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Modeling Open R&D Eco-system via System Dynamics Approach A case study: Nanotechnology

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Abstract

Today, business environments are fast-changing and Nanotechnology-driven firms are opening up their organizational boundaries to tap into an external source for R&D activities. To reform the structure of the R&D activities in order to be successful, firms face challenges in finding a proper place in the R&D ecosystem. Therefore, this research examines the open R&D ecosystem through these key questions. Which components can form an open R&D ecosystem and how do interactions behave in a dynamic model? This research is done in 3 stages; the first stage is data collection based on the Fuzzy questionnaire, then the data analysis through the Fuzzy-DEMATEL method, and finally modeling the dynamics of the open R&D ecosystem. This research is applied in terms of purpose and descriptive survey information in terms of collecting information. The findings suggest that Nano-tech in Iran relies on two main components that affect each other: technological innovation performance and ecosystems. The result shows that inside the ecosystem, the most shares of activities is related to the Human Resources and governance sub-ecosystems. In addition, scientific works under the concept of technological innovation performance have the greatest impact from sub-ecosystems, and the balance between performance and ecosystem is a possibility for Nano-firms to do more R&D activities. Overall, this study provides a better understanding of open R&D by suggesting that further opening of the R&D ecosystem is necessary for nanotechnology.
Keywords: R & D Ecosystem, Technological innovation performance, Open R&D, System Dynamics

Introduction

R&D activities in a particular field cannot be limited to the same field, because these activities are composed of large and intertwined networks and influenced by performances (with inside), interactions (with outside), and environment (establishment) from the national to the firm-level simultaneously. In previous studies (Järvi et al. 2018) researchers demonstrate that recognizing, acquiring and exploiting external knowledge is important because discovering knowledge outside of a sector, industry and even geographical boundaries can create interaction and collaboration. The R&D activities are carried out through technological cooperation with cross-border that followed by border failure (at the macro, national, and micro levels, corporate or organizational level) which leads to the absorption capacity. These issues have been repeatedly evaluated by economists as they believe that R&D activities as the main driver of growth and sustainable economic growth; but what has been overlooked is that researchers look at a competitive advantage through knowledge acquisition, absorption capacity, or even technology transfer, but make no mention of environmental (context) impact. The context/environment has a unique opportunity

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to show the influencing, acquiring knowledge, data transformation, and business tasks of any actor across R&D activities borders. However, when it comes to how contexts affect research and development activities, researchers' views are quite different; this is the main issue that present study seeks to extract. As noted, in previous studies, most researchers have focused solely on the performance outputs of a system or unit independently and abandoned system analysis based on a holistic (ecosystem) approach. Obviously, mere attention to the performance of a system regardless of the deployment environment can lead to deviations in research; but the question arises is how to define the boundaries? (Inayatullah et al., 2016) are contended that language constitutes reality and a metaphor shapes and creates what you have to describe. Therefore, using a metaphor with a holistic concept can be a useful tool for better comprehension and ecosystem is one of these concepts. An ecosystem depicts a system as a set of different actors and networks that interact based on a wide range of goals. Therefore, identifying R&D components based on the concept of an ecosystem and evaluating the interactions between them can lead to accurate fact-based cognition. This requires real-world evidence, and nanotechnology has been chosen as a case study because it is based on a woven and interactive network. But here the question arises that:

Which components form an open R&D ecosystem in nanotechnology and how do they interact in it?

How is the behavior of the dynamic model of an open R&D ecosystem?

Therefore, the theoretical foundations and research background with a focus on the ecosystem concept and the technological innovation performance are presented in Section 2. The methodology is presented in Section 3 and the research findings and the dynamic model of the open R&D ecosystem are presented in Section 4. In addition, the results are presented in the final section to fill the research gap.

Literature Review

The basic definition of ecosystem entered the field of biology from 1935 by Sir Arthur Tansley in the field of business and James F. Moore considered its concept and model. Although the concept of ecosystem is used in the field of technology management and innovation without a clear definition or theoretical support(Adner, 2017; Tsujimoto et al., 2018),but the use of this concept has recently increased. So, in the first section, the concept of ecosystem is discussed as the aggregation of sub-ecosystems or value creation.

