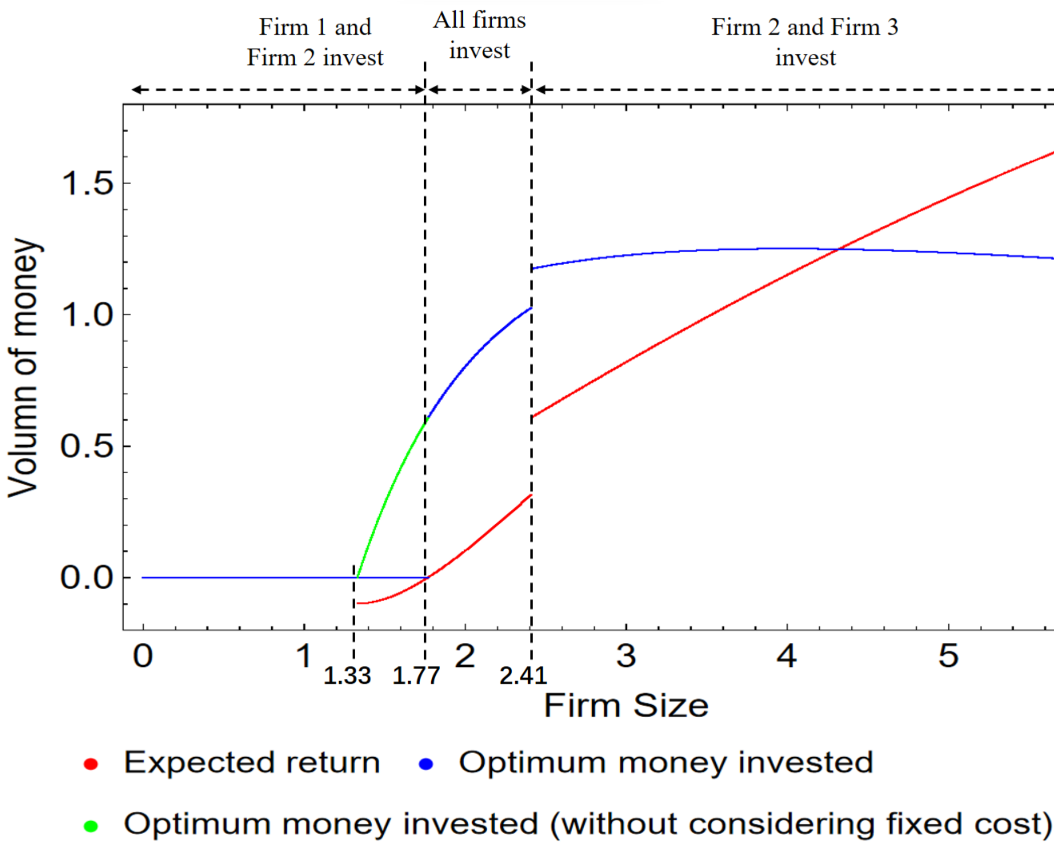

Figure 1: In this simulation, there are three firms, Firms 1 (size is 2), Firm 2 (size is 4), and Firm 3 (Size is x) the fixed cost F equals 0.1, the revenue R equals 5. The graph presents the optimum choices for the Firm 3's money invested and expected return under different sizes. The curves illustrate how the optimal decisions vary with firm sizes.

increase in the size of one firm does not necessarily reduce the success time; instead, the effect of entering or exiting the competition matters more around these thresholds. Furthermore, the success time decreases significantly as the number of firms participating in the R&D competition increases.

Drawing upon the theoretical framework, I propose the hypothesis that larger-sized firms tend to allocate a greater proportion of their resources towards investment compared to smaller firms in response to systemic shocks that provide a large-scale R&D opportunity. Additionally, this phenomenon may exhibit a threshold effect: when a firm reaches a certain size that enables it to derive profit from R&D investment, it is more likely to allocate a significant amount of funds towards such endeavors. Conversely, if a firm falls below this

