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Simulation of research and development collaborations as complex socio-technical systems using a hybrid of agent-based modelling and system dynamics

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Abstract: Today, organisations collaborate to use more resources and reduce the risk of technological activities. The result of these collaborations is complex systems with socio-technical characteristics that, despite the many benefits, bring new and different problems and challenges for them. The current research intends to study these collaborations not as a static phenomenon but as a dynamic and heterogeneous system with various socio-technical characteristics, contrary to the prevailing practice in research in this field. Therefore, system dynamics and agent-based modelling are used to model an R&D collaboration system. Validation tests and comparison of simulation results with the actual behaviour of the system show success in recognising and representing the system under study. Findings show that using a socio-technical perspective and its methods helps to capture and structure the complexity and problems of systems and the interrelationships of these problems in a holistic view.

Keywords: socio-technical approach; research and development collaborations; system dynamics; agent-based modelling; AnyLogic software; modelling methods; simulation; cooperation; innovation; startups; applications.

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1 Introduction

Research and development collaborations are an alliance of two or more partners, entities, or individuals whose goal is to develop technology projects in collaboration with each other (Auster, 1994). R&D collaboration has features that can be described as complex socio-technical systems. The complexities of R&D collaborations stem from different sources such as different types of partners, diversity of information, structural complexity, and the diverse goals and content of R&D projects (Arroyabe et al., 2015). The existence of various social aspects such as working groups, staff, and professionals active in the form of teams and technical aspects such as technology and products being developed, have turned these systems into systems with both social and technical characteristics. In addition, collaboration systems similar to other complex socio-technical systems have features such as diversity, evolution and emerging behaviour. The R&D collaborations are a metasystem with a visible heterogeneity among its component systems (Arranz and Arroyabe, 2009). These systems are a combination of different partners and stakeholders and as a result, are more diverse compared to each of the component systems that make it up (Agusdinata and DeLaurentis, 2008). Also, during R&D collaborations, goals and functions are added or subtracted to the system, and gradually an evolutionary development process occurs as a result of partner learning (Chiesa and Manzini, 1998). In this evolution, an emerging capability is created (Boardman and Sauser, 2006) and the collaboration system reaches features and goals that are the result of the whole system and cannot be seen or met locally in any part of the system (Mostafavi et al., 2011). Organisations need to make decisions on a variety of issues to manage R&D collaborations. Among the most important of these issues are determining the purpose of collaboration, determining the type of partner, determining the organisational form of collaboration, and the mechanism of project management and control. But the complexities of such projects, which are in constant interaction with the environment, do not make it easy to manage and structure these problems. Despite numerous studies on R&D collaborations in recent years (for example Vom Brocke and Lippe, 2015; Carvalho et al., 2017; Ettlinger, 2017; Bacon et al., 2019; Eiteneyer, 2019), most of these studies either with the purpose of exploration and using inductive approaches and qualitative research strategies tried to discover dimensions and respond to specific issues in these collaborations or Using survey studies, they sought to identify the relationships between variables and provide static conceptual frameworks to explain R&D collaborations. Despite the valuable achievements of these studies, few studies have addressed the nature of these collaborations as a coherent, dynamic, and evolutionary whole with a complex structure with high heterogeneity. In addition, the issues of these collaborations have been discussed separately and without regard to the interdependence between them. This may be due to the lack of attention of these studies to the complex and dynamic systemic nature of these collaboration systems. Therefore, the current study tries to show that dealing with R&D collaborations from the perspective of a complex socio-technical system can help to understand these systems better and their problems. It also makes it possible to use powerful tools to model and simulate the behaviour of these systems and test different scenarios and policies. The hybrid uses of socio-technical systems modelling methods helps to model the various dimensions of the system under study and its complexities in a holistic view. Therefore, in the current study, an R&D collaboration system is simulated as a complex socio-technical system using a combination of agent-based modelling and system dynamics methods.

2 Research background

This section deals with the background of research and studies that are considered the most important features of R&D collaborations that make them referred to as complex socio-technical systems. It also discusses studies that address the most important issues of these systems, which should be considered in their modelling and simulation.

Arranz and Arroyabe (2009) introduce R&D collaborations as complex systems. Using the study of a large sample of collaborations in Europe, they show that the complexity of R&D collaborations stems from the heterogeneity of their constituent factors. They also point to other features of these collaborations with different network structures and subsystems. Another reason for the complexity of these systems from their point of view is the content and nature of R&D activities. However, the picture presented by this study regarding the problems and features of the system is static and fixed, which contradicts the systemic approach adopted by them. Uyarra et al. (2014) have examined and identified the most important problems in the collaboration between companies in innovation, especially in collaboration with the public sector. In this study, they show how issues related to processes, competencies, procedures, and relationships affect outcomes. The most important issues identified include lack of interaction with government agencies, low partner competencies, and poor risk management during the process. In this study, problems were identified using a survey. However, despite helping to identify issues and problems in innovation partnerships, these issues have been examined separately and an overview of the issues and the interconnections and relationship between these issues have not been examined. Arroyabe et al. (2015) have examined the structural factors of R&D collaboration systems as well as features such as multiplicity and diversity of elements and their impact on system performance. In an exploratory study using structural equation modelling and neural networks, they examined the role of structural variables on the performance of joint projects in Europe. This study examines the effect of structural variables, i.e., the number and type of partners and the intensity and density of interactions in networks and their impact on the performance of R&D collaborations, and show that these structural variables are good predictors of project performance. In this study, a static model has been proposed to describe the structural features of the system. But other characteristics, including social features, have not been considered. For example, a large number of partners can simultaneously increase the level of conflict in the system due to the different interests, views, and values of the partners. In this study, less attention has been paid to such factors and it is also not clear to what extent increasing diversity and multiplicity in partners leads to improved performance. Vom Brocke and Lippe (2015) in a comprehensive study have examined the most key issues in R&D collaboration. They claim that these collaborations generally face high levels of uncertainty and risk, heterogeneous partners in different places, and significant pressures on creativity and innovation. Therefore, they consider research collaborations as complex systems with a high degree of high uncertainty and variability. The study also concludes that R&D collaborations often face the problem of carefully planning and measuring the performance of research projects. Another issue addressed in this study is the high diversity of individuals and human elements of an R&D collaboration system. These collaborations are challenged by employing a diverse range of people, especially those with national backgrounds, job cultures, employment status, project rules, and specific skill sets. Different and sometimes conflicting expectations of stakeholders usually emerge in these partnerships. Another common issue in these collaborations is project management and control, despite the limited powers of managers due to the independence of partners and governance structures. In this study, all the issues raised have been analysed separately, and no attempt has been made to link the issues and look at them in the form of a system of issues. For example, in this study, high uncertainty is recognised as one of the problems of collaboration systems. This uncertainty can be related to other challenges of these systems, i.e., the diversity and the high number of stakeholders or the technological content of related activities, and lead to other challenges identified in the system, such as difficulty in evaluating and controlling performance. Ettlinger (2017) examines the dissatisfaction and problems of innovation collaborations. It is one of the few studies that examines the negative aspects of such projects from a critical perspective. It points to the fact that in these partnerships, innovations, and benefits are shared between the partners, and the parties benefit from a long-term relationship. But contrary to the strongly positive view of the benefits of such collaborations in the literature, problems like the failure of stakeholder expectations collaborations occur. Large corporations work with public and non-profit organisations to fulfil their social responsibilities ostensibly, but in practice and indirectly stimulate demand for their products and services. Even these companies reduce their internal R&D costs in the form of supporting start-ups or crowdsourcing competitions and enjoy the benefits of expert participation and new ideas without worrying about intellectual property rights and high costs. However, in this study, no case study or empirical study has been conducted to verify these claims, and to confirm the author's claims, only evidence from previous research has been provided. Carvalho et al. (2017) analyse the systems of innovation and R&D from a socio-technical perspective. They believe that innovation does not happen in an isolated environment, but depends on a variety of factors, especially within the organisational context, and it must be acknowledged that the relationship between system actors can influence the outcomes of these systems. Therefore, they claim that with the development of innovation studies, the socio-technical approach is used as one of the foremost perspectives to explain innovation processes. According to this view, innovation emerges through the interaction of processes and activities, elements, networks, etc. with the characteristics of a social and technical system, and institutions also play an important role in it. They see institutions as social structures that seek to balance the system when faced with social pressures. Institutions are actions that define the behaviour of a group and have meanings that legitimise it. This study well illustrates the value of using a socio-technical perspective to study innovation systems, but this study remains at an abstract level and does not provide a precise and objective approach or framework for studying innovation systems using a socio-technical perspective.