Ecosystem Metaphor; Aggregation or Value Creation

An ecosystem is defined as “A biological system composed of all the organisms found in a particular physical environment, interacting with it and each other (Tsujimoto et al., 2018). In his book -Mind and Nature- Bateson describes co-evolution as a process in which interdependent species evolve in an endless reciprocal cycle – in which “changes in species A set the stage for the natural selection of changes in species B” – and vice versa. Another insight comes from biologist Stephen Jay Gould, who has observed that natural ecosystems sometimes collapse when environmental conditions change too radically and new ecosystems then establish themselves, often with previously marginal plants and animals at the center. To extend a systematic approach to strategy, Moore(1993)in his research reveals that a company is viewed not as a member of a single industry but as part of a business ecosystem that crosses a variety of industries. The results of Adner's research(2017) provide a define the ecosystem: around the focal value proposition, not a focal firm; and in terms of elements that need to be brought into alignment, thus excluding those that are already in place and can be expected to stay put . In an ecosystem, if there are close (physically) and direct communication channels, participants will be more likely to interact with potential resources. Such views focus on that share a definition of the alignment structure of the multilateral set of partners that need to interact for a focal value proposition to materialize as well as provides the possibility to understand clearly about implications, boundaries, and relationships with alternative perspectives. Simon Marxon (1972) believed that research organizations often have various functions and ways of development in different ecosystems (space or climate)(Berchicci, 2013). The environment of every system is composed of factors which although not part of the system, a change in any of them can cause changes in the whole system. The system environment contains all the variables that can affect system status or be affected by it. The review of previous researches shows that a successful ecosystem has elements centered on the presence of key features (sources) like human capital, funding, services, the players concerned in this (talent, investors, mentors/advisors, entrepreneurial peers), the official (government & regulatory framework') and unofficial institutions (cultural support') facilitating entrepreneurship, and lastly contact to consumers in overseas marketplaces. Contrary to these opinions, some researchers believe that roots of an ecosystem should be considered regardless of similarities such as the types of coexistence (evolutionary, parasitic, and competitive) like seen in studies by Tsujimoto et al. (2018). They believe that the ecosystem has *five root* dimensions with which a system (national), a field (Nano-tech), or a set of activities (R&D) can be analyzed. These dimensions include *Attitude dimension, Actor dimension, Boundary dimension, Time dimension and Objective dimension.* Many firms are embedding in the "ecosystem" whose prosperity affects the success and survival of the ecosystem, which is further stabilized by shareholders and actors. If a firm is a "keystone" firm—the hub of a network—it should also act beyond its boundaries: "Keystones must manage the health of their ecosystems as a key business priority". Those involved in innovative activities are aware of the need for R&D collaboration to acquire expertise that cannot be produced in-house. This cooperation is defined as collaborations to achieve a common goal that is to develop new and improved products (technologies); Technological capabilities that can be improved for developing product and process innovations. In each government or country, Nano-tech is evaluated based on specific goals and approaches (the effect of environment on the field), however, countless similarities between them can be found. Iranian nanotechnology firms that are developing or improving new products need an effective search process to use new sources of knowledge and technology. As shown in the table1, most of the programs developed by policymakers include R&D activities with a network approach such as HR development, dissemination of scientific findings, development of laboratory infrastructure, intellectual property rights and patents, commercialization of R&D output, and increased investment in industries which seek to deepen the exploitation of this technology. Therefore, in this article, wherever the ecosystem is used, it conforms to Adner's definition and Tsujimoto's view. According to the explanations provided, the historical trend of Nano-tech in Iran is shown in the table below.

Table 1.
Dimensions of Nano-tech ecosystem based on Tsujimoto et al.(2018)

Objective	Attitude	Actors	Boundary / axis	Time	Wave
Presentation of Nano science Establishment of a technology committee Creation of a database	Laboratory network Scientific clusters	Scientific actors such as experts, students, professors	Service-oriented; R&D Publication of scientific works such as articles & dissertations	2000-2005	First

Objective	Attitude	Actors	Boundary / axis	Time	Wave
Content creation		Government actors (stakeholders such as executive institutions)			
Achieving a status among the top 15 countries Providing and training HRs. Providing infrastructure in technology development.	Scientific exchange networks Distinction between policy-making and Executive institutions Facilitating the path of technology-oriented firms to spoliation for scientific purposes outside the borders	*Commercial actors;* Small and medium firms *Government actors:* To activate the strategy of university, industry and government, such as science and technology parks *Knowledge actors;* Research networks in collaboration with international networks	*Service-oriented:* 10-year document of future strategy *product-oriented:* production of nanomaterials, production of equipment based on nanotechnology	2005-2015	Second
Demand-driven nanoscience Promoting international status Development of R collaborations with international actors Empowering the network of experts Provide incentives for the export of services and products.	Technology exchange networks Qualityism with the help of national and international standards Development of R&D environments Focusing on development with the help of incentives	*Commercial actors;* Large and industrial firms *Government actors* in the fields of automotive, metal, electricity, water, agriculture, food, medicine, oil, civil engineering and urban planning, environment, education *Knowledge actors;* from universities and research firms	*Service-oriented:* Second 10-year document; Develop the application of technology. *Product-oriented:* Production and export of engineering products, production of nanomaterials, production of equipment based on nanotechnology	2015-2025	Third

Ecosystem and Performance; Mutual or Bilateral Relation

The number of papers emphasizing the importance of value creation and capture in ecosystems and collaborative networks has been growing (Khademi, 2020). Firms build links and cooperate in R&D with their stakeholders, such as customers, suppliers, competitors, and public institutions. Moore believes that the interrelationships of components in an ecosystem and their support can be an important componentLike what the Iranian government does as a policy in nanotechnology; it is done through different institutions and with different policies tools. Governance acts as a metaphor in describing complex societies as a bridge across borders and is the response of policymakers to the dynamics of interactions in a changing policy environment(Sousa et al., 2020). How the ruler financially supports R&D projects in high-tech industries like Nano-tech (due to its high cost and failure rate) is a very complicated issue; nevertheless, the appropriate use of this policy tool can help the development of technology, knowledge, and commercialization in this. In the governmental policy system, good government refers to a normative term being defined in terms of "context" and good governance in countries has a significant positive effect on the intensity of R&D. The results of the study show that the relationship between suppliers and firms in the Nano sector is based on financial needs; this is the second strongest relationship that policymakers can influence to take action by ignoring boundaries. R&D activities, technological performance are affected by an intermediate component called commercialization(S. W. Kim & Choi, 2009). Among the definitions of commercialization, Ktepe's definition (2004) is the transfer of a scientific product created from the university to the industrial environment(Gholami & Hakak, 2021) and Downie's definition (2006) is the transformation of research results into products, services, and processes. Nevertheless, the commercialization of scientific research close to Downey's definition means the emergence of the benefits of science and has been used in this research. The relationship and interaction between the factors above mentioned are forming in a framework with the aim of facilitating the needs of society. As the research literature shows Nano sector uses various factors and components to affect the environment for R&D activities and the assessment of performance needs a systematic or comprehensive approach and requires the simultaneous investigation of the components with the environment or ecosystem. Therefore, to extract the structure of the ecosystem and examine how they relate to each other, it is necessary to use statistical and mathematical analysis that will be discussed in the next section.

