Dealing with complexity: a holistic participatory systems approach for improving construction innovation performance

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Abstract. This paper, as a part of an ongoing research project, presents an integrated participatory approach to address the innovation performance of a company within the construction industry in Russia by employing a stepwise process consisting of multi-stages analysis, stakeholder-based and modelling approaches. The primary objective of the paper is to understand, conceptualise and develop an initial dynamic model of a complex construction innovation system consisting of a range of elements such as resources, activities, performance, policies, strategies, and time. To build the foundations for such a dynamic model, a number of participatory workshops were conducted to assist the application of structural analysis (MICMAC — Cross-Impact Matrix Multiplication Applied to Classification) and system dynamics (SD) modelling. The proposed approach is an effective approach leading to a successful improvement of the construction innovation process. Moreover, it is capable of dealing with both quantitative and qualitative data, as well as, being able to capture feedback loops within a dynamic system. The inclusion of stakeholder engagement is an essential requirement given the multi-actors nature of the system under study and lack of data involved. Hence, the participatory modelling included academic and industry consultation, an opinion survey and a number of facilitated workshops. As a result, a comprehensive conceptual model was built as a causal loop diagram followed by the creation of a dynamic model revealing pathways to improving construction innovation performance in Russia and underpinning the future development of scenario-generating modelling.

Keywords: construction innovation diffusion, construction innovation system, stakeholder engagement, participatory modelling, system dynamics.

1. Introduction

It is generally accepted that a high level of innovation performance is extremely important for the construction industry which is one of the major economic drivers of a country (Aouad *et al.*, 2010; Suprun and Stewart, 2015; Davis *et al.*, 2016). Even so, the construction sector has always been criticised for its unwillingness to innovate, its slow pace of innovation and its conservative attitude regarding the construction firms that engage significantly less in innovation related activities than firms in other sectors (Xue *et al.*, 2014). There is an obvious need to improve innovative policies and supportive programs that promote research and technology transfer for the purpose of embracing construction innovations and industry performance. By doing so, a solid policy analysis and decision making process is required before innovative practices can be utilised on a wider scale.

An integrated modelling framework within a holistic approach is proposed to achieve the overarching goal of this research project. This research goes beyond previous studies about improving construction innovation performance (Aouad *et al.*, 2010; Van Egmond, 2012). Furthermore, it draws on systems modelling theory to examine interactions and build effective collaboration between construction companies, universities and research institutes, as well as, government in order to encourage and stimulate the industry to implement innovation. Hence, presented herein is an overview of dynamic relationships among government, the construction industry and academia in Russia. In the case of construction, cooperation and collaboration are critical as innovations becoming increasingly more complex and their benefits can only be observed by fully understanding the components of the entire innovation process that is based on innovation acquisition, development, imitation, and diffusion (Van Egmond, 2012).

The deployment of a holistic modelling approach allows the integration of empirical data with qualitative expert inputs (Hafezi *et al.*, 2017; Sahin *et al.*, 2017), which is especially relevant in the case of the construction industry where high uncertainty and lack of data is involved. Combining a number of different methods under the same framework is also beneficial compared to traditional modelling approaches, given the mostly qualitative and extremely complex nature of the system under study involves highly non-linear behaviours, feedbacks and interdependencies.

A brief literature review is provided by focusing on a systemic perception of innovation processes in the construction industry. The framework and modelling process of the research project is explained, following the literature review, and more specifically, the application of a coupled structural analysis and participatory modelling technique that has been incorporated into a novel integrated procedure is outlined. This is followed by results and discussion regarding the construction innovation system in the Russian Federation. As a result, a comprehensive conceptual model is presented to establish the foundations in order to build a system dynamics model for understanding relationships between government, the construction industry and academia. This research has shown that a country's ability to develop and diffuse construction innovation is determined by the level of R&D activities, as well as, government policies and supportive strategies for research and technology transfer. Eventually, the last sections highlight the work completed herein and future research directions.

