3.18 Exploring the Use of Computer Simulations in Unraveling Research and Development Governance Problems

Exploring the Use of Computer Simulations in Unraveling Research and Development Governance Problems

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Abstract. Understanding Research and Development (R&D) enterprise relationships and processes at a governance level is not a simple task, but valuable decision-making insight and evaluation capabilities can be gained from their exploration through computer simulations. This paper discusses current Modeling and Simulation (M&S) methods, addressing their applicability to R&D enterprise governance. Specifically, the authors analyze advantages and disadvantages of the four methodologies used most often by M&S practitioners: System Dynamics (SD), Discrete Event Simulation (DES), Agent Based Modeling (ABM), and formal Analytic Methods (AM) for modeling systems at the governance level. Moreover, the paper describes nesting models using a multi-method approach. Guidance is provided to those seeking to employ modeling techniques in an R&D enterprise for the purposes of understanding enterprise governance. Further, an example is modeled and explored for potential insight. The paper concludes with recommendations regarding opportunities for concentration of future work in modeling and simulating R&D governance relationships and processes.

1.0 INTRODUCTION TO RESEARCH AND DEVELOPMENT GOVERNANCE

Key tasks of governance depend on many considerations, but potential governance-level responsibilities may include strategy and operational framework design, vision or direction of organization propagation, goal setting, funding allocation, risk reduction and uncertainty assessment, effectiveness and performance assessment, decision making regarding management or lower level structures, policy adjustments, and policy adherence verification.

Governance of Research and Development (R&D) is a very broad term and has different implications for public and private sectors, however, some rules and perspectives are quite similar. The goals and objectives of these two groups are quite different, however both provide a frameworks that encourages desirable research outcomes for enhanced mission capabilities [1]. Here, it is important to understand major differences regarding how both sectors see and evaluate their mission capabilities. Private sector governance concentrates on investments, product lifetime cycle, future planning, and sustainability [2], but the primary goal of many private enterprises is to make money. Exceptions from this rule include non-profit organizations or corporations where effectiveness aligns closer to public sector measures. Public sector governance focuses on different outcomes such as leadership, policy soundness, and innovation creation, elements traditionally viewed as specific outputs from more detailed managed endeavors. Money spent is an important factor, but the main organizational objectives do not typically focus on a return on investment paradigm.

Another context to consider is the level of R&D governance, because it may span across a society, country, industry, company, or individual endeavor within an organization. Different approaches to R&D governance can be more effective with different organization sizes and complexities. Another factor to study is the composition of different R&D organizational structures, for example: centralized, de-centralized, or mixed; this can have a significant impact on performance of the organization [3]. Assessment of an R&D endeavor is tightly coupled with organizational goals. Input in the form of goal setting will direct the R&D process through execution of projects, and ultimately it will feedback to the governing cell in the form of, for example, higher profits, increased market share in the private sector, lowered crime rates, decreased cancer-related deaths, and an increase of the approval rating of a given organization in the public sector. A formulated governance strategy establishes a context for R&D entities and a consistent basis for funding requests, adjustment of programs or possible outsourcing to accomplish organizational goals. It is also an enabler of generating new ideas for future projects, which would help to fill the gap between current state, and desired organizational objectives.

The remainder of this paper is organized as follows. Section 2 discusses the applicability of M&S techniques to R&D governance. Section 3 briefly presents the most common M&S paradigms. Section 4 discusses the problem of choosing a modeling paradigm in the context of R&D governance. Section 5 presents a sample model. Finally, Section 6 provides some conclusions regarding this research.

2.0 NEEDS FOR MODELING IN R&D GOVERNANCE

Decision-making in complex systems without sufficient information and understanding could lead to catastrophic results. Further understanding of complex systems may be achieved through M&S techniques. Frequently, available data do not translate into valuable information that facilitates understanding. When investing a significant amount in a research project, one should first know that a proposed solution has a high chance of success, and if the proposed solution is actually addressing the concern [4]. Another problem can be discovered while looking at reports of government agencies where many voluminous reports do not provide clear information on the bigger picture context.