Table 2.
Summary of literature review

Reference	Variables and descriptions
J. E. Moore(1996);	The relationships between components in an ecosystem and their support can be important components.
Boucher et al. (1982);	In form of a member of an intertwined network of related units and institutions, it is related to causal and multifaceted relationships. The ecosystem has five main dimensions/roots.
Leigh (2010);	Although the environment of any system is composed of factors that not part of the system, a change in any of them can cause changes in the whole system.
Tsujimoto et al.,(2018); Mao(2015);	The HRs development network has features such as dynamism, balance, integrity / competitiveness Infrastructure ecosystem improves the planning, design and implementation of traditional infrastructure and provides services based on interactions with a larger complex.
Sun et al.(2020); K. Lee (2014);	Good Government in countries has a significant positive effect on the intensity of R&D Appropriate use of financial resources can help the development of technology, knowledge and business in this area.
Bogers et al.(2018); S. K. Kim et al.(2011);	Evaluating the performance of innovative technology requires a systematic and holistic approach; in R&D activities, technological performance is affected by an intermediary component called commercialization; Exchanging and combining new combinations with existing knowledge can convert new ideas and concepts into a new product or service.

3. Research Methodology

This research has been done in terms of applied purpose and descriptive survey information in terms of data collection and in three stage According to Table 3.

Table 3.
Steps of Research Implementation

Stage	description	Step goal	Required measures
First	Delphi Panel	Collecting the opinions of experts	Selecting experts, designing a Delphi-Fuzzy questionnaire, collecting data, calculating data, conducting question rounds to achieve consensus among experts
Second	Fuzzy DEMATEL method	Investigating the causal relationships and their impact factors	Constructing the direct relation matrix, calculating the complete matrix, determining the network relation map, drawing the causal map and estimating the impact factors
Third	Dynamic system modeling	Achieving a dynamic model through the impact factors of the studied factors	Determining flow and level, drawing relation vectors, formulating and implementing the model, and analyzing the results

Extraction of Components by Delphi Panel Method

The experts have selected by purposive sampling method. According to the *Delphi* method does not need a sample size to be a statistical representation of the population; instead, the criterion in evaluating the representation of selected experts is being an expert, not the sample size. Therefore, the panel in this study consisted of selected university professors from the academic department in the field of R&D policies (five people), selected policymakers from Nanotechnology Innovation Council (five people), selected managers or experts of firms licensed by Iran Nanotechnology Innovation Council (five people) which had these characteristics:

1. Have published articles or research in the field
2. Have 10 years of experience in this field

Table 4.
The Selected Group of Experts

Type of experts	Position	Identified	Agreed	Published article	Years of service
Academic expert	University professor	5	3	yes	Over 20 y.
Policy expert	policymakers	5	3	Yes	Over 15 y.
Research	Manager or expert	5	3	Yes	Over 15 y.
All selected experts		15	9		

At this stage, the fuzzy-Delphi questionnaire is used to collect data and experts' opinions are converted into fuzzy numbers according to linguistic terms/variables. The triangular Fuzzy numbers represented by three real numbers as $M = (l, m, u)$(Alahyari & Pilevari, 2021) that the membership function is as follows(Leekwijck et al., 1999; Rahmani et al., 2016): $\mu_f{}^{(x)} =$

$$\begin{cases} \frac{x-l}{m-l} \\ \frac{u-x}{u-m} \\ 0 \end{cases} \quad (l<x<m,\ m<x<u,\ otherwise) \qquad \textbf{Eq. 1}$$

Table 5.
Triangular Fuzzy numbers and their linguistic Terms/variables(Leekwijck et al., 1999; Rahmani et al., 2016)

linguistic Terms	Fuzzy-triangular numbers (l,m,u)
Completely impressive, very high	(0.75,1.00,1.00)
Somehow impressive, high	(0.5,0.75,1.00)
Abstinent, ineffective	(0.25,0.5,0.75)
Somewhat deterrent, low	(0.00,0.25,0.5)
Completely deterrent, very, very low	(0.00,0.00,0.25)

Table 6.
Steps to implementing the Fuzzy-Delphi questionnaire

Step	Measures	Description
1	Sending the questionnaire	Preparing a questionnaire with a spectrum of five scales and the possibility of including comments at the end of the questionnaire
2	Converting the comments	Converting the verbal variables to triangular Fuzzy numbers $\tilde{A}^{(i)}=(a_1^{(i)},a_2^{(i)},a_3^{(i)})$ i=1,2,3,…,n
3	Measuring the sets	Collective measurement of experts' responses to the questionnaire using Eq. $\tilde{A}_m = (a_{m^1}, a_{m^2}, a_{m^3}) = (\frac{1}{n}\sum_{i=1}^{n} a_1^i, \frac{1}{n}\sum_{i=1}^{n} a_2^i, \frac{1}{n}\sum_{i=1}^{n} a_3^i)$
4	Defuzzification	The center of gravity method using Eq. $S_j = \frac{u_j+4m_j+l_j}{6}$
5	Evaluating the consensus of experts	Repeating the Delphi steps until the disagreement among the experts between the two polling stages reaches a very low threshold (0.2) using the following equation .$S(\tilde{B}_m, \tilde{A}_m) = \left|\frac{1}{6}[(a_{m^1}, a_{m^2}, a_{m^3}) - (b_{m^1}, b_{m^2}, b_{m^3})]\right|$

Network Relationship analysis with F-DEMATEL method

For analyzing of influence the factors extracted in the previous step, the causal relationships between them and the effectiveness of each factor on its corresponding factors are investigated by the Fuzzy-DEMATEL method. Thus, the pairwise comparison matrix is designed based on the variables extracted in the first stage and the data collected using the opinions of experts in the range 0 to 4. In this stage, the study population includes previous experts. Experts were chosen based on table 4.