Table 1 summarises the most important features of R&D collaborations as complex socio-technical systems:

Table 1 Characteristics of R&D collaboration systems as socio-technical systems

Characteristic	*Description*	*References*
Dynamics	R&D collaboration systems are dynamic phenomena that change their characteristics and elements over time	Vom Brocke and Lippe (2015) and Carvalho et al. (2017)
Evolutionary development	As a result of learning, a collaboration between partners, and efforts to adapt to the environment, R&D systems gradually take shape over time	Chiesa and Manzini (1998) and Mostafavi et al. (2011)
Emerging behaviour	In R&D collaboration systems, functions, features, and behaviours emerge that do not exist in each of its constituent elements or subsystems	Mostafavi et al. (2011) and Arroyabe et al. (2015)
Independence	The elements and subsystems that make up R&D systems, despite their efforts to achieve common goals, have relative independence for membership, decision-making, and action	Vom Brocke and Lippe (2015) and Ettlinger (2017)
Diversity	Heterogeneity is deliberately increased in R&D systems to take advantage of it to achieve system goals	Sampson (2005) and Arranz and Arroyabe (2009)
Multi-level and network structure	R&D collaboration systems themselves consist of small systems and possibly part of a larger system, and within this multilevel structure, different networks are created	Chiesa (2000) and Arroyabe et al. (2014)

3 Research methodology

To better understand the case study as an example of R&D collaboration systems and the complexity of its behaviour in this study, simulation is used because of its various advantages (Grigoriev, 2016). First, simulation models make it possible to analyse solutions to complex system problems that approaches such as analytical methods and linear programming fail to solve. Also, because of the high abstract level of systemic approaches, it is easier to develop a simulation model than an analytical model, due to the modular and gradual nature of the simulation process. Also, a simulation model reflects the structure and behaviour of the system relatively naturally, and comparing it to the actual behaviour of the system can well illustrate our understanding of the complexities of the system. Moreover, the use of the simulation model makes it possible to measure the value and examine the behaviour of individual elements of the system, besides the overall behaviour of the system. The methods used to simulate the system under study are system dynamics and agent-based modelling. The main reasons for choosing these two methods for simulation are:

- The two methods of Agent-based modelling and system dynamics are widely used for simulating complex systems (Gómez et al., 2014; Held et al., 2014; Bukowski, 2016) and have computer simulation capabilities dislike other methods for modelling socio-technical systems (McDowall, 2014; Ray and Robinson, 2015)
- Agent-based modelling and system dynamics both help to create a learning and quasi-realistic environment (Sterman, 2000; Nikolic and Kasmire, 2013). This feature makes it possible to understand the behaviour of a system even with a socio-technical nature through simulation.
- Agent-based modelling and system dynamics both seek the same goal of recognising and representing system behaviour but with different approaches. Agent-based modelling with a bottom-up approach helps to understand system behaviour when there is no information about system behaviour at the aggregate and high level, but there is a relative understanding of how components work individually (Nikolic and Kasmire, 2013). While system dynamics with a top-down approach helps to understand the main determinant structure of system behaviour and leverage points affecting system behaviour (Sterman, 2000). Therefore, the hybrid use of two methods is very effective in understanding the behaviour of the system.

AnyLogic 8.2.2 software is used for simulation. This software has been welcomed by researchers in systems modelling due to the possibility of simulating different models of system dynamics, Agent-based and discrete-events. One of the most critical features of AnyLogic that distinguishes it from other simulation software is the ability to combine models made by different methods in a software environment and run an integrated model simulation (Borshchev, 2013; Ivanov, 2017).

But to create a computational model, a basic knowledge of the elements and their demands on each other must be obtained. This was done through document review and interviews with stakeholders. Documents were collected and interpreted, as well as interviews, using predefined protocols to ensure sufficient transparency and reproducibility.

4 Data analysis

The Case study is an R&D collaboration between an international company operating in the electronics industry, from now on referred to as the Company, and a technical university from now referred to as the University. The partnership is aimed at establishing a start-up support Center for application software development called the

Center. In this Center, teams of creative people, mainly students, develop application software with the hardware and financial support of the University and the Company. Because of this collaboration, a system has been formed that includes different actors and subsystems that, while having independence, pursue common goals and at the same time have different interests. Also, this system is in the growth stage, and its evolution largely depends on the function of each factor and the whole system. To identify the issues, the documentation of the collaboration system was carefully reviewed and several interviews were conducted with the system stakeholders to identify the technical and social issues to prepare a conceptual model. Then the conceptual model was translated to a computational model. Table 2 summarises the reasons for recognising the system as a complex socio-technical system.