Measures of "target met"-type results for particular research endeavors do not provide a sufficient way to validate a decision-making process and its evaluation. On the other hand, this situation is likely due to a lack of knowledge on how to successfully describe R&D processes, and their relations at a sufficient level of abstraction. The problem can be instantiated into the scope of conceptual understanding to see how this system works. If one knew how the system behaves, a model could be built out of this knowledge to aid in decision-making process. This sounds straightforward, but in fact, it is not. There are many parts of the system influencing each other and it is difficult to describe these relations in a mathematical formalism. Further, human-in-the-loop concerns are still a big challenge to model efficiently, and when dealing with innovation it is obvious that not only qualifications of scientific staff, but also other factors such as their motivation, character, and needs, which could influence the culture and performance of the working group are important. Therefore, evaluation of the process of innovation generation can be subjective and a decision-maker concerned with organizational governance should be aware of that. M&S practitioners are working diligently trying to fill this gap, because common analytical techniques cannot.

Agent Based Modeling is one of the most promising techniques that could generate an understanding of innovation phenomenon and emerging group behaviors. A question often asked is how to asses and measure R&D effectiveness. One way of approaching the problem is to focus on internal and external factors that facilitate effectiveness and not on the innovation product itself, especially when assessing a long-term project, where it is difficult to gauge the progress of research. Another way is to find variables directly coupled with outcomes from an R&D endeavor, keeping in mind that some variables can be measured, but some can only be observed as relative trends. Length and difficulty of the R&D endeavor can have a significant impact on accuracy of the prediction, therefore overall assessment as well. When considering the length it is apparent that long-term R&D endeavors should be more difficult to appraise and the probability that one will conduct an erroneous assessment is higher. By employing modeling techniques, one could address some of the problems mentioned here. Modeling the innovation process and its supporting activities can be achieved using modeling techniques. They can alleviate a problem of R&D effectiveness assessment and help to evaluate trends and conduct "what if" analysis on different styles of decision-making and different polices of R&D governance that oversee innovation generation. Successful conclusion of R&D innovation generation is not the end of the lifecycle process. Another responsibility of R&D governance is to incorporate a new product or concept into a market or its functional target place. This task can be very complex and traditional methods may not suffice. M&S can mimic time-related variables and environmental relationships related to new inventions to optimize the process of integration to maximize outcomes, and to avoid pitfalls that could possibly occur.

Another area where M&S can be invaluable is assessment of future R&D direction. Conducting analysis of R&D effectiveness using modeling techniques in the context of organizational mission can reveal serious strategy flaws and could help to avoid them. M&S methods are relatively new approaches, as a choice for aid in decision-making and evaluation of R&D governance. Authors were looking into areas where M&S is already more advanced to analyze options in applying robust knowledge to R&D governance.

The most prevalent area of M&S is associated with, and sponsored by, military organizations. In [5], authors used ABM to model Political, Military, Economic, Social, Information and Infrastructure (PMESII) entities to mitigate the impact of disasters and military operations. This model has been used to represent the rebuilding and expansion of critical infrastructure in Afghanistan. The ability to gain insight into the process of reconstruction and development can be a very valuable tool for a decision-maker in enterprise or government structures. Because of the multi-dimensional scheme of the model, the authors believe that it would be possible to apply this approach to R&D governance.

Adding modules that would allow agents to model innovation generation and knowledge sharing is possible with modeling by connecting this lower level to middle and higher-level agents, e.g. department, organization, and society. A model could allow the analysis of the robustness of policy choices under different scenarios. This approach can be used in the public as well as private sector. Adding more complexity to the model would theoretically allow for modeling human evolution as a function of R&D progress. Because the progress of R&D could be an enabler for actual change of the system and can spur achievements of higher objectives of system of systems, it can be invaluable to be able to model this process. As a futuristic perspective, such a model can provide valuable information on R&D as a stabilizer or destabilizer of the world, and perhaps allow answering the following questions:
Is advancement of R&D proportional with civilization advancement?
Is our direction of R&D advancement taking us where we want to be?