2. The systemic overview of construction innovation system

Construction is a diverse and project-based sector where the innovation process occurs as an inherently fragmented and complex issue involving multiple actors that interact, as well as, jointly and individually contributing to the development, adaptation and diffusion of innovations (Seaden and Manseau, 2001). Considering multi-dimensional and dynamic nature of the construction sector, role of stakeholders and their interrelationships, analysis of innovation performance should be performed using the innovation system approach from a comprehensive and systemic construction industry-wide perspective. This is an appropriate approach to present an innovation process in construction as a framework considering various influences of the institutional environment (Figure 1).

The presented model illustrates a communication system among government, industry and academia in the construction sector, wherein the properties and behaviour of each actor affect all the others and the system as a whole. *Capacity* is represented by input resources such as human, financial, information, scientific and technology resources, and so on. The extent to which the systems actors have various resources available for innovation-related activities reflects the system's ability to initiate the operation of innovation processes. The factors of *activities and enablers* involve interrelated actors' actions that shape innovation-related flows such as, level of public and private R&D activity, government regulations and incentives, R&D collaboration, to name a few. *Expectations* include improvements in construction performance in terms of level of innovation and productivity. *Outputs* involve main outcomes of the innovation process at the industry level such as quality and cost of construction projects, client satisfaction and profitability level. *Motivations* represent the primary reasons for the systems actors to innovate such as industry performance and sector attractiveness. By *broader environment* we mean factors that inhibit innovation and work against the innovation system.

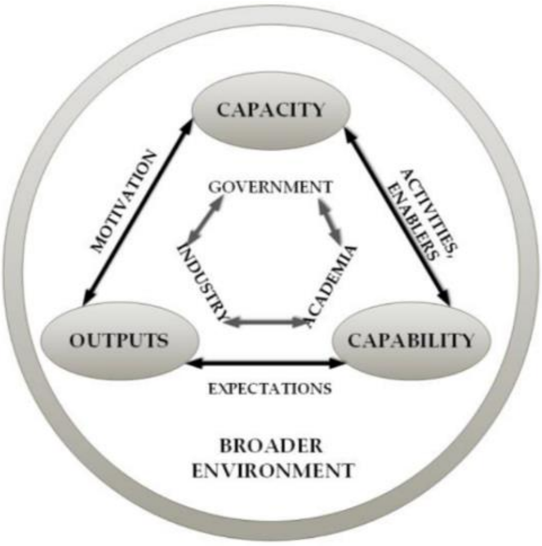

Figure 1. Theoretical model of innovation system in the construction industry (Suprun *et al*., 2016)

As previously mentioned, innovation performance of the construction industry depends not only on how the individual actors perform in isolation, but on how they interact with each other as components of a complex system of the creation and use of resources, which is subject to dynamic processes (Figure 2). The interaction and collaboration of actors is caused by the existence of positive and negative feedback mechanisms that link the innovation development and diffusion to the performance improvement of the industry, as well as, supporting or hindering activities by other institutions. Nevertheless, the actions of actors may also delay the improvement of innovation performance due to time delays in the decision-making process.

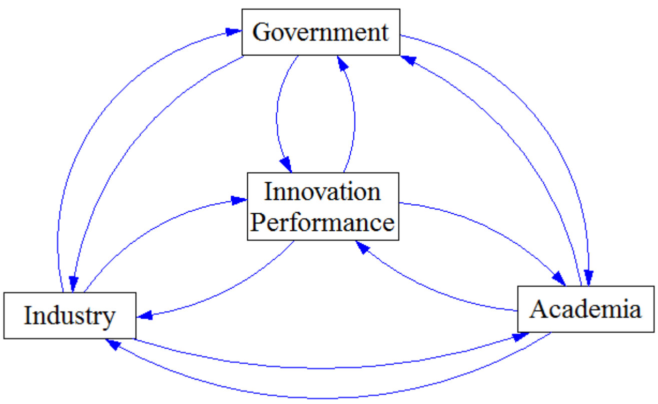

Figure 2. Dynamic model of construction innovation system

Effective and systematic relationship among government, industry and academia provides the continuous achievement of innovation and also navigates R&D activities (Leydesdorff, 2010). According to van Egmond (2012), construction companies engage less in R&D and innovation and receive less financial support for innovation than firms in other sectors. The widest gaps can be found in sector R&D expenditures as a share of sector revenue, and in the rate of current industry and academia collaboration. Overall, the majority of experts interviewed previously argues in favour of the general belief holding construction as a low-productivity low-technology industry, and of a sector generally seen to be underperforming (Suprun and Stewart, 2015).