Table 2 Characteristics of the studied system as socio-technical systems

Characteristic	*The system*
Dynamics	Changes in the number of startups, number of products developed and under development, credit allocated to startups, number of consultants, and training courses over time
Evolutionary development	Becoming a reputable Center for supporting entrepreneurship and software developers with the support of a large number of startups from a fledgling growth Center providing services to a small number of idea owners
Emerging behaviour	An R&D Center to implement the Company's social responsibilities and help to develop ideas and entrepreneurial growth that provides professional, hardware, and financial support to idea owners and startups that seek to develop their ideas and applications for Release and market entry
Independency	The executive management team of the Center has relative independence in making decisions in the executive areas. Also, startups have sufficient independence in other matters of their product development project, except for setting deadlines and performance standards
Diversity	The Center has a large number of startups and each startup consists of specialists in the fields of specialisation, computer programming, marketing, and so on. Also, team members have different ages, genders, majors, education, and experiences. This is especially critical when discussing the transfer and sharing of knowledge and experiences in a co-working space
Multi-level and network structure	The Center consists of a large number of startups, and each of these startups consists of a network of idea owners. The network is becoming more complex by improving collaboration between startups and transferring experiences. The Center itself is part of an R&D collaboration between the Company and the University, which, is part of the country's research system and can be defined as a wider network of actors active in innovation, i.e., the national innovation system

- *Structuring the problems*

By investigation the documentation, contractual boundaries, levels, goals and activities, resources and functions of the system were identified which are described below:

Contractual boundaries of the system: To comprehend the system, a contract boundary is first determined. Depending on the dynamics of the system, these boundaries will change as problems are identified and defined. Hence, the boundaries of the Center were determined. The boundaries of the system include all aspects of hardware, software, and humans belonging to the Center. The system has been created as a long-term collaboration agreement between the University and the Company, but it has temporary elements. Some of the elements are startups that are often temporary members of the system and leave it after a while. However, only activities and problems within the boundaries of the system that are related to the Center are considered, and other activities or problems related to the University or Company, that are not related to the Center, are not included in the system.

- *Formal goals*: The main goal of the Center is the growth and development of start-ups and knowledge-intensive companies active in application production and providing innovative solutions in the fields of health, education, energy, and environment.

Main activities: The key operation of the Center is to support R&D by developing new ideas in the field of health, environment, energy, and education with a focus on smartphone applications. Therefore, the Center provides hardware facilities and physical space for the development of technology projects, training, and technical and managerial advice to teams or startups, a mechanism for transferring knowledge and experience among teams, funding. Moreover, it can accept top applications in the Company's Apps store.

- *Formal structure*: At the top of the management pyramid is a board of directors consisting of three members of the Company and two members of the University. With the votes of this board, a chairman of the Center is elected. The following is defined as the head of the Center, the public-relations manager, the event manager, the IT manager, the training program manager, and the team control manager. There is also staff for welfare services in this Center. Startups are teams of idea owners, technical experts, and marketing experts whose innovative ideas for applications are accepted by the Center and are operating at the Center. Although these startups are being formed with the support of the Center, they have an independent identity as start-ups.

After identifying the structure and technical aspects of the system, it was necessary to identify the stakeholders and their interests. Initially, system agents were identified by studying the documentation and discussing it with the system stakeholders. Interviews were conducted with a university administrator, a Center administrator, a former member of a startup that previously operated at the Center and a current member of the Center. In these interviews, various problems were identified. The current paper deals with those problems with socio-technical nature that can be investigated and represented using a simulation model. The most critical problems are described below:

- *Ambiguity in the goals of the Center*: There is an ambiguity in determining the goals and evaluating the performance of the Center, especially by the Company and at the policy level of the Center. The managers of the Company and consequently the managers of the Center seek to increase public awareness of the Center's activities and provide services to *more teams* to strengthen the Company's image through social responsibility. But at the same time, the Center seeks to increase the *number of applications developed* in the Center. Because if the startups do not succeed in product development, the Center will fail to carry out its mission properly, and this will damage the Company's image. This problem has wider dimensions or in other words is related to other problems in the system, which are discussed below.

- *The role of startups in the Center*: In line with the previous issue, the question arises about startups whether startups have the role of service receiver or are part of the operating system. If the Center's goal is only to provide services, startups are known as the Center's customers, but if the Center's goal is to develop products and applications, the startups themselves are part of the operating system.
- *Expectations of startups from the Center*: Startups have different demands despite being satisfied with the Center. For example, startups need more financial support and believe that the process of receiving and using this support should be transparent. Team members had no information about the amounts allocated to each team as credit. Also, despite being satisfied with the evaluation mechanism, some considered the deadlines for evaluating the achievements of startups and selecting top startups to enter more advanced stages to be very tight and the opportunities for startups to go through the product development stages were short. Another expectation of members from policymakers and managers of the Center is to increase the number of consultants and hold more specialised workshops at the request of startups.
- *Exit of startups from the Center*: One of the problems raised by the managers of the Center is the departure of startups before the final development of the product or going through the initial stages of development and joining other similar centers. The Center does not claim direct financial benefits from the successful products, and due to the Center's financial constraints on investing, many startups that are in the final stages of developing their product will move to similar centers. They give more financial and technical assistance to startups in exchange for a share. However, managers believe that this will happen less if there is more financial support and transfer of technical knowledge from the Company and the University.
- *Unfamiliarity of idea owners with the Center*: The awareness-raising mechanism of the Center has limited itself to holding periodic entrepreneurship and startup events at universities and other entrepreneurship centers. From the managers' point of view, the reason for this is the lack of funding for advertising and the non-profit nature of the Center. Meanwhile, one of the goals of the public awareness Center, especially the owners of ideas about the responsibility of the Company and the implementation of its social obligations. Of course, interviews with members of some teams showed that they became aware of the existence of such a Center not through events but word of mouth.

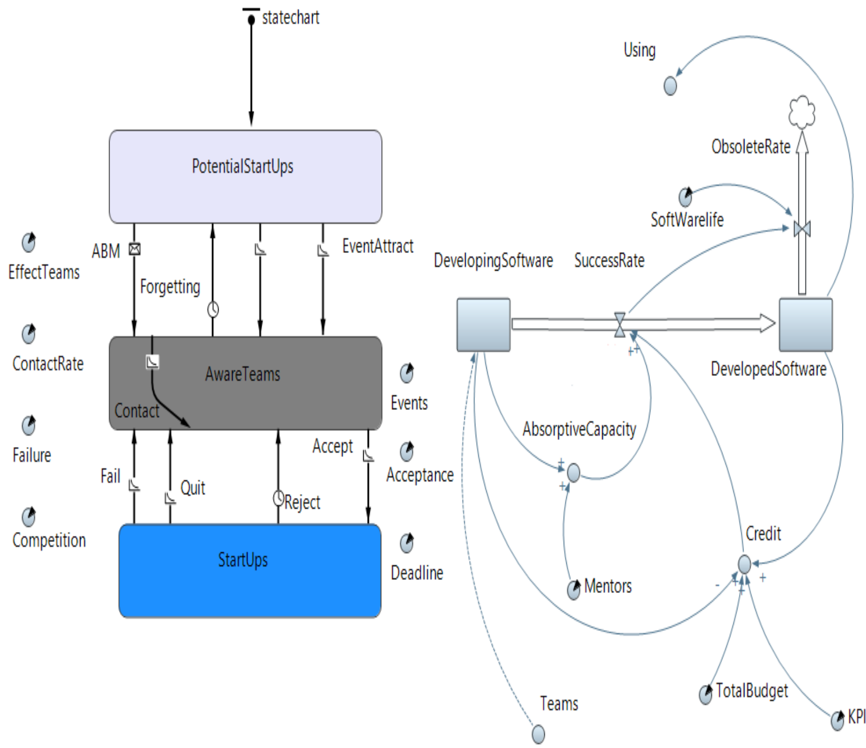
4.1 Creating a simulation model

After identifying the elements, structure, and problems of the system, it is tried to model the structure and general behaviour of the system using the Stock and Flow diagram of the system dynamics. Also, the behaviour and institutional rules governing the main agents of the system, namely startups, are modelled using the state-chart diagram in the Agent-Based modelling. Both models are created and integrated with the same software environment. Figure 1 shows the simulation model of the system in the AnyLogic software environment. This model consists of three main parts: operating mode, which shows the behaviour of agents and changes in their mode according to the rules of behaviour, system mode, which shows the overall behaviour and performance of the system in product development, and leverage or decision points that their changes can lead to changes in the overall behaviour of the system and agents. In the following, the constituent elements of the model are examined.