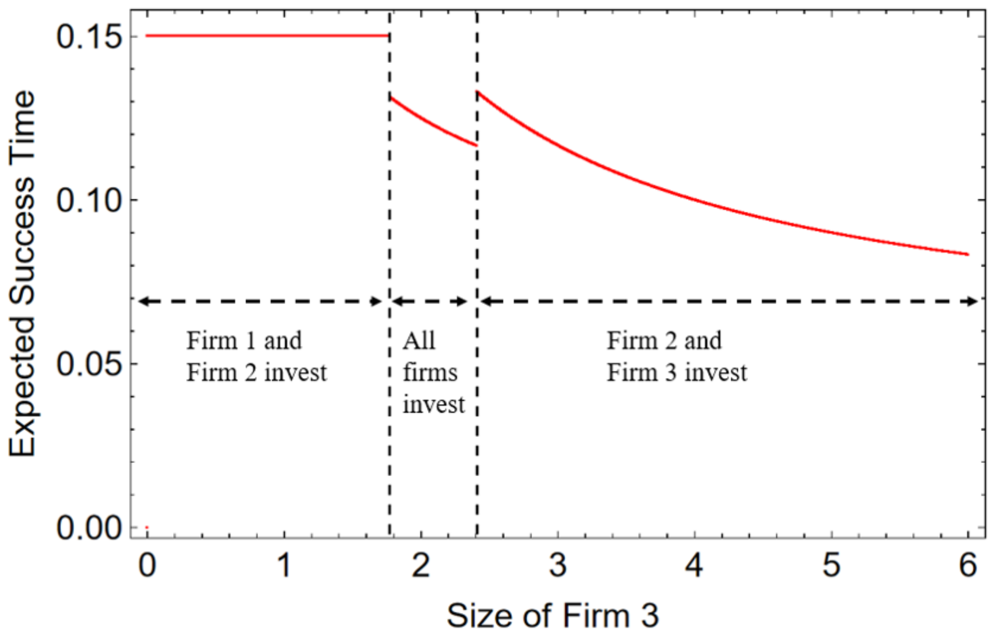

Figure 2: The settings are the same as Figure 1. This figure presents the expected success time of the industry (The time any firm succeeds in inventing the product), which is the inverse of SUM.

threshold, it may not engage in the competition of R&D investment. Moreover, when a firm is sufficiently large, the optimal amount of money to be invested in R&D might exhibit a slight decrease as the firm size increases.

4 Research Design

4.1 Data source

This study is based on all listed enterprises in the pharmaceutical industry in China spanning from 2010 to 2021. The data is mainly divided into two categories: corporate research and development data and enterprise characteristic data. The research and development data (R&D investment) of enterprises are from the Chinese Research Data Services Platform (CNRDS) and Chinese Innovation Research Database (CIRD), which is subordinate to CNRDS. In addition, enterprise characteristic data come from the China Stock Market & Accounting Research (CSMAR) database.

Relevant adjustments to the samples are made according to the following standards: (1) data of listed enterprises with abnormal trading, including ST (enterprises with abnormal financial or other conditions) and PT (stop any trading, clear the price and wait for delisting) are excluded; data of listed enterprises that fall into the category of finance and insurance are excluded; (3) relevant data of listed enterprises with missing data are excluded; and (4) in order to avoid the influence of abnormal values, the continuous variables are winsorized at 1% level. After the data collecting and processing mentioned above, I obtained 2118 firm-year observations.

4.2 Empirical construction

Covid-19 broke out in 2020, which can be regarded as a huge systematic shock, providing a quasi-experiment for this study. The first model[5] (4.1) I constructed is to test whether big firms increased R&D investment during Covid-19. I adopted the dual fixed effect model that controls firm fixed effects and year fixed effects.

$$RD_{it} = \alpha_0 + \beta_1 bigfirm_i \times covid_t + \gamma Controls_{it} + \eta_i + \tau_t + \epsilon_{it} \tag{4.1}$$

The explained variable is RD, indicating the R&D investment ratio of the enterprise. Consistent with the existing research (Li et al., 2018), I use proportion of R&D investment amount in total operating revenue to measure the R&D investment. $bigfirm_i \times covid_t$ is the core explanatory variable. $covid$ is a dummy variable that takes 1 in and after the year of the Covid outbreak (2020) and takes 0 before 2020; and $bigfirm$ denotes a dummy variable indicating whether the enterprise is a big firm: if the enterprise is a big firm, the value of treated is 1; otherwise, it is assigned as 0. If the size (natural logarithm of total assets amount) of a firm-year observation is no less than 23 [6], it is referred to be a big firm. η_i is the firm fixed effects and τ_t is the year fixed effects. I select control variables following existing literature (Li et al., 2018).

Then, I run the regression (4.2) for big firms and small firms separately to test whether the R&D increase during Covid-19 of big firms is larger than small firms.

$$RD_{it} = \alpha_0 + \beta_1 covid_t + \gamma Controls_{it} + \eta_i + \epsilon_{it} \tag{4.2}$$

[5] It should be noted that the first model is not a difference-in-difference model, since there are not control groups, both big firms and small firms face shock during the Covid-19.

[6] The threshold is based on the scatter plot presented in Figure 2 in the Data overview section. A more precise threshold level will be presented in next section, panel threshold model

The dependent variable in this model is denoted as "$covid_t$," which is the same as the model (4.1). Due to the presence of collinearity after incorporating year-fixed effects, I have utilized the firm fixed effect model exclusively.