In the construction sector, mainly technological and organisational innovations occur (Davis *et al.*, 2016). Technological innovations involve the utilization of technical approaches of either process or product innovation. These include improvements in construction methods that are designed or developed for the accomplishment of traditional construction operations, or the improvement in the efficiency (e.g. methods of construction, safety for workers during process, efficiency of processes), as well as, introduction of a new idea which is transformed into a new component of a constructed product of economic, technological or functional value of a standard operation (e.g. environmental features, new technology, functionality of a product). Organisational innovations include changes in organisational structure, introduction of advanced management techniques, and implementation of new corporate strategic orientations such as level of communication and collaboration, improved organizational management competencies, introducing new business models internally, to name a few. The change in the amount of construction companies over time, including percentage of innovative firms is presented in Figure 3.

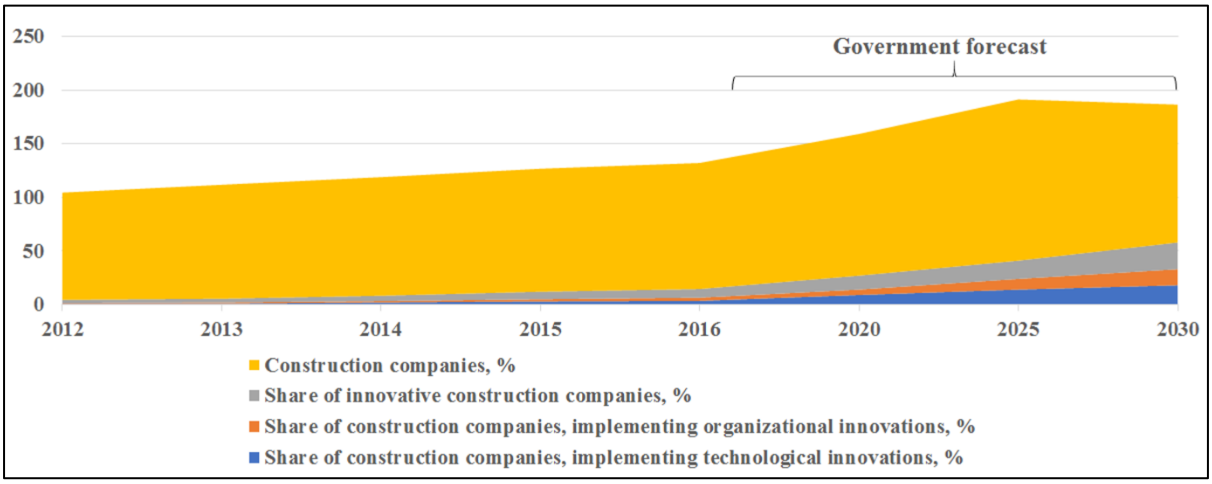

Figure 3. Share of innovative companies in the construction industry in Russia 2012 – 2030 (FSSS, 2017)

As can be seen, the Russian government is expecting the amount of innovative construction companies to be doubled by 2020 and practically tripled by 2030. Nevertheless, it is a very ambitious plan given the relatively short period of time and the lack of targeted strategies. In fact, the current situation in the Russian construction industry does not show the sufficient capacity allowing to achieve such a significant growth (Suprun and Stewart, 2015). Hence, this problem motivated this research in general and the chosen research approach in particular as it is capable of exploring potential innovation outcomes resulting from a range of different innovation planning strategies and uncertain situational context scenarios that take into account time factor.

As previously mentioned, collaboration is a critical factor for construction innovation, especially considering the fragmented nature of the construction industry (Van Egmond, 2012). Hence, engaging business with a research and educational community through supportive innovative incentives, technological gains and joint R&D should be an underpinning activity of the innovation system. Moreover, in such conditions as current import substitution as Russia's response to imposed Western sanctions, raising awareness is extremely important (Suprun *et al.*, 2016). As such, familiarity established through joint research activities can lead to better understanding of academia capabilities and the consequent identification of research institutes as partners in solving pressing industry problems.