- *PotentialStartUps*: Shows the state of idea owners for agents and shows the number of people, teams, or start-ups who are looking for an opportunity to develop and commercialise their ideas and are willing to enter the Center.
- *AwareTeams*: Shows the status of informed teams or volunteers to enter the Center for agents and shows the number of teams that are aware of the existence of the Center and have applied to enter the Center through startup events or individually.
- *EventAttract*: is one of the institutions or rules that change the state of agents, which represents the effect of informing the idea owners of the existence of the Center through holding startup events.
- *ABM*: Another law that changes the state of agents, through which the effect of informing the idea owners through word of mouth is modelled. This is inspired by the proposed word of mouth model of Grigoryev (2016). To avoid the excessive complexity of the model, it is assumed that teams that are aware of the existence of the Center are also volunteers and applicants to enter the Center.
- *EffectTeams*: is a parameter through which the effectiveness rate of word of mouth is determined after the idea owners deal with volunteer teams through word of mouth.
- *Forgetting*: It is one of the rules of behaviour that represents the forgetfulness or cancellation of volunteer teams to enter the Center after a certain period that they have not been able to attend the Center.
- *Use*: The effect of informing the idea owners is modelled through the use of applications developed by the Center.
- *Contact*: To represent the possibility of informed teams coming into contact with idea owners or teams that are unaware of the Center.
- *Events*: It is a parameter that determines the rate of impact of events on the idea owners' awareness of the existence of the Center.
- *ContactRate*: It is another parameter that determines the probability of one of the teams or members of the teams aware or volunteering to enter the Center with teams unaware of the existence of the Center or one of their members.
- *Project team*: This shows the status of accepted startups and members of the Center and shows the number of startups that are currently operating in the Center or have continued to operate in the Center until the final phase.
- *Accept*: A behavioural rule to represents how agents change from volunteers to teams or startups that are members of the Center.
- *Acceptance*: It is a parameter that has been created to determine the acceptance rate of volunteer teams to join the Center in the form of a startup.
- *Reject*: A behavioural rule to represents how agents change from a startup member to a team that is no longer a member of the Center. This institution explains the

exclusion of startups from the Center due to their failure to meet the necessary criteria in certain periods.

Figure 1 A simulation model of the system in AnyLogic (see online version for colours)



- *Deadline*: It is a parameter that has been created to determine the time and deadline for startups to achieve the necessary criteria in specific periods.
- *Quit*: A behavioural rule to represent the effect of competition and how to change the state of agents from startups members of the Center to teams aware of the existence of the Center due to being attracted by other centers and competitors.
- *Competition*: A parameter used to determine the exit rate of startups from the Center to join other similar and competing centers.
- *Fail*: A behavioural rule to represent the departure of startups from the Center due to failure in product development and change the state to a team aware of the Center.
- *Failure*: A parameter that determines the failure rate of teams in product development and cancellation of presence in the Center.
- *Teams*: A dynamic variable that determines the number of teams in the Center at any given time based on the factors that are in the Startups state.

- *DevelopingSoftware*: A stock variable to display the number of applications being developed by startups in the Center. Each startup works on only one application software and if the product is finalised, it can start developing its second product.
- *Entrance*: An Event to represent the start-up event of teams admitted to the Center. This variable also helps to model the possibility of second product development by teams that have successfully developed a product.
- *Success rate*: A flow variable to show the success rate in the development of products by startups based in the Center. For the success of the Center and its active startups in product development, knowledge, experience, and financial credentials are required.
- *Developed Software*: A stock variable to display the number of applications developed in the Center.
- *Using*: A dynamic variable that determines the number of applications developed in the Center. It helps to model the possibility of idea owners to know the existence of the Center through the use of Center applications.
- *ObsoleteRate*: A flow variable to display the obsolescence rate of applications developed by startups in the Center.
- *SoftWareLife*: A parameter to indicate the lifespan of the Center applications before they become obsolete.
- *AbsorptiveCapacity*: A dynamic variable created to model the absorptive capacity of the Center. Absorptive capacity is a dynamic organisational capability that enhances the accumulation of organisational knowledge through routine activities. With the increase of innovations and the number of products developed in the organisation, the absorptive capacity increases. In addition to the number of products being developed at the Center, which leads to a more effective sharing of knowledge and experience among startups, the use of the experience of consultants and experts from the University and successful startups also raises this capacity. Enhancing the absorptive capacity of the organisation means increasing the probability of its success in R&D and innovation activities (Kokshagina et al., 2017).
- *Mentors*: A parameter for determining the number of consultants and specialists active in the Center to provide advice and evaluate the activities of startups.
- *Total Budget*: A parameter to determine the total budget approved for allocation to startups operating in the Center by the Company.
- *KPI*: A parameter that determines the total budget deficit to be allocated to startups if they meet the Key performance indicators set by the Center.
- *Credit*: A dynamic variable that displays the amount of credit allocated to each startup. The amount of credit allocation increases with the number of software developed in the Center. Of course, this increase is possible if the Center allocates the revenue of each software to the credit provided to the teams. Also, with the increase in the number of software being developed, which is equivalent to the number of startups operating in the Center; this amount will decrease due to the allocation of the total budget among more teams.

4.2 Model validation

To validate the model, the approach of Louis and Carly (2008) and several other tests were used. According to this approach, the first validation was the evaluation of the elements and components of the model by the managers and stakeholders of the Center and the experts. Partial testing of model components was also used to ensure the validity of the various parts of the model alone. Since the simulation model was a representation of aspects of the system with different components and problems, this test helps to examine the accuracy of the operation of each part of the model separately. The second validation was to check the validity of the data used in the model. The data are historical and based on managers' experience. Attempts were also made to remove concepts with a high level of abstraction for which there is little reliable data from the simulation model. However, critical concepts like Absorptive Capacity, research background, and adjusted numerical coefficients were used in such a way that the model simulates the actual behaviour of the system. The third validation is computational validation related to the calculations of variables and the relationships between them. These variables and relationships were reviewed and approved by experts. Also, the fourth validation is operational validation, which is related to matching the behaviour of the simulated model with the actual behaviour of the system. To further evaluate the computational and operational validity, the system behaviour reproduction test in equilibrium was used (Forrester and Singh, 1980). In this test, the values of all variables were manually determined in the logical balance mode of the model and entered into the model. The behaviour of the simulated model was rational and consistent. Due to the limited pages of the paper, just the tests performed to check the validity of the computational and operational model which are the extreme limit test (Forrester and Singh, 1980) and parametric sensitivity (Sushil, 1993) are discussed in the next section. We also examine different scenarios on system behaviour and the effect of different values of model components on overall system behaviour.