Finally, to test the existence of the threshold effect obtained from the theoretical framework, I adopt the panel threshold model proposed by Hansen (Hansen, 1999) and take Firm size as the threshold variable to test whether there is a turning point in the impact of Covid-19 on enterprise R&D innovation, and analyzes their threshold effect afterward. Here is the panel threshold model:

$$RD_{it} = \alpha_0 + \beta_1 Size_{it}\boldsymbol{I}(Size_it \leq r) + \beta_2 Size_{it}\boldsymbol{I}(Size_{it} > r) + \boldsymbol{\gamma} Controls + \epsilon_{it} \tag{4.3}$$

where r is a threshold value, $\boldsymbol{I}(\cdot)$ is an indicator funtion, when $Size_{it}$ is larger than r, the value of $\boldsymbol{I}(Size_it > r)$ is 1, otherwise it is 0. β_1 and β_2 are the coefficient estimates for threshold variables for $Size_{it} \leq r$ and $Size_{it} > r$ respectively. Another representation of the model (4.3) is:

$$RD_{it} = \begin{cases} \alpha_0 + \beta_1 Size_{it} + \boldsymbol{\gamma} Controls + \epsilon_{it}, & Size_{it} \leq r \\ \alpha_0 + \beta_2 Size_{it} + \boldsymbol{\gamma} Controls + \epsilon_{it}, & Size_{it} > r \end{cases} \tag{4.4}$$

When there are two thresholds r_1 and r_2, the model could be represented as follows:

$$RD_{it} = \begin{cases} \alpha_0 + \beta_1 Size_{it} + \boldsymbol{\gamma} Controls + \epsilon_{it}, & Size_{it} \leq r_1 \\ \alpha_0 + \beta_2 Size_{it} + \boldsymbol{\gamma} Controls + \epsilon_{it}, & r_1 < Size_{it} \leq r_2 \\ \alpha_0 + \beta_3 Size_{it} + \boldsymbol{\gamma} Controls + \epsilon_{it}, & Size_{it} > r_2 \end{cases} \tag{4.5}$$

It is important to note that the findings based on the Chinese Pharmaceutical Industry data have strong external validity. It covers all of the listed firms and also has a long time span. The pharmaceutical firms' R&D behavior observed during the Covid outbreak is similar to the pattern of other firms' R&D behavior in other systematic shocks. However, it is also worth noting that the data have some flaws. For example, R&D investment data only includes the total R&D investment, and it does not contain detailed R&D investment (e.g. R&D investment in developing the Covid vaccine or other drugs or cost reduction). Therefore, it is difficult to identify whether a firm increased or decreased total R&D investment

Table 1: Summary statistics.

SIZE is the natural logarithm of firms' total assets. RD1 is R&D investment divided by the total asset of firms. RD2 is R&D investment divided by the operation revenue of firms. LEV is the asset-liability ratio. ROA is the net profit margin of total assets. ATO is the total asset turnover rate. TOP1 is the share ratio of the largest shareholder. CASH is the cash ratio (cash and cash equivalent divided by current liability). Growth is the annual increase rate of business revenue. TOBINQ is the market value divided by total assets. FIXED is the proportion of fixed assets, AGE is the natural logarithm of the current year minus the list year plus one.

variable	N	mean	sd	min	max
SIZE	2118	21.913	0.994	19.58	25.36
RD1	2118	0.0260	0.0210	0	0.128
RD2	2118	0.0560	0.0520	0	0.319
LEV	2118	0.304	0.178	0.0250	0.925
ROA	2117	0.0700	0.0740	-0.353	0.254
ATO	2117	0.566	0.263	0.0620	2.361
Top1	2113	0.333	0.136	0.0810	0.748
CASH	2118	0.0660	0.0650	-0.168	0.256
GROWTH	2116	0.181	0.359	-0.652	3.303
TOBINQ	2091	2.619	1.679	0.802	16.65
FIXED	2118	0.207	0.112	0.00200	0.662
AGE	2118	2.018	0.954	0	3.367

is due to investment in Covid vaccines or other things. Unfortunately, the detailed R&D investment is not currently disclosed by any Chinese pharmaceutical firms, I use total R&D investment data as a proxy.

4.3 Data overview

Table 1 reports the descriptive statistics of the main variables of the baseline regression. The minimum and maximum of RD2 are 0 and 0.319, which illustrates that there are great differences in R&D investment between big firms and other firms. The mean of LEV, ROA, ATO, $TOP1$, $CASHw$, $GROWTH$, $TOBINQ$, $FIXED$, and AGE is 0.304, 0.070, 0.566, 0.333, 0.066, 0.181, 2.619, 0.207 and 2.018. Control variables are consistent with the existing literature (Li et al., 2018; Lim et al., 2010).