3. Approach

The purpose of this research is to combine the systemic approach, participatory and computer modelling and the simulation discipline into an integrated dynamic consideration of the construction innovation system. In other words, this study aims to develop a systems model describing the patterns of construction innovation and analysing interactions between the resources and activities flows due to the actors working together by underlying essential cause and effect relationships.

A complete system dynamics modelling of construction innovation performance requires the study of a large number of variables using different levels of system parameters. Given the lack of numerical and experimental data for policy analysis in Russia, it is extremely important to combine a range of data sources, views and knowledge with stakeholder participation in supporting decision making (Sahin *et al*., 2016; Sahin *et al*., 2017). Hence, the proposed holistic modelling strategy is especially beneficial due to stakeholder engagement helping to support the understanding of complex policy development and implementation issues, as well as, to improve the value of a built model.

Our research approach uses a systematic exploration of stakeholders and innovation policies impacts based on expert knowledge and various authorities contributions, combining a range of systems-based techniques such as stakeholder driven system conceptualisation, structural analysis of a conceptual model using MICMAC approach and SD modelling represented by multiple cycles (Figure 4).

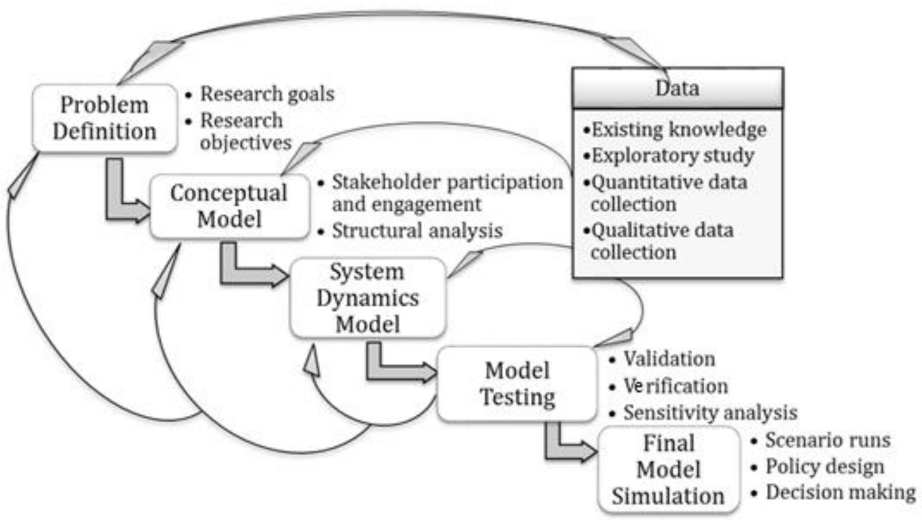

Figure 4. Systems approach step-by-step modelling process (Suprun *et al*., 2016)

A participatory modelling approach methodology, as described in (Van den Belt *et al.*, 2004; Sahin *et al.*, 2016; Suprun *et al.*, 2016), is very beneficial for achieving a shared, consistent level of understanding and, as a result, producing a logical simulation model. Moreover, innovation in construction is not well represented by official statistics and stakeholder engagement is required to develop appropriate metrics for the dynamic system construction. In fact, the modelling process of the research includes continuous stakeholder engagement carried out in the following stages:

1. Stakeholder identification and engagement, stakeholder analysis;
2. Preliminary investigation: questionnaire-based survey and face-to-face interviews to gather data about the barriers, enablers and strategies that most significantly affect construction innovation diffusion in Russia;
3. Problem scoping and systems thinking: consultations with academic and industry professionals;
4. Structural analysis and model conceptualisation: opinion survey on construction innovation system;
5. SD model development: workshops on construction innovation performance in order to design, build, edit and refine the model structure;
6. Model calibration, validation and verification: consultation meetings with experts.

In the present article, we show results from stages 4 and 5 dedicated to a conceptual model construction followed by an initial simulation model formulation.