- *Test scenarios and decision options*:

Scenario 1: Selecting the number of products developed in the Center as an evaluation criterion(policy 1) instead of the number of startups attracted to the Center(Policy 2);

Figure 2 compares the Center's performance in product development, the percentage of awareness of the Center among idea owners, and the credit allocated to each startup over 160 weeks based on two policies. In the first policy, a part of the income of each product developed is paid to each startup in the form of credit. While in the second policy, a fixed budget is provided for the Center and allocated to startups. As shown in Figure 2, the ratio of awareness of idea owners and start-ups about the existence of the Center is not only higher in policy 2 than policy 1, but also close to 2% is lower.

But as expected, the number of startups present in the Center in policy 2 is more than the situation where policy 1 is adopted. Despite the small number of startups, the number of final products developed in policy 2 is greater than the policy 1. One of the reasons for this is the decrease in the share of credit received by each startup in policy 2 due to the fixed budget of the Center and the increase of startups in this policy. While in policy 1, even if the number of startups present in the Center increases due to the increase in the number of products developed, the credibility of startups will not decrease and may even increase. Over time, differences in system performance become apparent, even in increasing public awareness of the Center. Because in policy 1, due to the entry of application software into the market and being in well-known App stores and their utilisation by users, the level of awareness of the Center due to the use of its products will also increase. These results can be seen in Figures 3 and 4. Over time and in week 200, the performance gap between the two policies increases and in fact, policy 1 achieves its goal, but policy 2, as shown in Figure 3, in the long run, and week 200, in the amount of Awareness of the existence of the Center and the number of startups active in the Center leads to poorer performance compared to the policy 1. This could be due to a decrease in awareness of the Center because of the lower number of final products developed, as well as teams leaving the Center owing to less support and financial credit for the teams.

Figure 2 Comparison of system performance in two policies by the end of week 160 (see online version for colours)

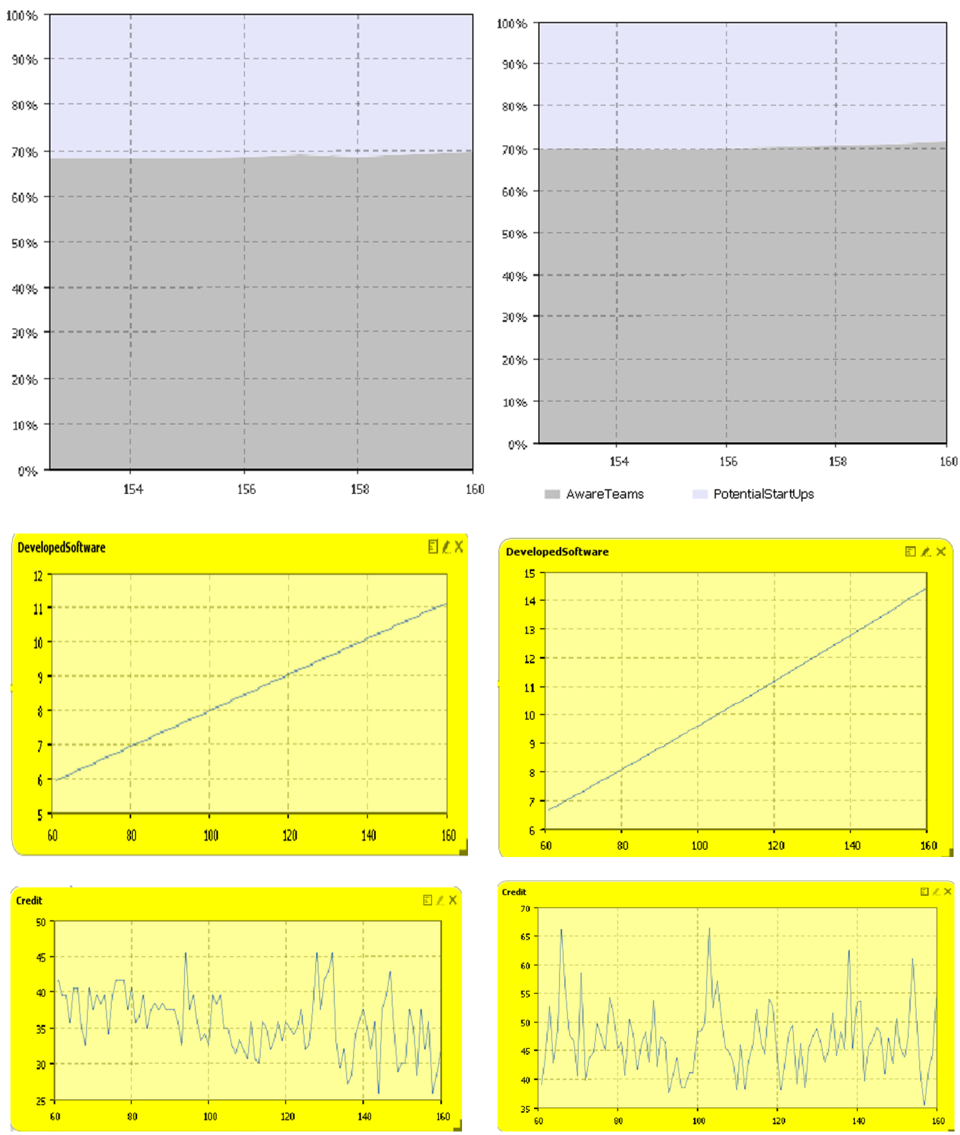


Figure 4 also shows the difference in the amount of credit received by each startup after 200 weeks based on the two policies. As shown in Figure 4, in policy 1, the credit received by startups is significantly more than the credit received by them if policy 1 is adopted.

Scenario 2: Investigate the impact of changes in the Center's rules of conduct and policies on system behaviour.

Institutions that determine the behaviour of agents and policies of the Center concerning the allocation of resources are modelled using parameters. Therefore, the quantitative controllers have been used to apply changes in policies and institutions during the implementation of the simulation and to investigate the consequences of implementing different policies on the performance of the Center. The creation of controllers helps to perform the final limit test to validate the computational and operational model. Thus, all variable values were at their lowest and highest possible values. However, the simulation operation was performed without any problems by the software and the expected results were obtained. These results are shown in Figure 5 and the system performance is compared in two opposite situations.