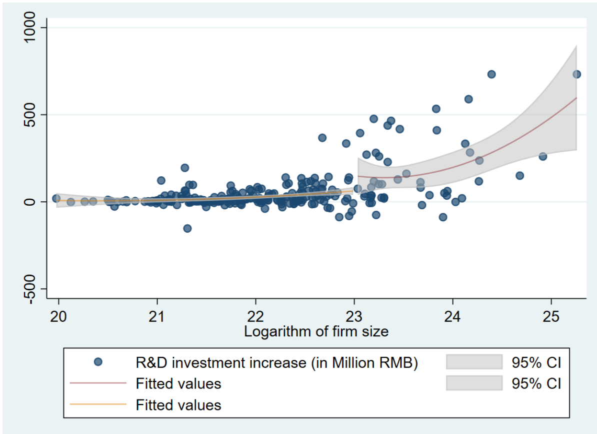

Figure 3: R&D increase in 2020

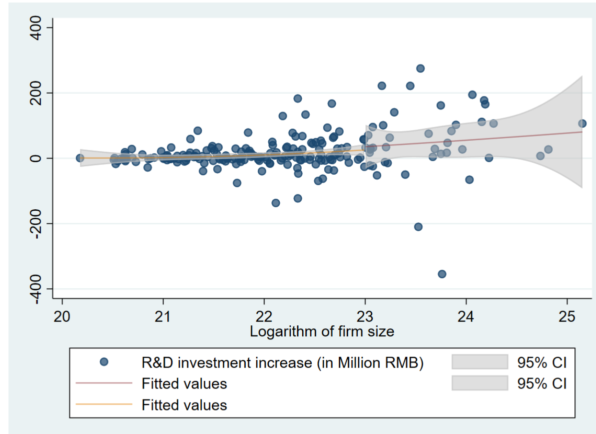

Figure 4: R&D increase in 2019

Note: Figure 3 and Figure 4 present scatter plots illustrating the relationship between R&D increase and the natural logarithm of firm size in the years 2020 and 2019, respectively. The quadratic fitted line represents the trend, and the shaded grey area surrounding the fitted line represents the 95% confidence interval.

These two figures provide compelling evidence of a threshold effect, suggesting that when a firm exceeds a certain size, there is a significant rise in R&D spending during the COVID-19 outbreak. In contrast, no similar pattern is observed prior to the outbreak. While it is true that certain firms decreased their R&D spending during the Covid-19 outbreak, it is important to consider the influence of field-specific differences. For instance, large pharmaceutical firms specializing in neuroscience may not find it profitable to invest in Covid-19 R&D. Hence, these scatter plots strongly support the theoretical framework.

4.4 Data strength and weakness

This study benefits from several strengths regarding the data used. First, the sample encompasses all listed firms in the Chinese pharmaceutical industry, ensuring external validation and representative coverage of the industry. Additionally, I have incorporated detailed firm information, such as leverage ratio, as control variables, which helps mitigate potential omitted variable biases.

However, there are certain limitations associated with the data. The core variable only includes the total R&D spending ratio, as detailed R&D spending data are not disclosed by any firm. Thus, R&D spending of some firms might be caused by investing in cost reduction, rather than developing COVID-related drugs. As the theoretical framework discusses the situation where there is only one costly R&D opportunity, but many smaller R&D opportunities might be caused by COVID-19 in reality, such as cough syrup, the result obtained from empirical research might deviate slightly from the theory.

5 Empirical Results and Analysis

5.1 Baseline

Column (1) of Table 2 presents the regression results of the Covid outbreak on corporate R&D investment of different firm sizes in the pharmaceutical industry. The coefficient of $Big \times Covid$ is significantly positive at a 1% significant level, which is 0.00608, indicating that the Covid outbreak is significantly and positively correlated with corporate R&D investment. Therefore, firms with a larger size increase their proportion of money invested in R&D spending more than firms with a smaller size.

Additionally, the share ratio of the largest shareholder and market value divided by total assets exercise a significantly positive impact on R&D investment of enterprises. Enterprises with a higher $TOP1$ and $TOBINQ$ are more willing to increase their investment in R&D. The proportion of fixed assets and listed age has no significant impact on R&D investment, and other control variables have a negative influence on R&D investment.

Furthermore, I use the model to estimate the magnitude of the R&D spending increase for both big-sized firms and small-sized firms separately. This allows for an investigation into whether small-sized firms also experienced an upsurge in R&D expenditure during the Covid-19 outbreak.

In Table 2, columns (2) and (3) present the coefficients of $Covid$ as 0.0189 and 0.00784 for large-sized firms and other firms, respectively. These coefficients are statistically significant at the 1% level, indicating a substantial disparity in R&D investment between large firms and other firms before and after 2020. The findings suggest that both small and large firms increased their R&D investment during the Covid-19 outbreak, with larger firms exhibiting a greater increase relative to their total assets.