Table 7.
Calculation steps, derived from the research(Bigdeli et al.(2019)

Step	Measures	Description
1	Interview with experts	Criteria of triangular Fuzzy numbers
2	Converting comments to Fuzzy numbers	$X_{ij} = (I_{ij}, m_{ij}, U_{ij})$
3	Direct relation matrix	Using Eq. $Z = \frac{x_1+x_2+x_3+\cdots+x_p}{p}$ Where P represents the number of experts and $Z_{ij} = (I_{ij}, m_{ij}, U_{ij}$ represents I_{ij}, m_{ij}, U_{ij}
4	Direct connection matrix normalization	By dividing each element DCM by K $\left(K = Max_{1\le i\le n}\left(\sum_{j=1}^{n} \acute{u}_{ij}\right)\right)$ and $\sum_{j=1}^{n} \acute{u}_{ij}$
5	dividing the normalized matrix into three definite sub-matrices	Dividing the normalized DMC into three definite sub-matrices $N_i \begin{bmatrix} 0 & \cdots & i_{1n} \\ \vdots & \ddots & \vdots \\ i_{n1} & \cdots & 0 \end{bmatrix} N_m \begin{bmatrix} 0 & \cdots & m_{1n} \\ \vdots & \ddots & \vdots \\ m_{n1} & \cdots & 0 \end{bmatrix} N_u \begin{bmatrix} 0 & \cdots & u_{1n} \\ \vdots & \ddots & \vdots \\ u_{n1} & \cdots & 0 \end{bmatrix}$

Step	Measures	Description
6	Obtaining a complete relation matrix	Every element FCM is calculated using $t_{ij} = (t_{ij}{}^{l}, t_{ij}{}^{m}, t_{ij}{}^{u})$, $T_i = N_i(I - N_i)^{-1}$, $T_m = N_m(I - N_m)^{-1}$ and $T_u = N_u(I - N_u)^{-1}$
7	Matrix defuzzification	Using the mean method $\frac{i+m+u}{3}$

Dynamic Model

System dynamics modeling is a tool for addressing complexity and combining feedback loops in systems, and the results of system dynamics models are valuable in identifying the factors influencing the results of processes, programs, and decisions. Therefore, in the third stage, the open R&D ecosystem model creates based on the output of the previous stage (Fuzzy-DEMATEL method). The input of this model is the amount of effect of each element on the system (effective factors on open R&D ecosystem) in various environments and conditions that can be computed by different methods such as DEMATEL. The output of the model determines:

How are the relationship between the factors and which factors affect the system and are affected by them?

VENSIM is one of the software platforms used to develop SD models and the mathematical equation for stocks (Swanson,2002):

$$stock(t) = \int_{t_0}^{t} [inflow(s) - outflow(s)]\, ds + stock(t_0) \quad \text{Eq.2}$$

The causal and stocks relationships are designed through VENSIM software. Toward SD model studied factors, the stock-flow diagram can be plotted after obtaining the casual model from Stage 2. Each factor allocates stock to itself. The outflow for each stock is a constant value, which is calculated based on the NRM in Stage 2 by means of computing R for each factor. Connectors are drawn from the outflow of each factor to the inflow of its corresponding factors based on the casual diagram.

Research Findings

Delphi Questionnaire with Fuzzy Data

As indicated in the previous sections, the questionnaire was designed based on the extracted factors so that the experts could determine the effect of each criterion on the other criterion. According to the research literature, it was determined which variables have been studied and can play a role in the ecosystem. Therefore, to achieve a theoretical consensus, the questionnaire designed and distributed among experts; in other words, the data is collected this way in the first stage. In the following, different rounds were held between them, and in the second round, a theoretical consensus was achieved. Table 8 shows the calculation.

Table 8.
Calculating Defuzzification numbers; consensus of experts in the third round

Factors	Lower bound	Middle bound	Upper bound	Defuzzificated values
HR development	0.75	1.00	1.00	0.96
Government	0.69	0.94	1.00	0.91
Scientific works	0.75	1.00	1.00	0.96
Infrastructure	0.50	0.75	1.00	0.75
Patent	0.54	0.79	1.00	0.79
Government	0.50	0.75	1.00	0.75
Commercialization	0.54	0.79	1.00	0.79

Since the Delphi stage must be repeated in such a way that the disagreement of experts in the two stages of the survey reaches a very low threshold (0.2) (Latifi et al.,2018). So the average opinion of the experts was calculated using the fifth stage and the results indicate a stop in the continuation of the survey.

Table 9.
Consensus in the average opinions of experts

Defuzzification geometric mean	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7
S_1	0.96	0.91	0.96	0.75	0.79	0.75	0.79
S_2	0.96	0.91	0.96	0.79	0.75	0.75	0.79
$\lvert S_1 - S_2 \rvert$	0.00	0.00	0.00	0.04	0.04	0.00	0.00

The theoretical consensus among experts indicates that the sub-ecosystems consist of HRs(Mao, 2015), financial resources, Government and infrastructure(Lee, et al., 2014), and sub-performances consist of Scientific works (Al.Ansari,2013), commercialization(Kimet al,2011) and patents are effective variables in the R&D ecosystem. Nevertheless, it is not yet clear which of them are effective and which are affected. So, in accordance with the question of research, (how do the components interact in the R&D ecosystem?) The fuzzy DEMATEL method is used to determine the relationship between them.

Table 10.
Classification of factors and sub-factors

Main Factors	Sub-Factors	Code
R&D ecosystem	HRs	S_1
	Financial resources	S_2
	Infrastructure	S_5
	Government	S_6
Technological innovation performance	Scientific works	S_3
	Patent	S_4
	Commercialization	S_7

DEMATEL Method with Fuzzy Data

To discover a casual model and efficiency coefficients, data were collected by pairwise comparison matrix among experts of the Nano-tech. The mathematical computation of DEMATEL with Fuzzy data has been performed by using Excel 2016. After setting *DCM* by using Fuzzy mean, *K* is calculated and all elements of *DCM* divided by *K* in order to normalize the matrix. Next, *FCM* has been set according to the method shown in table 4. Finally, defuzzification of FCM's elements has been done by using the averaging method.