Because of its complexity, currently only large organizations can handle expenses related to investing in complicated models conveying many levels of abstraction, but this can change as the field of M&S advances, providing for easier model reuse and better interoperability. The following section discusses the most common modeling paradigms to familiarize the reader with what approaches are available.

3.0 MODELING PARADIGMS

In this section, the authors would like to provide quick overview of three popular and often-used-by-practitioner M&S methodologies. Understanding principles of them is an important step in understanding their possible usage, as discussed in the next section.

3.1 System Dynamics

System dynamics (SD) models consist of feedback loops in the form of differential equations that provide for building relations between variables. SD is useful for studying complex nonlinear systems, especially finding cause and effect relationships [6]. From the practical perspective on how to build model, one should know about stocks, flows, auxiliary variables, and constants as the main blocks providing for metaphors of the complex system. The initial phase of building SD model is creating a causal diagram. A causal diagram represents the most important elements of a system and relations within the system in form of links that end with arrows indicating which element influences which. In addition, you can denote a "+" or "-" on the flow to specify a positive or negative relationship. The positive one means that second variable follows the direction of change of the first variable, and vice versa. Links with variables form loops, and they can be positive or negative as well. The negative loop can exist only if the number of negative relationships is odd. Having at least one negative loop is a minimum requirement to stabilize the system. Models built with this methodology can help in framing problems, revealing dynamics related to change imposed on the system. Models are typically used to show trends of relationships and not precisely computing specific values. This methodology can be an invaluable tool in assessing a big picture problem, testing alternative policies and strategies at the governance or enterprise level.

3.2 Agent-Based Modeling

The world is full of interactions between different types of systems and many of them are not well understood. Agent-based modeling (ABM) is a methodology that aims to capture many types of interactions by using computer created entities called "agents". These agents are assigned attributes, rules of behaviors, mimicking and carrying sets of interactions to gain an understanding of the real system, and providing for emerging behaviors. ABM can be used to model perception, autonomous and group behaviors, goal setting, a static or dynamic environment, the ability to mimic inference and adaptation, and social interactions among other possibilities [7]. ABM in R&D governance allows for the examination of different types of relations between individuals, groups, and organizations, with the notion of independence of agents, when modeling for example open innovation or supplier-customer relations. These concepts clearly could take advantage of ABM to reveal some of their intricacies. For these reasons, it is popular to use ABM to generate hypotheses about system behavior. From the scientific point of view, this is a very powerful feature, but there are some practical limitations related to an inability to logically validate such models. Consequently, verification and validation (V&V) is an issue that needs to be resolved to take full advantage of ABM. One way of partially alleviating this drawback is by proving a hypothesis false.

Complexity and dynamic behavior of systems encourages the use of ABM for investigation of adaptive systems, which are often non-linear and chaotic. Furthermore, provided mechanisms lead to model evolution of adapting agents [8]. This capability sets the ABM methodology apart from other methodologies discussed in this paper. It is worth mentioning that relatively high complexity can be achieved by imposing relatively simple interaction rules on agents. There are many platforms for implementing AMB, e.g. NetLogo, Swarm, Mason, Repast, and AnyLogic. The choice of one of these platforms would greatly depend on the complexity of system that one would like to model and the problem that the constructed model is supposed to address.

3.3 Discrete Event Simulation

In a discrete model, changes in a virtual system can occur only at separate points in time. These changes are called events, and everything in the model is related to them in one way or another. For example, an event could be an arrival of a R&D project for its approval, then decision made would mark next event, following with outcome event from the project e.g. success or failure. Discrete Event Simulation (DES) model consists of entities, which in an R&D environment could be represented by R&D projects flowing through model logic. Events are stored in a calendar, which contain information that allows the model to be executed in accordance with its logic. The central idea of DES is that variables of the model will not change between successive events.