Figure 3 Comparison of the number of startups active in the center by the end of week 200 (see online version for colours)

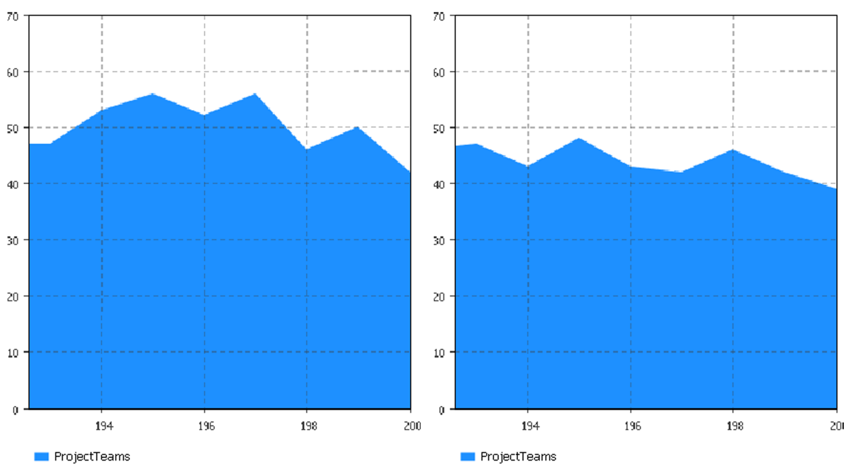


Figure 4 Comparison of the amount of credit received by each startup after 200 weeks based on the two policies (see online version for colours)

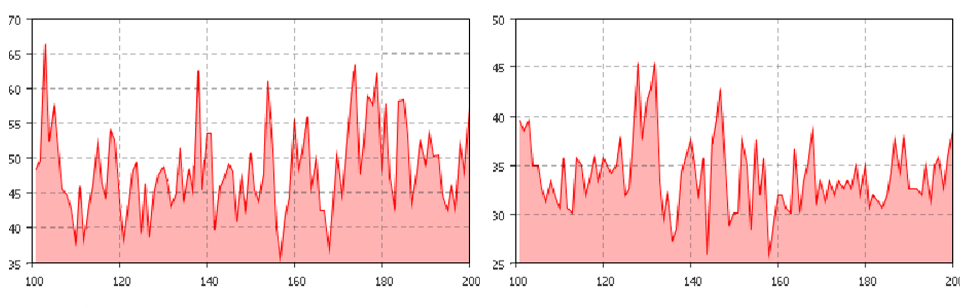
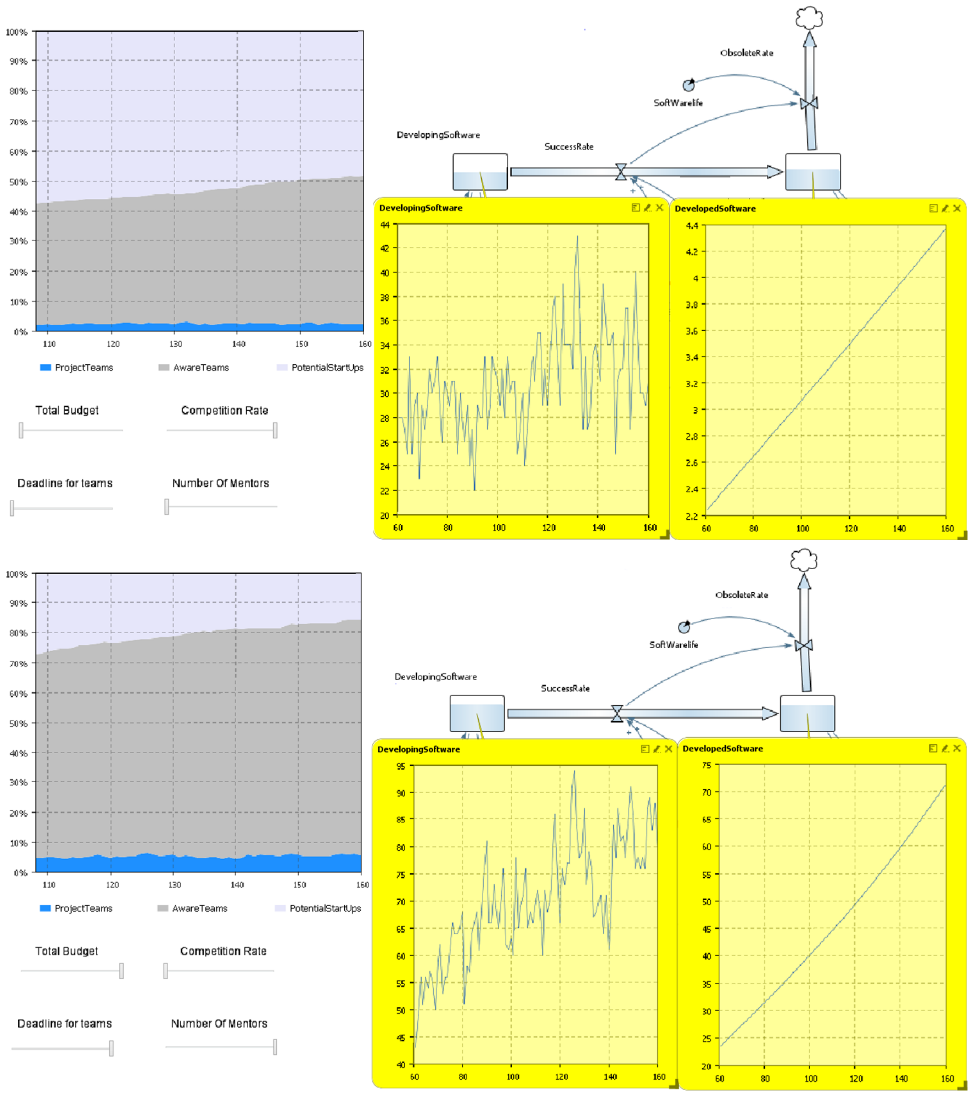


Figure 5 An extreme limit test using controllers (see online version for colours)