It is important to note that these results slightly deviate from the hypotheses stated in the theoretical framework. The theoretical framework shows that small firms will not

Table 2: Empirical results

	(1)	(2)	(3)
	RD2	RD2	RD2
	All sample	Large firm	Small firm
Big×Covid	0.00608***		
	(3.13)		
Covid		0.0289***	0.00784***
		(3.14)	(3.32)
Lev	-0.0175**	0.0163	-0.0223**
	(-2.64)	(0.17)	(-2.18)
ROA	-0.0859***	-0.268	-0.0910***
	(-3.58)	(-1.09)	(-3.90)
ATO	-0.0342***	0.0462	-0.0369***
	(-5.89)	(0.65)	(-6.74)
Top1	0.0379***	0.0424	0.0323*
	(3.23)	(0.33)	(1.67)
Cashflow	-0.0463**	-0.107	-0.0378**
	(-2.32)	(-0.84)	(-2.00)
Growth	-0.00529*	0.0268	-0.00520**
	(-1.99)	(1.79)	(-2.08)
TobinQ	0.00232**	-0.00120	0.000745
	(3.09)	(-0.31)	(1.11)
FIXED	0.00136	-0.0965	-0.00721
	(0.20)	(-0.94)	(-0.60)
Constant	0.00416***	0.00532***	0.00500***
	(5.33)	(6.41)	(4.24)
N	2039	401	1638
r2	0.823	0.958	0.819
Year_FE	Yes	No	No
Firm_FE	Yes	Yes	Yes

t statistics in parentheses, standard error are clustered by firm

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

increase R&D spending during a shock, and firms exceeding a threshold will increase R&D investment largely; but the empirical results show that both small-sized firms and large-sized firms increased R&D spending during a shock, with large firms increasing more. This discrepancy might arise from the fact that the data only considers overall R&D expenditure, without distinguishing R&D spending on a specific large-scale project (such as Covid vaccine development). Small to medium-sized firms may have been engaged in other smaller R&D projects related to Covid-19, such as the development of products aimed at alleviating symptoms (e.g., cough syrup). Consequently, while the R&D spending of small to medium-sized firms did increase during this disruptive period, it does not negate the hypothesis under examination.

5.2 Threshold effect test

I first test whether there exists any threshold between R&D spending increase and firm size. Accordingly, the null hypothesis $H_0 : \beta_1 = \beta_2$; the alternative hypothesis is set as $H_1 : \beta_1 \neq \beta_2$. If the null hypothesis is true, then the threshold effect does not exist; otherwise, it indicates that the threshold effect exists. By using this approach, I can also test whether there are second or third thresholds. The bootstrap method is used to obtain an approximation of the p-values. For each of the bootstrap tests, 500 bootstrap replications are used. Table 3 presents the result of the threshold effect. For the Pre-Covid period, there is only one threshold exists, and for the Post-Covid period, there are two thresholds and significance at a 5% significant level. Hence, for the following threshold analysis, I use a double threshold model for the Post-Covid sample and use single threshold model for the Pred-Covid sample.

Table 3: Test of threshold effect

Period	Number of Thresholds	Threshold Value	p-value
Post-Covid	single threshold effect	22.831	0.004
	double threshold effect	22.831, 23.548	0.011
	tripple threshold effect	23.831, 23.548, 24.760	0.656
Pre-Covid	single threshold effect	22.032	0.031
	double threshold effect	22.032, 23.109	0.351
	tripple threshold effect	22.032, 23.109, 23.991	0.847

Pre-Covid are years before 2019 (includes 2019), Post-Covid are 2020 and 2021

Table 4: Analysis of threshold

Dependent variable	R&D ratio increasement	
	Pre-Covid	Post-Covid
Size$\leq r_1$	0.0120	0.0441*
	(1.33)	(1.85)
$r_1 < Size \leq r_2$	0.0234*	0.127***
	(1.91)	(3.93)
$Size > r_2$		0.0350*
		(1.93)
LEV	-0.0230**	-0.0730**
	(-2.27)	(-2.26)
ROA	-0.0932***	-0.0438***
	(-4.01)	(-4.92)
ATO	-0.0346***	-0.0245***
	(-6.39)	(-4.37)
Top1	0.0354*	0.0318*
	(1.85)	(1.91)
CASH	-0.0390**	-0.0561**
	(-2.07)	(-2.38)
GROWTH	-0.00534**	-0.00719**
	(-2.16)	(-2.46)
TOBINQ	0.00100	0.00203
	(1.48)	(1.29)
FIXED	-0.00678	-0.00425
	(-0.56)	(-0.54)
Constant	0.00401***	0.00351***
	(4.31)	(4.55)
N	1453	416
r2	0.613	0.536

t statistics in parentheses. Standard errors are clustered by firm.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 4 presents the result of the threshold analysis. For the Pre-Covid sample, firm size does not increase the R&D spending increase at a 10% significant level before the threshold 22.03. After the threshold, the influence of firm size on R&D increase is also trivial, only significant at a 10% significant level. This result indicates that before the shock, the firm size does not influence the increase of the R&D ratio, and the threshold effect is weak.