In addition, understanding the concept of a queue is often necessary to the understanding of DES. A queue can be visualized like a line in a store, and can be modeled to mimic the system's real queue, which may have limitations for the number of elements that can fit into it, and can have different rules reflecting the priority of leaving it by the stored elements, e.g. a first in first out relationship.

Essential components of DES are represented by resources, which relate to personnel, equipment, etc. of the real system. They will be used by entities while going through the process. DES is often used to capture stochastic behavior of a system [9, 10].

4.0 MODEL CHOICE

One can model R&D governance at various levels of abstraction, complexity, and fidelity depending on purpose of a model [11]. It is important to understand some basic limitations of M&S to proceed with this discussion further. One needs to remember that modeling activity is not free, but can, if executed properly, save a great deal of money and time.

Model development and validation often requires a significant amount of time and resources. No one model answers all questions, so it is important to evaluate cost effectiveness when deciding to use M&S techniques, meaning, if one can address a problem with simple deterministic and analytical calculations, then M&S is most likely not needed. Analytical Methods (AM) are usually quicker and cheaper. AM are often used to get an exact answer to a problem, usually where there is a direct and known relationship between input and output.

Short length term R&D endeavors should be especially good candidates for use of AM in effectiveness assessment at the managerial level. This could be done, for example, by combining R&D into business process. In some cases, AM allow for quick estimates for a problem, which then needs to be addressed more thoroughly with a M&S paradigm, as AM would not allow to capture the bigger scope or an appropriately complex problem.

Generally, the choice of a modeling technique depends on what features of a system can be effectively manipulated with different methods. Aggregation level is another factor that will influence the choice of modeling technique. It is important to understand that a lower level of aggregation does not necessarily translate into lower risk associated with, e.g., prediction. At the lower level of abstraction of R&D governance one can focus on innovation generation, knowledge management, process of innovation control and supervision, and project management scope. These could provide an instrument used for medium and higher level structures, or can be studied on their own as separate models. Modeling emerging behavior using ABM could potentially be a method to use at the lowest level of abstraction of R&D governance. One could get insight into new order, new patterns, and structures of R&D by learning from the interaction of individual agents or groups.

One possible approach to implementation would consist of distributed agents in the form of humans, information storage, or groups working together, with attributes such as goals, knowledge, and imposing adaptive tension on one another [12]. Outcomes from the emerging behavior can be greater than the sum of its components, e.g. knowledge generation; tacit knowledge depends on interaction and direct experience, whereas explicit knowledge could easily be transferred across distance. Modeling a spectrum of interactions would allow for a better understanding of complex emerging behaviors, along with quantification of expected knowledge increase. Different structures at different levels in enterprise or government along with imposed interactions could, for example, increase chances for innovation generation. Emerging behavior capabilities of ABM can provide for building new theories, which in turn can be translated into better structures, encouraging motivation, and knowledge sharing in an organization that enables creativity. As discussed, it is feasible that ABM can be mostly suitable for theoretical development, which should be later validated using methods that are more empirical, as ABM is generally difficult to validate. ABM can also be suitable at higher levels of R&D governance modeling, where individual agents mimic projects, organizations, societies, regions, and countries, and agents' independence can provide for different perspectives comparing to one obtained from, e.g., the SD method.

DES seems appropriate to use when looking at R&D governance from the processing perspective [13]. Every big enterprise or government entity has to manage many R&D projects, evaluate them, and properly allocate resources. DES allows for modeling of R&D endeavors throughout their stages in a life cycle. In DES, R&D projects can be represented as entities going through their life cycle, starting from project approval request, which can end up as a rejection, then the development phase through stages at which it is possible for a project to be rejected from continuation due to, e.g. a lack of funding. This would allow the transferring of resources allocated to this project to another project, increasing its chances of success. Finally, a project's output needs to be incorporated into production, then into market, or another environment than for which it was initially conceptualized. Additionally, one cannot forget about a product's maintenance tasks throughout its life cycle. The R&D process calls for a method that can easily incorporate its stochastic character, and DES provides that capability. The ability to mimic the logic of the organization, and evaluate alternative structural alignments, for example, centralized versus decentralized, makes DES especially valuable. In addition, the stochastic character of R&D endeavors makes DES a very powerful tool that could be used for assessment of, e.g., outsourcing versus "in-house" R&D, and prediction of estimated return of investment. DES can exhibit a detailed level of abstraction depending on the modeler's need, and it is flexible and easy when managing different levels of aggregation. Moreover, many commercial DES packages provide techniques that can mimic different methods like SD and some even ABM.