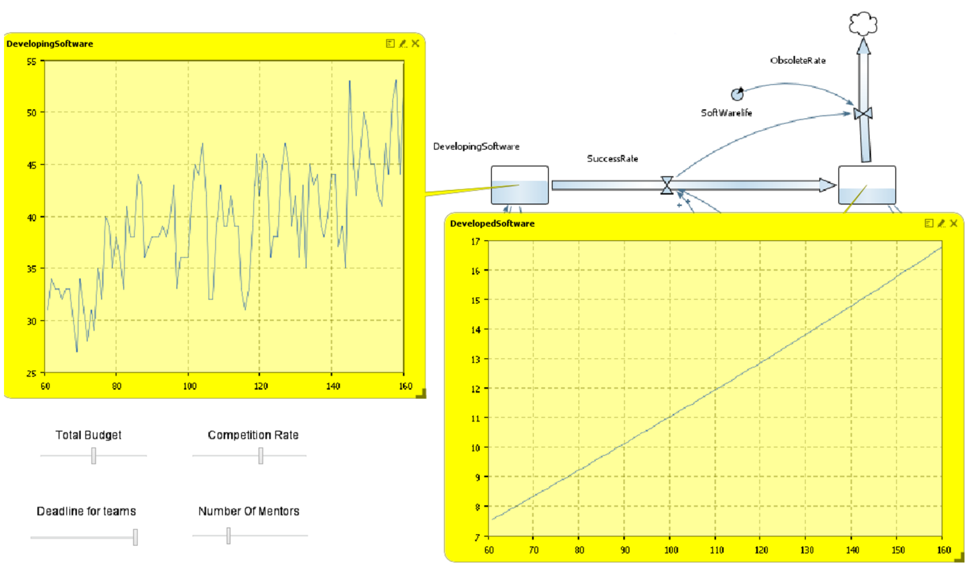


After creating the controllers in the model and performing the extreme limit test, the effects of decisions and policies on the behaviour of the model using the controllers were investigated. For example, one of the options was to increase the timeframe for startups to achieve key performance indicators and product development. Figure 6 shows the performance of the system in the case of doubling the time limit. Increasing the deadline for startups leads to an increase in the final products developed in the Center as well as the number of software being developed in the Center. Although this increase is not significant (parameter sensitivity test), it can confirm the view that creating inflexible timelines for research and innovative projects is not very effective.

Scenario 3: Increased competition in the system environment and exit of startups to join competitors

In this scenario, the effect of an exogenous factor, namely competitors, on system performance is investigated. As shown in Figure 7, with increasing competition and the creation of more similar Centers, active startups in the Center and consequently developing software in the Center will decrease. Because some startups leave the Center due to dissatisfaction with the Center's services compared to competitors. But the simulation results show that there is no obvious difference between the number of final products developed. The reduction in the number of startups helps to allocate more consulting, educational and financial services to the remaining startups.

Figure 6 The effect of increasing deadlines for startups on system performance (see online version for colours)



Scenario 4: Increase the absorptive capacity of the Center by increasing the number of final products developed

As previously discussed, there is a two-way relationship between the absorptive capacity of the organisation and its ability to innovate and develop new products, especially in collaboration with partners in the form of open innovation. This means that increasing the organisation's experience in product development leads to the creation of absorptive capacity and increasing the organisation's absorptive capacity contributes to the organisation's success in developing new products. This relationship was also confirmed in the simulation of the studied system as shown in Figure 8.

Figure 7 Impact of increased competition on system performance (see online version for colours)

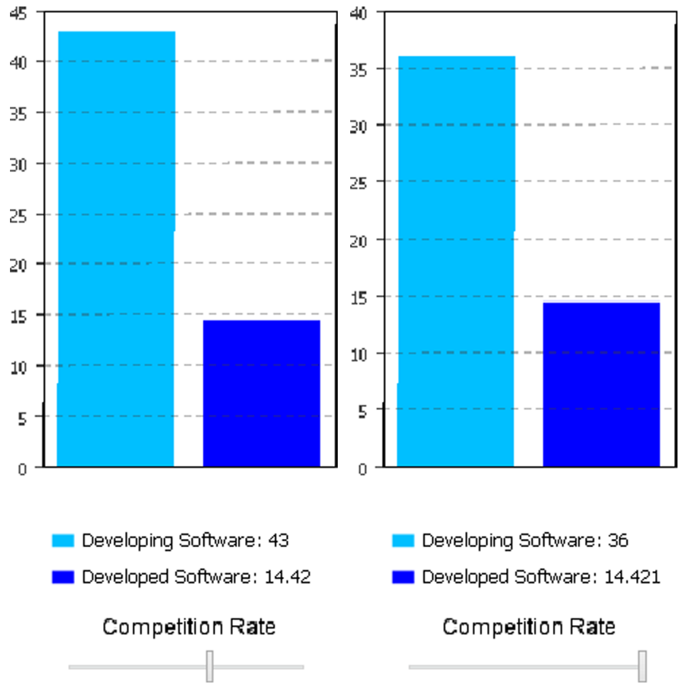
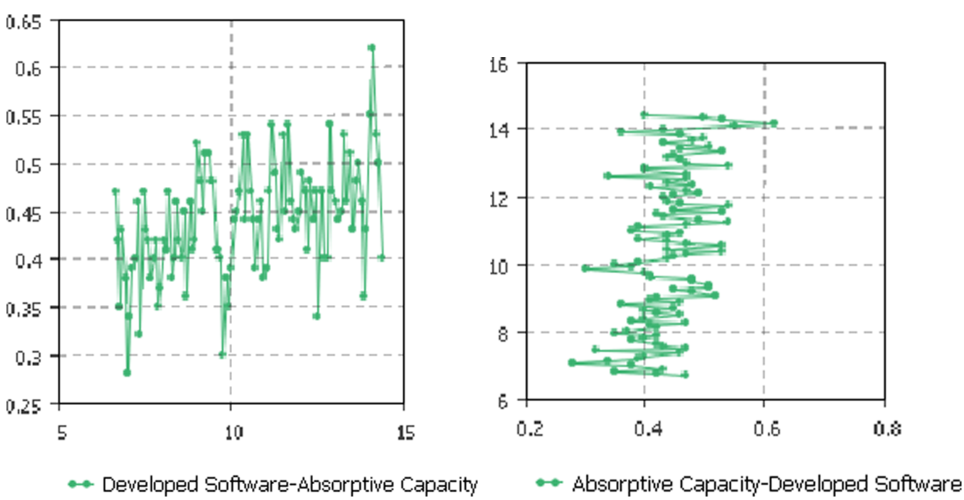


Figure 8 Investigating the relationship between increasing the absorptive capacity of the center and increasing the final products and vice versa (see online version for colours)



5 Conclusions

The current paper aims to study R&D collaboration from the perspective of complex socio-technical systems and to apply the modelling methods of these systems to simulate an R&D collaboration system. Therefore, an attempt was made to discuss the features of R&D collaborations that reflect the complex socio-technical characteristics of these systems. Then, using a hybrid of two methods used to model complex socio-technical systems, an example of this R&D collaboration was simulated in the form of a case study. In fact, in the current study, for the first time, an integrated hybrid of Agent-based and system dynamics models has been used to simulate R&D collaborations as socio-technical systems. The use of socio-technical perspective and its modelling methods made it possible to identify different social and technical problems of the system as a whole. Moreover, the impact of policies and decisions related to the problems on the whole system were identified and simulated. One of the most key problems identified in the system is an issue related to the goals of stakeholders in R&D collaboration. This problem has also been mentioned in studies such as Miotti and Sachwald (2003) and Belderbos et al. (2004). In the collaboration system, obvious differences in the partners' goals of collaboration can be identified. This difference in collaboration does not mean conflict or contradiction in goals. But if clear goals and consequently precise performance appraisal criteria are not defined for the collaboration system, it can lead to an imbalance in the long run, under the influence of financial support or greater managerial power of one of the parties, or system inefficiency. Simulation findings showed that replacing the number of products developed in the system with the number of startups receiving the service as the goal of the system brings better results for the system, which can be due to its alignment with the aim of startups. Another important issue in such collaborations is the inherent technological complexity of R&D projects. The effect of technology complexity on the problems of these systems in the studied manifests itself in the form of impact on the software life cycle. Meanwhile, the startups active in this Center are under pressure to achieve certain results in the set intervals and deadlines. In fact, on the one hand, companies and universities need to use the results of these projects as soon as possible to solve their problems, but on the other hand, startups need sufficient and flexible resources, facilities, and time to be creative and use their new capabilities and ideas. Similar to the current study, Aranz and Arroyabe (2009) believe that the main indicator of joint R&D processes is the existence of a technological complexity that can lead to unbalanced achievements. How to coordinate and control the progress of projects was another identifiable problem in the case study that has been considered in studies such as Chiesa (2000) and Yang et al. (2015). In fact, due to the high uncertainty of R&D projects, there is a high need for freedom and flexibility of teams. But this issue can be examined from another angle. Because of this uncertainty, it emphasises the need to establish regular and accurate coordination and control mechanisms in projects to transform innovations into usable results. A problem that Brooke and Lip (2015) refer to as a contradiction in these projects. For example, in the system under study, the rigor of this mechanism has been raised as a challenge by some stakeholders, while not paying attention to it also causes serious problems for the system. The current study, like any other research, has its limitations. The use of the hybrid method of the present study helps to understand the problems of the system better and provides a learning environment, but R&D collaboration systems have problems of a purely technical nature and optimisation that can be solved through mathematical modelling methods. There are also plenty of purely social issues in such systems that can be identified and structured using soft operations research and problem structuring methods.