Table11.
General relation matrix of sub-factors, k= 0.26434

	Total rows	Total columns	Total rows	Vertical vector
	D	**R**	**R+D**	**R-D**
HRs	1.2104	0.60671	1.81710	0.60367
Financial resources	1.14891	0.84785	1.99676	0.30106
Scientific works	0.37096	1.07746	1.44842	-0.70650
Infrastructure	0.61085	0.60543	1.21628	0.00542
Commercialization	0.82134	0.94483	1.76618	-0.12349
Government	1.15033	0.58335	1.73639	0.5698
Patent	0.40344	0.05058	0.45402	-0.64714

The sum of the elements in each row *(D)* shows the degree of its effectiveness on other factors and the sum of the elements in each column*(R)*shows the degree of effectiveness of the factors. The product of the sum $(\tilde{D}+\tilde{R})$ constitutes the matrix of superiority and the product of the difference $(\widetilde{D-R})$ forms the relation matrix. According to the overall relation matrix, technological innovation performance affects the R&D ecosystem and the sub-factors of technological innovation performance are affected by the ecosystem.

Table 12.
Effectiveness and Efficiency Matrix, Threshold Value=0.15255

	S1	S2	S3	S4	S5	S6	S7
S_1	0.12096	0.25802	0.23825	0.18653	0.18071	0.17310	0.17378
S_2	0.22480	0.13274	0.17661	0.18349	0.18931	0.17023	0.20448
S_3	0.09383	0.10428	0.10239	0.010	0.19337	0.07815	0.17759
S_4	0.19351	0.17732	0.13116	0.07964	0.11924	0.24003	0.11930
S_5	0.11474	0.22544	0.26468	0.10615	0.14290	0.10321	0.33122
S_6	0.18841	0.18707	0.20475	0.23541	0.17117	0.11339	0.16352
S_7	0.08613	0.11632	0.19316	0.08204	0.21027	0.08050	0.11235

In Table 13, the calculation of the impact factors is obtained by adding the level of the impact factor in the system on the elements of each row in the NRM.

Table 13.
The effect of factors on other factors

Patent	Government	Commercialization	Infrastructure	Scientific Works	Financial resources	HR
0.4034	1.1503	0.8213	0.6109	0.3710	1.1489	1.2104

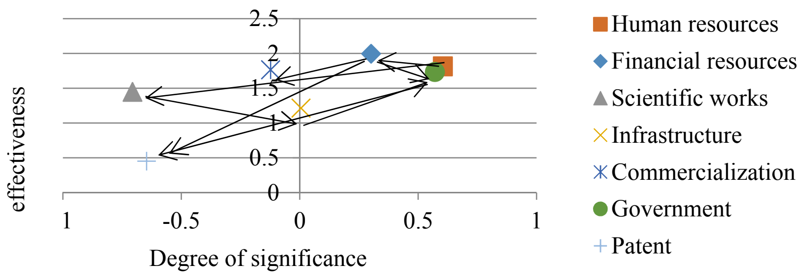

Figure1. Network Relationship Map

According to Asgharpour (2006), the DEMATEL method is used to determine the relationships between features and a causal structure that occurs between the factors instead of a direct structure. According to the opinions of experts and the quantitative values obtained in the normal direct relationship matrix, the values obtained can be used for the next stage which is called the modeling stage by system dynamic. The obtained values -which are not the same as well as directly related to each other- are used as a small degree of effectiveness and efficiency of the agents; For instance, infrastructure with a vector has no effect on commercialization, patent, inventions, and scientific works and has no impact vector.

Dynamic Modeling

A dynamic system is a way to study complex systems and since it is composed of semantic and feedback loops, linear and nonlinear relationships are analyzed behaviorally. In order to indicate a comprehensive image of the behavior between them, modeling can explain how relationships between them in the past and the effect of policies in the future become possible(Zolaikhaei & Radfar, 2020). Therefore, after determining the casual diagram and efficiency coefficients (Stage 2), the stock-flow diagram of studied factors can be drawn according to Figure 2. Comparing outflows by using Table 13, or outflow values indicates that "HRs development sub-ecosystem" has been the highest and "Scientific Works" has the least influence on the system. Since the field of nanotechnology in Iran is not very old, the period from the beginning of 2006 to the end of 2036 is considered and the details of the existing relationships (direct and indirect) are presented in the causal model of the process (Table 14).

Table 14.
Relationships between variables

Description	Sign	Relationship
Government has a positive relationship with HR development and creates a good two-way relationship between government and HR development. Government improving HR development and economic growth in countries	+	Government→ HR
Ćudić(2021) and Ganzert et al.(2014): there is a direct and positive relationship between the HRs development index and patent.	+	HR → Patent
Mirghfoori et al.(2018): the HRs and financial resources are key options in innovation development and commercialization	+	HR→ commercialization
Baycan(2013): The commercialization of academic knowledge is increasingly seen as a improve capabilities and performance.	+	HR →scientific works
The patent law is a significant policy tool for promoting innovation, developing new technologies (Mahmoudpour et al., 2021)	+	Government → Patent
Government has a significant positive effect on knowledge overflow in developing countries.	+	Government→ Scientific works
Mirghfoori et a,(2018): most of the macro-policy in motivating factors for registering different types of intellectual property is in the government.	+	Government→ Commercialization
The quality of Government (average of six good Government indicators) has a positive effect on the HR development index	+	Government→ HR
The impact of abundant and natural resources depends on the government of a country, and the government can be the source of resources.	+	Government→ infrastructure
Financial and economic interaction outside their climate borders will be able to affect human development indicators effectively.	+	Financial resources → HR
Mirghfoori et a,(2018) indicated that human and financial resources are key options in the development of innovation and commercialization of knowledge-based companies.	+	Financial res.→ Commercialization
Government financial support use as policy tool to development of technology, commercialization and dissemination of knowledge Mirghfoori et a,(2018)	+	Financial resources →scientific works
Ćudić (2021): the existence of a long-term and two-way relationship between the indicators of intellectual property protection index and economic growth; Patent is as R&D outputs and is one of the performance indicators of science and technology, indicating the effectiveness of R&D costs	+	Financial res. → Patent
K. Lee (2014) : the supply of services based on infrastructure and vital resources is formed in a larger ecosystem and population growth is directly related to the infrastructure index	+	Infrastructure→ HR
Dunn(2020): The commercialization of scientific research means the emergence of benefits from science and transfer of a scientific product created.	+	Commercialization → patent