The second column presents the results of the Covid outbreak. It is shown that firm size could increase R&D increase, and the effect is the most significant and the largest (0.127) between the first threshold r_1 (22.831) and r_2 (23.548). When the firm size is lower than the first threshold r_1 or larger than the second threshold r_2, the effect is comparatively weak, but still significant at a 10% significant level.

The result of the threshold analysis effectively verified the result obtained in the theoretical framework. First, when an industry faces a systematic shock, firms with a larger size tend to invest more in R&D. Second, when firm size is below a certain threshold, the effect of firm size is weak, but when a firm exceeds a certain size, its R&D will increase tremendously. Third, when a firm is large enough, the effect of firm size on R&D increase becomes weak again.

5.3 Robustness test

To ensure the validity of the result, I also conducted a series of robustness tests, which include change of measurement of R&D, and change of sample time span. The results of the robustness test are displayed in the Appendix.

Instead of using $RD2$ (proportion of R&D investment amount in total operating revenue), I use $RD1$ (proportion of R&D investment amount in total assets). As is shown in column (1) of Table 4, the coefficient of $Big \times Covid$ is significantly positive at 1% level. After replacing the indicator of R&D investment, the regression results are still significant.

Meanwhile, there are many relatively small firms that increase or decrease R&D spending proportion dramatically, while the absolute number is not large. which may lead to some outliers in the sample. Therefore, I replace the R&D investment ratio with the natural logarithm of R&D, the result is presented in column (2) in Table 4, again validating the hypothesis.

Moreover, I adjusted the size. If the size (natural logarithm of total assets amount) of a firm-year observation is no less than the median (22.18), it is referred to be a big firm. size denotes a dummy variable indicating whether the enterprise is a big firm: if the enterprise is a big firm, the value of treated is 1; otherwise, it is 0. In column (3) of Table 4, the coefficient of $Big \times Covid$ is still significantly positive at 1% level, thus the result is still valid.

6 Conclusion

R&D investment plays a critical role in driving growth and productivity across industries. However, the magnitude of R&D investment varies among different industries and firms. In this study, I use a panel threshold model and analyze data from China's pharmaceutical industry from 2010 to 2021, I investigated the impact of the Covid-19 outbreak on R&D investment between different firms.

Based on the constructed one-shot R&D competition model, I hypothesized that big firms would respond more significantly to R&D opportunities compared to small-sized firms when faced with a systematic shock that provides R&D opportunities. Additionally, I proposed the existence of a threshold effect, where firms above a certain size level are more likely to allocate substantial financial resources towards R&D, while smaller firms may not participate in the R&D competition at all.

Additionally, by examining data from the Chinese pharmaceutical industry spanning the same period, I found that large pharmaceutical firms increased their proportion of R&D spending more significantly than small to medium-sized firms. In addition, I also observed a small but statistically significant increase in R&D spending among small-sized firms during the Covid-19 outbreak. This does not contradict the theoretical framework, because small-sized firms might invest in small-scale products related Covid such as cough syrup, while the model studies one large-scale R&D project competition such as Covid-vaccine.

Furthermore, by employing the panel threshold model, I verified the existence of a threshold effect in R&D spending during shock: if a firm is smaller than a certain threshold, the relationship between firm size and R&D spending increase is weak; above a certain threshold, this relationship becomes very strong and significant; when the firm size is even larger, this relationship weakens again.

These findings hold implications for both governments and firms, particularly within the pharmaceutical industry. For governments, these findings can inform decisions regarding subsidies to firms during systematic shocks like the Covid-19 pandemic and help in policy making. For firms, our findings can guide decisions on whether and how much to invest in R&D to pursue enhanced development opportunities.

References

Aghion, P., Bloom, N., Blundell, R., Griffith, R., & Howitt, P. (2005). Competition and innovation: An inverted-u relationship. *Quarterly Journal of Economics*, *120*(2), 701–728.

Aghion, P., & Howitt, P. W. (2008). *The economics of growth*. MIT press.

Aghion, P., & Tirole, J. (1994). The management of innovation. *Quarterly Journal of Economics*, *109*(4), 1185–1209.

Ayati, N., Saiyarsarai, P., & Nikfar, S. (2020). Short and long term impacts of covid-19 on the pharmaceutical sector. *DARU Journal of Pharmaceutical Sciences*, *28*, 799–805.

Ballot, G., Fakhfakh, F., & Taymaz, E. (2001). Firms' human capital, r&d and performance: A study on french and swedish firms. *Labour Economics*, *8*(4), 443–462.