SD is a method that can be very useful, especially at the enterprise modeling level when trying to capture big-picture or global scope of the problem. SD should be used where there is an existing feedback loop between model variables, and it is hard to explain the relationship by intuition itself, which often appears in the representation of R&D governance. Problems of choosing between various strategic options can be addressed with SD, as it is often hard to model high-level of socio-political phenomenon providing exact numerical information. This method could be particularly appropriate to a long-term model. SD structure is based on differential equations, but most of the commercial simulation packages allow for the incorporation of stochastic behavior into a model. Using this method for testing policies and future trends can be invaluable when trying to plan in long term, which is specifically related to R&D governance type decision-making. Modeling competing environments allows for a comprehensive perspective of what is needed to obtain desired outcome. An important advantage of SD is that data used to drive a model do not have to be ample or even direct. Often one would like to learn the system and restore its behavior without direct knowledge of it, by building relations that are only correlated with it or related to this phenomenon. Another area where SD may be appropriate is to learn about how significant the roles of parts of a complex system are in the functioning of the whole body, e.g. not only how outsourcing affects a single project outcome, but also what are the long time implications.

To manage different levels of abstraction one could potentially increase effectiveness by using nested, also known as, hybrid, models [14]. These models use different methodologies that can be arranged hierarchically depending on type of problem the model is to address. Multiple layers of ABM, DES, and SD methods could be constructed, allowing communication between layers and so influencing each other. Some structures can be also embedded by another if that reflects actual system structure. M&S practitioners often combine ABM and SD. These two methods can work well together and provide good combination of, e.g. lower level ABM with SD capturing a larger view of the system. Alignment of ABM-SD can be multi-layered, for instance, some part of agent behavior (internals of agent) can be described using differential equations from SD, then the environment level can be described in ABM terms with agents at different level of aggregation, and on top of that SD world-view, capturing global dependencies. Some of commercial as well as free software packages allow for that kind of configuration e.g. ANYLOGIC, and NETLOGO. In Figure 1, the authors propose an example of how a configuration of a hybrid R&D governance model could be assembled.

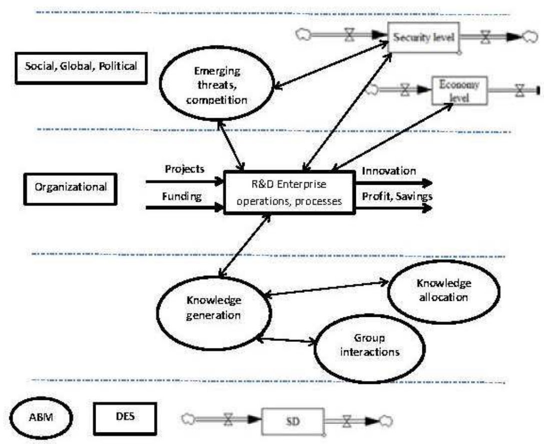


Figure 1. One possible configuration of a hybrid model of R&D governance

5.0 MODEL EXAMPLE

The estimated number of illegal immigrants ranged from 8.5 to 11.8 million people between 2000 to 2009 [15]. While this can be an under- or over-estimation, many unofficial sources estimate it as high as over 20 million people, which if true could cause a significant problem in calculations of many statistics and biasing the true picture of the U.S. border security problem.

Figure 2 presents a simplified conceptual example which captures relationships between two competing environments, (represented as capabilities: Department of Homeland Security (DHS) capabilities and criminal force capabilities), in relation to U.S. border security.