Following the previous table and second stage, it is possible to draw a circular diagram

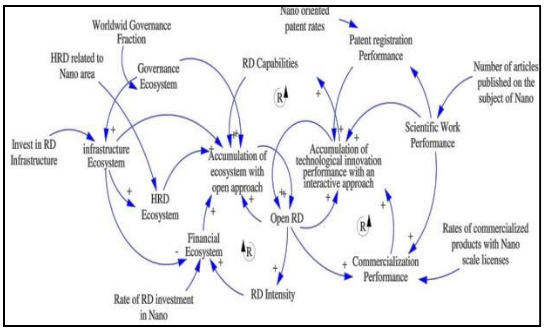

Figure2. Cause diagram (loop)

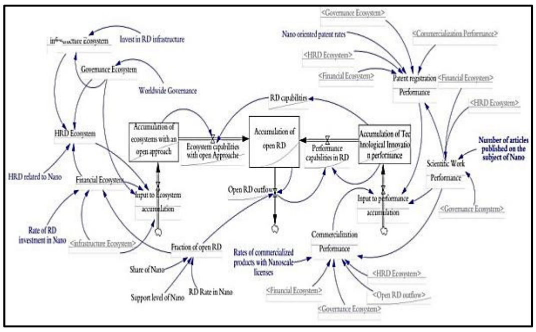

Figure3. Flow diagram

Technological Innovation Performance accumulation Loop; with interactive approach; Increasing commercialized products has a positive effect on commercialization performance (J. Kim & Choi,2020)in the Nano-tech and leads to the accumulation of technological innovation performance in this field. Furthermore, growth in accumulation causes R&D capabilities to have a positive effect on ecosystem accumulation (Jianmin & Li,2020) and consequently, on open R&D. Accumulation in the performance of technological innovation will directly stimulate the rate of open R&D and will have a positive effect on the performance of commercialization (Matricano, 2020) in this area, representing a strengthening loop.

Open Approach ecosystem accumulation loop; This loop is composed of HRs, ecosystem accumulation with an open approach, open R&D and intensity of R&D in the field of nanotechnology. Increasing investment in nanotechnology leads to growth in the financial resource ecosystem (including venture capital funds, related institutions such as Iran Nanotechnology Innovation Council, and banks operating facilities in the field) and accumulation in the ecosystem that can increase the rate of open R&D in the field of nanotechnology. Open R&D has a positive effect on the intensity of R&D in line with the reinforcement of the loop. Although it is highly useful to draw the structure based on causal loops to start modeling, state and flow variables are used for evaluating the policies. The state variable shows the state of the system at a given time and involves the concept of its accumulations. On the other hand, the rate variable involves the input and output current of the state variables. Fig. 4 indicates a comprehensive dynamic model of the open R&D ecosystem in Nano-tech, which is the result of literature review, theoretical agreements between experts and the output of the DEMATEL method with Fuzzy data.

between the variables and explain the systemic feedback of the loops (equilibrium or reinforcement). In the cause diagram, three reinforcing feedback loops are described as follows.

Model Validation Test

In the evaluation of the validity of the dynamic model by Sterman (2000), various tests for model validation mentioned. In the following, three tests are based on structural and one test is based on behavioral validity.

<u>*Model Structure Test;*</u> the basis of model behavior is model structure. This test is whether the model structure matches the structure of the modeled system. Every element of the model should have a real-world counterpart, and every important factor in the real system should be reflected in the model. Experts adapted the structure to the real world and affirmed it.

<u>*Dimensional/ Consistency Test;*</u> this test is a powerful test to establish the internal validity of the model. The test checks the dimensional consistency of measurement in its expressions on both sides of an equation. For this reason, the

dimensional test was reviewed and the model experts approved.

Boundary adequacy Test; the model boundaries must match the purpose for which the model is designed, if the model is to be used with confidence: that is, the model must include all of the important factors affecting the behavior of interest. This test was also performed and experts approved the model. As mentioned before, in this section, the model behavioral test, so the square root errors (RMSPE) test was chosen. In this regard, the error rate is calculated based on the following formula:

$$RMSPE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}\left(\frac{S_t - A_t}{A_t}\right)^2} * 100$$

Eq. 3

S_t : results of stimulating the model variable

A_t : real data

n : number of observations

Identification of error roots: Due to the significance of error in forecasting, the error roots are related to three factors:

Base error: Model outputs and data are not related to each other

Deviation error: The variance of real data and simulation are different.

Covariance inequality error: The results of the model and the data are not correlated.

Table 15.

Results of testing the model errors in terms of simulation (research findings)

Error test indication of key model variables	Deviation error	Base error	RMSPE	Covariance inequality error
Scientific works	0.025	0.054	2.41	0.089
HRs	0.03	0.07	0.21	0.00

The results of testing the error in the table in terms of two key variables (maximum effectiveness and efficiency) indicate that it is at an acceptable level.