Buchheim, L., Dovern, J., Krolage, C., & Link, S. (2020). Firm-level expectations and behavior in response to the covid-19 crisis.

Dakhli, M., & De Clercq, D. (2004). Human capital, social capital, and innovation: A multi-country study. *Entrepreneurship & Regional Development*, *16*(2), 107–128.

Druedahl, L. C., Minssen, T., & Price, W. N. (2021). Collaboration in times of crisis: A study on covid-19 vaccine r&d partnerships. *Vaccine*, *39*(42), 6291–6295.

Fang, X., Paez, N. R., & Zeng, B. (2021). The nonlinear effects of firm size on innovation: An empirical investigation. *Economics of Innovation and New Technology*, *30*(1), 48–65.

Griffith, R., Harrison, R., & Van Reenen, J. (2006). How special is the special relationship? using the impact of u.s. r&d spillovers on u.k. firms as a test of technology sourcing. *American Economic Review*, *96*(5), 1859–1875.

Hansen, B. E. (1999). Threshold effects in non-dynamic panels: Estimation, testing, and inference. *Journal of Econometrics*, *93*(2), 345–368.

Ishibashi, I., & Matsumura, T. (2006). R&d competition between public and private sectors. *European Economic Review*, *50*(6), 1347–1366.

Li, C., Li, Y., & Li, M. (2018). Controlling shareholder equity pledge and enterprise innovation investment. *Financial Research*, (7), 143–157.

Lim, K., Chesbrough, H., & Yi, R. (2010). Open innovation and patterns of r&d competition. *International Journal of Technology Management*, *52*(3/4), 295–321.

Loury, G. C. (1979). Market structure and innovation. *Quarterly Journal of Economics*, *93*(3), 395–410.

Malueg, D. A., & Tsutsui, S. O. (1997). Dynamic r&d competition with learning. *The RAND Journal of Economics*, 751–772.

Melnick, R. S. (2010). *Regulation and the courts: The case of the clean air act*. Brookings Institution Press.

Quirmbach, H. C. (1993). R&d: Competition, risk, and performance. *The RAND Journal of Economics*, 157–197.

Rafols, I., Hopkins, M. M., Hoekman, J., Siepel, J., O'Hare, A., Perianes-Rodríguez, A., & Nightingale, P. (2014). Big pharma, little science?: A bibliometric perspective on big pharma's r&d decline. *Technological Forecasting and Social Change*, *81*, 22–38.

Roper, S., & Turner, J. (2020). R&d and innovation after covid-19: What can we expect? a review of prior research and data trends after the great financial crisis. *International Small Business Journal*, *38*(6), 504–514.

Scherer, F. M. (1967). Research and development resource allocation under rivalry. *Quarterly Journal of Economics*, *81*(3), 359–394.

Schuhmacher, A., Gassmann, O., & Hinder, M. (2016). Changing r&d models in research-based pharmaceutical companies. *Journal of Translational Medicine*, *14*(1), 1–11.

Shefer, D., & Frenkel, A. (2005). R&d, firm size and innovation: An empirical analysis. *Technovation*, *25*(1), 25–32.

Shi, D., & Li, S. (2022). Research on the survival resilience of enterprises under the impact of the covid-19: Evidence from chinese listed companies. *Economic Management*, *44*(1), 5–26.

Van Uden, A., Knoben, J., & Vermeulen, P. (2017). Human capital and innovation in sub-saharan countries: A firm-level study. *Innovation*, *19*(2), 103–124.

Waheed, A. (2011). Size, competition, and innovative activities: A developing world perspective.

Yin, X., & Zuscovitch, E. (1998). Is firm size conducive to r&d choice? a strategic analysis of product and process innovations. *Journal of Economic Behavior & Organization*, *35*(2), 243–262.

Yuan, F., Yuan, P., & Zheng, Y. (2022). Research on the development opportunities of biomedical industry under the covid-19 epidemic. *Global Technology and Economic Outlook*, *37*(11), 28–33.

Appendix A: Robustness test

Table 5: Robustness test

	(1)	(2)	(3)
	RD1	LnRD	RD2
Big×Covid	0.00402***	0.8231***	0.00608***
	(7.16)	(4.19)	(3.13)
LEV	-0.00721**	-0.0174**	-0.0175**
	(-2.76)	(-2.64)	(-2.64)
ROA	-0.0157**	-0.0858***	-0.0859***
	(-2.63)	(-3.59)	(-3.58)
ATO	0.0107***	-0.0342***	-0.0342***
	(7.81)	(-5.92)	(-5.89)
TOP1	0.0279***	0.0383***	0.0379***
	(6.39)	(3.18)	(3.23)
CASH	-0.00391	-0.0471**	-0.0463**
	(-0.66)	(-2.35)	(-2.32)
GROWTH	-0.00143*	-0.00529*	-0.00529*
	(-2.07)	(-1.98)	(-1.99)
TOBINQ	0.00101***	0.00234***	0.00232**
	(3.37)	(3.12)	(3.09)
FIXED	0.00960**	0.00193	0.00136
	(2.79)	(0.28)	(0.20)
Constant	0.00537***	0.000427***	0.00416***
	(5.87)	(5.19)	(5.33)
N	2039	2039	2039
r2	0.839	0.823	0.823
Year_FE	Yes	Yes	Yes
Firm_FE	Yes	Yes	Yes