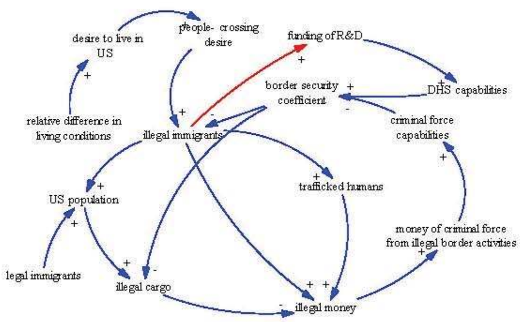
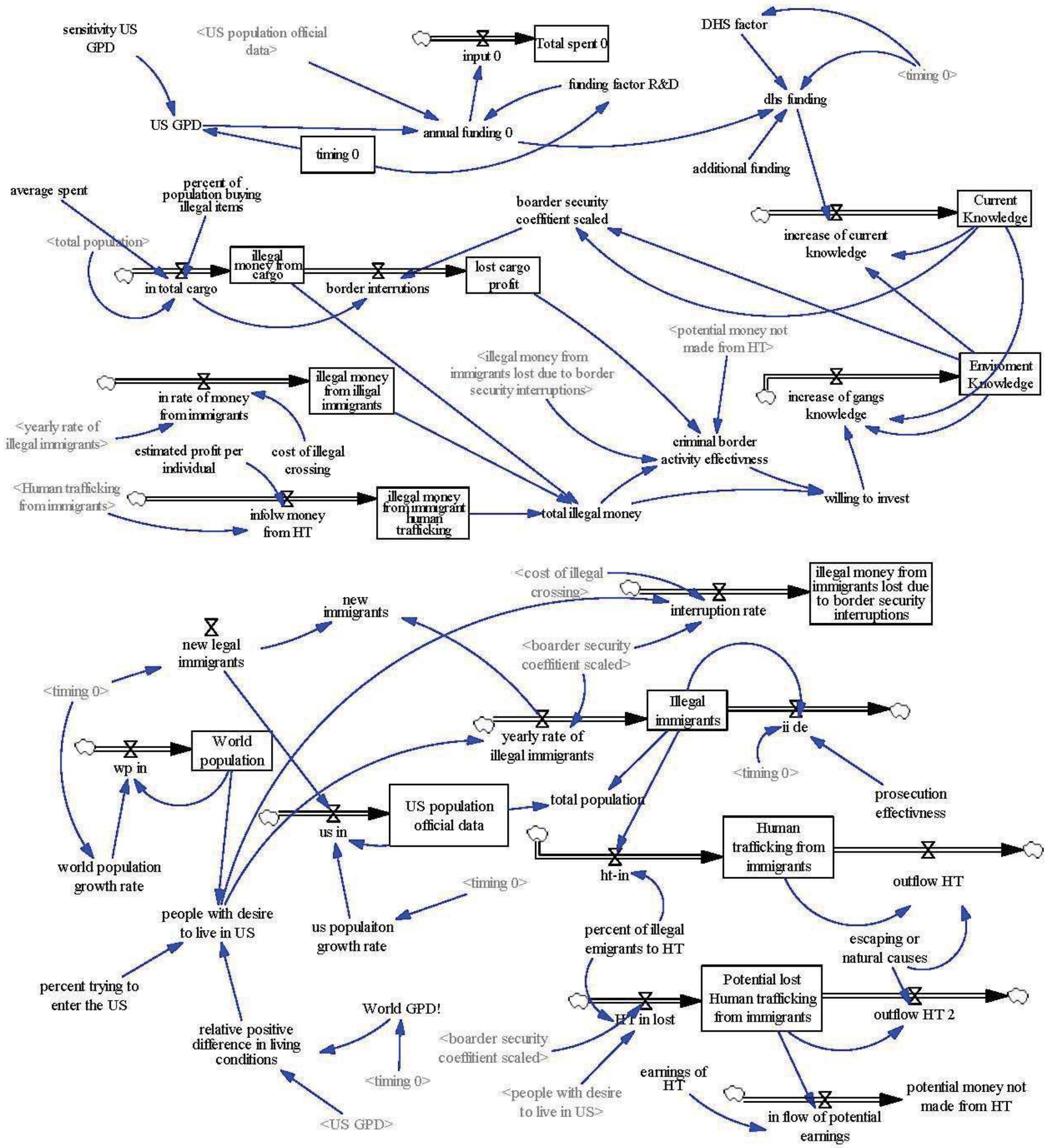