Scenario Development; Adopting Appropriate Policies

Scenarios are not merely the choice of the desired future, the realization of the future, or its implementation, but it is a strategic decision for a wise future. When the behavior of several variables is studied simultaneously, there is a need to evaluate the interrelationship between these variables in the form of a simultaneous equation model called the dynamic equation model. Therefore, the two main policies related to the dynamic model should be analyzed and for this purpose, the role of sensitivity analysis by the Monte Carlo method will be explained and then the policies will be examined. The ***first central policy; Impact of sub-ecosystems on the ecosystem***; The *Monte Carlo simulation* method is a computational algorithm that uses random sampling to calculate the results. Importantly, as the more repetitions of the simulation are more, the results will be more reliable; thus, the number of repetitions in the simulation was considered 200 times. Due to the research findings and the maximum effect of HR development and Government in the open R&D ecosystem (DEMATEL stage), the focus of scenarios is based on them. For this reason, both components are analyzed by ±20% variation and selective random uniform distribution in the production of random numbers through Vensim software. The simulation results indicated that the worldwide Government component will increase the output of the open R&D ecosystem in the Nano-tech by 12% and the HR development (HRs ecosystem) will increase it by 6% will the end of the simulation year (2036). The results of some studies indicated the powerful role of the government in Nano-tech. The formation of nanotechnology development functions is conducted by institutionalizing and enacting laws and forming the market and entrepreneurial activities through directing research, innovation, supply and allocation of resources for creating, developing, and disseminating knowledge through the government or the ruler. In order to confirm the research findings, the results of some research (Kutasi & Marton, 2020) indicated that Government has a significant positive effect on economic growth in the long term. In addition, a 1% increase in the Government index will lead to a 0.02% increase in economic growth. In recent years, there is a general belief that institutions are the main cause of differences in different levels of per capita income, economic growth and development of countries. Numerous studies indicated a positive correlation between sustainable performance in HR management and firm performance in terms of environment or ecosystem(Piwowar-Sulej, 2021). Nevertheless, there are some concerns that HRs, who are significant actors in the ecosystem, may not be in line with the complex environment (Cross & Swart, 2021).

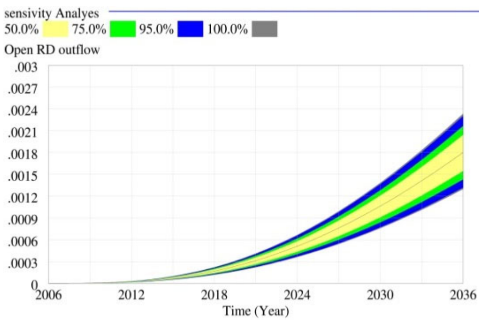

Figure 4- Open R&D relative to WG index

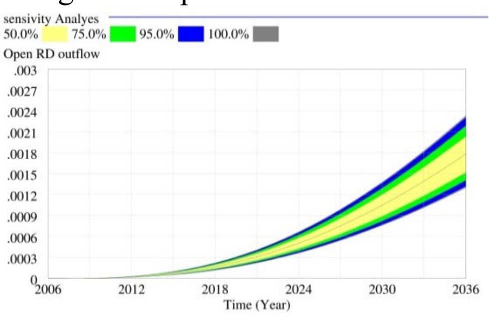

Figure 5- Open R&D relative to HRD index

The second central policy; Impact of performances on the ecosystem; in this section, published articles, commercialization rate and patent with ± 50%variation and uniform distribution selection the production of random numbers in Vensim software are analyzed. The results indicated that published articles increase the output (as performance) of the open R&D ecosystem in the amount of 0.0231%, the component of commercialized and certified nanoscale products in the amount of 0.0006% and patents in the amount of 0.0007% at the end of the simulation year (2036).

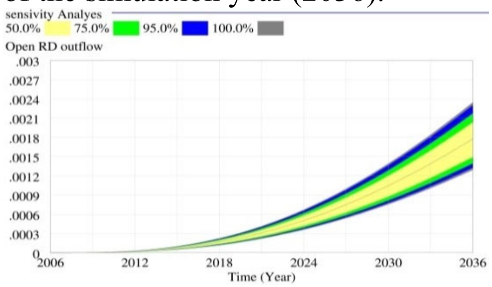

Figure 6- changes by published article index

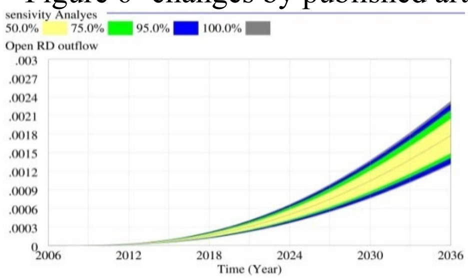

Figure 7- changes by commercialization index

According to findings, scientific works (such as related books, dissertations related to nanotechnology, and articles in the Nano) have the affected by sub-ecosystems. In confirmation of this issue right policies to guide inputs (such as vertical policies like supporting priority subjects aimed at patent growth, commercialization of products, and creation of start-ups and horizontal policies like financial incentives for articles and patents) can lead toward output such as article, book or even patent. The dynamic model of the open R&D ecosystem also shows the factors/components of commercialization, scientific works, and patents (intellectual property) are affected by other sub-ecosystem.

Conclusion

In previous studies, it was observed that there is a theoretical gap due to incoherence or dispersion in the research topic and the overlooked issue is which components shape the structure of the open R&D ecosystem and how they played in it. Therefore, this study seeks to answer these questions and examine the components/factors of the open R&D ecosystem in the field of nanotechnology as well as their complex behavior through a dynamic model. The findings of the literature review show that the open R&D ecosystem has two main dimensions: *ecosystem and performance*, and each dimension are influenced by sub-factors. The ecosystem dimension included *HR development, financial resources, Infrastructure, Government* and performance included *scientific works, commercialization and IP*.