t statistics in parentheses. Standard errors are clustered by firm.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Appendix B: Solution for the equation system

Equation (6.1) is the equation system that needs to be solved to obtain the equilibrium of the R&D competition, where m_i represents the unknown variable, and the other variables are parameters.

$$\begin{cases} SUM = \sum_{k=1}^{n} S_k m_k \\ \frac{\partial E_1}{\partial m_1} = \frac{RS_1 SUM - RS_1^2 m_1}{SUM^2} - 1 = 0 \\ \frac{\partial E_2}{\partial m_2} = \frac{RS_2 SUM - RS_2^2 m_2}{SUM^2} - 1 = 0 \\ \vdots \\ \frac{\partial E_n}{\partial m_n} = \frac{RS_n SUM - RS_n^2 m_n}{SUM^2} - 1 = 0 \end{cases} \tag{6.1}$$

To solve the equation system, I convert it to an augmented matrix:

$$\left[\begin{array}{ccccc|c} 0 & S_1S_2 & S_1S_3 & \dots & S_1S_n & SUM^2/R \\ S_2S_1 & 0 & S_2S_3 & \dots & S_2S_n & SUM^2/R \\ S_3S_1 & S_3S_2 & 0 & \dots & S_3S_n & SUM^2/R \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ S_nS_1 & S_nS_2 & S_nS_3 & \dots & 0 & SUM^2/R \end{array}\right] \tag{6.2}$$

By applying elementary row operations (Gaussian elimination), I transform the given matrix into a diagonal matrix, from which I deduce the linear relationship between $m_1, m_2, ..., m_n$.

$$\left[\begin{array}{ccccc|c} 1 & 0 & 0 & \dots & 0 & f_1(S_1, S_2..S_n)SUM^2/R \\ 0 & 1 & 0 & \dots & 0 & f_2(S_1, S_2..S_n)SUM^2/R \\ 0 & 0 & 1 & \dots & 0 & f_3(S_1, S_2..S_n)SUM^2/R \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & 1 & f_n(S_1, S_2..S_n)SUM^2/R \end{array}\right] \tag{6.3}$$

$$f_k(S_1, S_2..S_n) = \frac{(\sum_{i=1}^{n}(\prod_{j,j\neq i}^{n} S_j)) - (n-1)\prod_{i,i\neq k}^{n} S_i}{(n-1)S_k(\prod_{i,i=1}^{n} S_i)} \tag{6.4}$$

Then I get the following equation according to the definition of SUM:

$$\frac{S_1 f_1 SUM^2}{R} + \frac{S_2 f_2 SUM^2}{R} + \ldots + \frac{S_n f_n SUM^2}{R} = SUM \tag{6.5}$$

$$\begin{aligned} SUM =& \frac{R}{S_1 f_1 + S_2 f_2 + S_3 f_3 + \ldots + S_n f_n} \\ =& \frac{R(n-1)\prod_{i=1}^{n} S_i}{\sum_{i=1}^{n}(\prod_{j,j\neq i}^{n} S_j)} \end{aligned} \tag{6.6}$$

Substitute the result (6.6) of to (6.3), the generalized solution for the equation system is:

$$m_k = \frac{R(n-1)(\prod_{i,i\neq k}^{n} S_i)[(\sum_{i=1}^{n}(\prod_{j,j\neq i}^{n} S_j)) - (n-1)\prod_{i,i\neq k}^{n} S_i]}{(\sum_{i=1}^{n}(\prod_{j,j\neq i}^{n} S_j))^2} \tag{6.7}$$

It can be simplified by replacing S_i with C_i:

$$C_i = \frac{1}{S_i} \tag{6.8}$$

$$m_k = \frac{R(n-1)C_k[\sum_{i=1}^{n} C_i - (n-1)C_k]}{(\sum_{i=1}^{n} C_i)^2} \tag{6.9}$$

Then replace it back, the final result is present as follows:

$$m_k = \frac{R(n-1)[\sum_{i=1}^{n} \frac{1}{S_i} - \frac{n-1}{S_k}]}{S_k(\sum_{i=1}^{n} \frac{1}{S_i})^2} \tag{6.10}$$