Figure 2. Conceptual model of border security

Money is used as a main metric in this model, used for both funding an increase in DHS capabilities and to provide illegal money to a criminal force. A defined coefficient of security influences number of illegal immigrants entering the U.S. and the amount of illegal cargo. The model allows for estimating the number of unauthorized immigrants in the U.S.

The model has the following data-driven variables: population growth rates, legal immigration rate, Gross Domestic Products (GPDs) of the U.S. and the world rates, and federal R&D funding for the U.S. Figure 3 presents a detailed view of the model. The model correlates the U.S. GPD with total spent money on public R&D and further on DHS. This can allow analysis to be conducted on both the country, as well as departmental level. The U.S. GPD further influences the relative ratio of difference in living conditions between the U.S. and the world. The R&D portion of the model is built on the concept of knowledge generation by both environments: one being the R&D environment, where conducted or contracted-out research by DHS is supposed to help eliminate illegal activity around the U.S. border, and the second environment represents knowledge of the criminal force to continue with their illegal endeavor.

There is an assumption on the time delay between the reaction time needed to discover new techniques by both competitors. The authors hope that there is an effective way of breaking this pattern, but for a simplification, breaking the pattern is not considered in this model. Future study of this phenomenon using agent-based modeling approach is foreseen, and it would possibly allow for assessment of how fast a criminal force can adjust to changes imposed by border security advancements and vice versa. An increased border security coefficient can decrease effective smuggling and illegal border crossing, which in turn decreases money flow used by criminal force. The last part of the model focuses on different groups of people. Here, the key elements for our analysis are represented by the number of illegal immigrants and the level of human trafficking. The basis for obtaining those outputs is the assumption that the majority of illegal immigrants are those who cross the borders for economic reasons. Hence, the authors were looking at estimating differences between (GPDs) as a factor of estimating the number of people with a desire to live in the U.S. Additionally, human trafficking is strongly correlated with illegal immigration [16]. This model was partially validated by comparing estimated data from [15] and model output as shown in Fig. 4. The model shows potential for gaining valuable insight into border security, including estimation of the funding level necessary to lower illegal activity related to the U.S. borders.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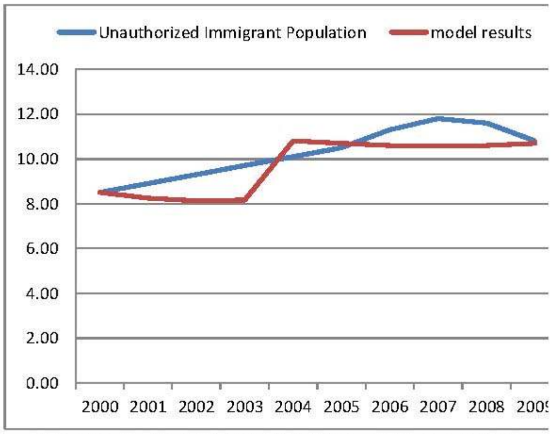

Figure 4. Partial validation of the model

6.0 Conclusions

This paper presents insights into governance of R&D. The authors moved from theoretical knowledge of R&D governance, through description of popular approaches available for M&S practitioners, ending up with discussion on how one could model R&D governance. In addition, authors showed an example of SD model that could be used by DHS or other similar agency to determine R&D funding. The constructed model allows for estimation of the projected number of unauthorized immigrants given a current or augmented rate of R&D funding. Future work is foreseen that would incorporate hybrid modeling to better capture the complexities of R&D governance.

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