References

Agusdinata, D.B. and DeLaurentis, D. (2008) 'Specification of system-of-systems for policymaking in the energy sector', *Integrated Assessment*, Vol. 8, No. 2, pp.1–24.

Arranz, N. and Arroyabe, J.C. (2009) 'Complex joint R & D projects: from empirical evidence to managerial implications', *Complexity*, Vol. 15, No. 1, pp.61–70.

Arroyabe, M.F., Arranz, N. and de Arroyabe, J.C.F. (2015) 'R&D partnerships: an exploratory approach to the role of structural variables in joint project performance', *Technological Forecasting and Social Change*, Vol. 90, pp.623–634.

Auster, E.R. (1994) 'Macro and strategic perspectives on interorganizational linkages: a comparative analysis and review with suggestions for reorientation', *Advances in Strategic Management*, Vol. 10, No. 1, pp.3–40.

Bacon, E., Williams, M.D. and Davies, G.H. (2019) 'Recipes for success: conditions for knowledge transfer across open innovation ecosystems', *International Journal of Information Management,* Vol. 49, pp.377–387.

Belderbos, R., Carree, M., Diederen, B., Lokshin, B. and Veugelers, R. (2004) 'Heterogeneity in R & D collaboration strategies', *International Journal of Industrial Organization,* Vol. 22, No. 8, pp.1237–1263.

Boardman, J. and Sauser, B. (2006) 'System of Systems – the meaning of *of*', *2006 IEEE/SMC International Conference on System of Systems Engineering*, April, IEEE, pp.6-pp.

Borshchev, A. (2013) *The Big Book of Simulation Modeling: Multimethod Modeling with AnyLogic* 6, AnyLogic, North America.

Bukowski, L. (2016) 'System of systems dependability–theoretical models and applications examples', *Reliability Engineering and System Safety*, Vol. 151, pp.76–92.

Carvalho, A.D.P., da Cunha, S.K., Lima, L.F. and Carstens, D.D. (2017) 'The role and contributions of sociological institutional theory to the socio-technical approach to innovation theory', *RAI Revista De Administração e Inovação*, Vol. 14, No. 3, pp.250–259.

Chiesa, V. (2000) 'Global R & D project management and organization: a taxonomy', *Journal of Product Innovation Management,* Vol. 17, No. 5, pp.341–359.

Chiesa, V. and Manzini, R. (1998) 'Organizing for technological collaborations: a managerial perspective', *R & D Management*, Vol. 28, No. 3, pp.199–212.

Eiteneyer, N., Bendig, D. and Brettel, M. (2019) 'Social capital and the digital crowd: involving backers to promote new product innovativeness', *Research Policy*, Vol. 48, No. 8, p.103744.

Ettlinger, N. (2017) 'Open innovation and its discontents', *Geoforum*, Vol. 80, pp.61–71.

Gómez, C., Sánchez-Silva, M. and Dueñas-Osorio, L. (2014) 'An applied complex systems framework for risk-based decision-making in infrastructure engineering', *Structural Safety*, Vol. 50, pp.66–77.

Grigoryev, I. (2016) *AnyLogic 7 in Three Days*, A Quick Course in Simulation Modeling, p.2.

Held, F.P., Wilkinson, I.F., Marks, R.E. and Young, L. (2014) 'Agent-based modelling, a new kind of research', *Australasian Marketing Journal* (*AMJ*), Vol. 22, No. 1, pp.4–14.

Ivanov, D. (2017) *Operations and Supply Chain Simulation with AnyLogic: Decision-Oriented Introductory Notes for Master Students*, 2nd ed., E-Textbook, Berlin School of Economics and Law.

Kokshagina, O., Le Masson, P. and Bories, F. (2017) 'Fast-connecting search practices: on the role of open innovation intermediary to accelerate the absorptive capacity', *Technological Forecasting and Social Change*, Vol. 120, pp.232–239.

McDowall, W. (2014) 'Exploring possible transition pathways for hydrogen energy: a hybrid approach using socio-technical scenarios and energy system modelling', *Futures*, Vol. 63, pp.1–14.

Miotti, L. and Sachwald, F. (2003) 'Co-operative R & D: why and with whom?: an integrated framework of analysis', *Research Policy*, Vol. 32, No. 8, pp.1481–1499.

Mostafavi, A., Abraham, D.M., DeLaurentis, D. and Sinfield, J. (2011) 'Exploring the dimensions of systems of innovation analysis: a system of systems framework', *IEEE Systems Journal,* Vol. 5, No. 2, pp.256–265.

Nikolic, I. and Kasmire, J. (2013) *Agent-Based Social Systems*, Deguchi, H (Ed.): Springer, New York.

Sampson, R.C. (2005) 'Experience effects and collaborative returns in R & D alliances', *Strategic Management Journal,* Vol. 26, No. 11, pp.1009–1031.

Sterman, J.D. (2000) Business dynamics: Systems thinking and modeling for a complex world. McGraw-Hill. New York.

Uyarra, E., Edler, J., Garcia-Estevez, J., Georghiou, L. and Yeow, J. (2014) 'Barriers to innovation through public procurement: a supplier perspective', *Technovation*, Vol. 34, No. 10, pp.631–645.

Vom Brocke, J. and Lippe, S. (2015) 'Managing collaborative research projects: a synthesis of project management literature and directives for future research', *International Journal of Project Management,* Vol. 33, No. 5, pp.1022–1039.

Yang, Q., Kherbachi, S., Hong, Y.S. and Shan, C. (2015) 'Identifying and managing coordination complexity in global product development project', *International Journal of Project Management,* Vol. 33, No. 7, pp.1464–1475.