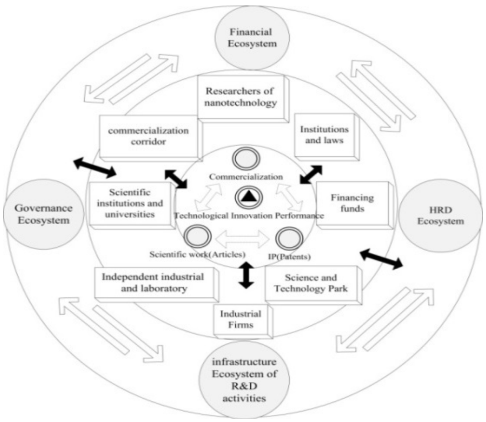

Figure 8 - Components of open R&D ecosystem (Research Findings)

Findings from the causal analysis indicated that the HRs sub-ecosystem with a value of 1.2104 units and scientific work with a value of 0.3710 units have the most effective and most affected factors among other components in the structure, respectively. But the question is; how do the performance and sub-ecosystems are behaving in the model? For this reason, two scenarios were considered which are the performance approach and the sub-ecosystem approach. One of the components of science and technology performance is the published article Index in a specific field. However, it should be noted that despite the decrease of citations to published articles, the number of published articles has increased, As well as for this reason Iran has ranked fourth in the production of science in nanotechnology. The index of publishing scientific articles can be misleading and far from reality, and replacing citation index with published article index can show the quality and visibility of scientific studies, the flow of activities resulting from R&D and output resulting from science and technology policies. Therefore, in this scenario, a citation index is used instead of the index of the published article. Finding shows that scientific works have the highest effectiveness among factors with a value of 1.0746 units. The accumulated performance follows a linear function, and the performance of scientific works *(O_s)* is affected by $Output_S^d = f(G_x, H_x, F_x)$ factors, which are the government ecosystem *(G)*, HRs development *(H)*, and financial resources *(F)*, resources. Since scientific works affect technological innovation performance, the slope of effectiveness can be changed through this variable, which also has been identified as the most affected factor in the model in its Fuzzy-DEMATEL analysis. This policy is based on a demand-driven approach and can change the slope (degree) in a short time. As shown in the figure below, the results show that every 0.1% increase in scientific works (such as the number of published articles) can increase the output of R&D by 0.2%.

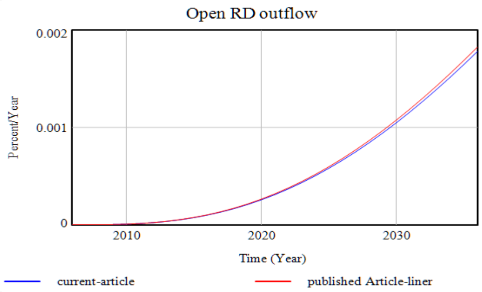

Figure 9- the publication of articles

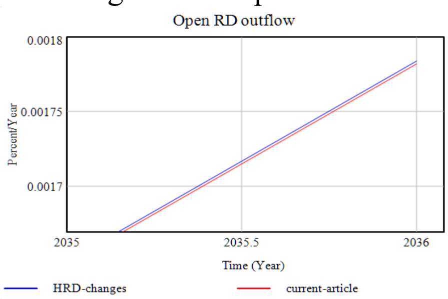

Figure10- the HRs

Another result of the dynamic model shows that R&D is accumulated from flows (TIP and sub-ecosystem) and is sensitive to all components affecting accumulations. The accumulation of the linear behavior performance follows the function $f(y) = ax + b$ and the accumulation of the exponential behavior follows the function $f(y) = a^x$ because$a > 1$. Since the goal of the ruling policies in the field of nanotechnology in Iran is to increase the output of R&D activities, it is possible to increase the slope of effectiveness in the model through the HRs development ecosystem, which was identified as the most effective factor in the model. This policy is based on the supply-oriented approach, and in this case, the obtained result is an exponential function with relation $f(t) = h(1 + r)^t$ in which f(t) represents the final value in the HR ecosystem, h represents the initial amount of HRs, and r represents the growth rate and t represents the time which is 30 years. What the dynamic ecosystem model shows in the final year of the simulation is an increase of 0.0189%, as shown in the figur10. The open R&D ecosystem as open innovation is a spectrum: from closed to open spectrum. Since open R&D can no longer be a zero-sum choice, analyzing the degree of openness (fully open or semi-open) behind stabilizing their position is a necessity for nanotechnology companies.

The dynamic model simulation showed that scientific works, commercialization and patent as technological innovation performance can evaluate the ecosystem in terms of openness. In confirming this issue, A study by Camisón-Haba et al., 2019 showed the correlation between R&D and the number of patents. Therefore, the presence of product data in the international database, disclosure of inventions in foreign offices and the amount of h index related to published articles can determine the degree of openness of an ecosystem under the concept of degree of performance. In other words, a change in the rate of accumulation of sub ecosystems causes a change in the accumulation of performance in the Open R&D ecosystem.

This is the first study to address the issue of the open R&D ecosystem. As mentioned earlier, the issue of this study has not been done before or there is no similar research. One of the innovations of the research is the aggregation of experts' opinions in the intuitive Fuzzy method and its transformation into influential factors (combined approach) as well as the analysis of their impact on similar factors in the field of nanotechnology. The current situation in the Nano sector was analyzed based on facts and not on plans or policies and even strategies. Nanotechnology policymakers can monitor the impact of their policies on short-term or long-term plans based on the proposed dynamic model. Based on the research results, the existence of a performance indicator to evaluate the efficiency of the ecosystem is suggested. Because this index helps to calibrate the ecosystem and one of the limitations of this research is this index. This hybrid index can be generalized to high-tech sectors such as biotechnology, where technology-based companies are often located. Therefore, it is proposed to create a hybrid index and utilize the proposed model to assess the position of the companies in order to expand the R&D activities.

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