Structural analysis and model conceptualisation

Researchers in the modelling field have worked on the model conceptualisation steps by implementing group model building (Vennix, 1996), coding textual data (Eker and Zimmermann, 2016), and using mental databases (Sterman, 2000). In our study, we employed a method which utilised an integrated stakeholder-based participatory approach coupled with a structural analysis (Onyango *et al.*, 2016; Suprun *et al.*, 2016).

The system under study presented in the form of a group of interrelated variables derived from the literature review by identifying generic and specific model inputs. Moreover, the data and information were obtained from the other research components (i.e. questionnaire-based survey and interviews) (Suprun and Stewart, 2015). The system's elements were then reviewed and refined following consultations with experts. As a next step, the opinion survey was then conducted in Russia in December 2015 – February 2016 in order to identify the relationships between variables within a structural matrix. Stakeholders represented experts in construction and innovation policies area such as researchers and academic staff, private and public construction companies' employees and contractors, consultants (design engineers), manufacturers and representatives of public authorities.

Further structural analysis using MICMAC analysis was enriched to classify the variables of a system by using algorithms embedded in the software (MICMAC, 2017). What is more important for modelling purposes, the MICMAC analysis findings aid the detailed understanding of the role of each component in the system under study, which in-turn assists in the further SD modelling of particularly important system's elements. In other words, the interrelations between variables assist a modeller with revealing the dynamic characteristics of a system. Furthermore, the analysis outcomes provide necessary information required for the analytical integration of culpable system's parts and for further understanding of which variables to focus on while drawing the system boundary and testing different scenarios. Eventually, a generated cross-impact matrix along with its graphic representation provide visual understanding of the existing systematic relationships between the system's elements and furthermore work as a reference for creating a comprehensive conceptual model in the form of a causal loop diagram.

SDM development

The outcomes of the structural analysis were presented to stakeholders during the second round of workshops, as a prelude to the exploration of construction innovation performance using SD modelling. The main purpose of this research stage was to design an initial simulation model, implying that differences in the structuring of such complex systems create different innovation performance.

Two rounds of workshops in December 2016 – February 2017 were held at the locations under study including: Belgorod and Moscow regions (Russia). Each workshop involved 6 – 12 participants and commenced with the stakeholders being provided with contextual information regarding the research. The initial workshops included three mini "pilot" rounds to obtain the opinion of experts and also capture valuable insights about specific construction and innovation management issues in the context of the key innovation-related variables acting on the system in order to refine the initial conceptual model generated from the research outcomes. Participants represented mostly academics and experts from the industry (senior managers, project managers, design engineers), as well as, representatives from the Department of Construction, Transport and Housing of the Belgorod region.

Then, in order to review the preliminary model and its sub-models, the following two facilitated workshops aimed to: (i) identify and confirm key stock and flow structure for the system under study; (ii) refine the initial model draft with a focus on portraying the behaviour of a system and underlying assumptions, data and potential equations; (iii) suggest possible public policies, strategies for management, potential leverage points, recommendations and scenarios to achieve a higher level of innovation by construction firms; (iv) consider the effects of possible strategies and policy guidelines under different scenarios related to the construction industry development and innovation diffusion within an innovation systems perspective. Participants represented decision makers who have played a role in managing the innovation implementation and diffusion in construction and innovation policy field in Russia (directors of construction and design companies, government representatives from the Russian Academy of Architecture and Construction Sciences as well as academics). The following example questions were used to filter invalid data in order to capture the realities of the Russian construction innovation system:

- Within the current system, what management and/or decision-making interventions are available to you (and how/where are these connected to the existing elements within the emerging system)?
- What is the priority issue that emerges from the preliminary model that you would like to investigate further?
- What importance do you currently give to this loop (process)?
- Do you expect this importance to increase, remain the same, or decrease in the future?
- What are the motives to continue R&D investment and what are the criteria used to make a decision to increase or decrease R&D investment?
- What factors are essential to complete technological innovation projects?

4. *Results and discussion*

Conceptual model development

As a major step in this research stage, 30 key system's variables were identified based on the literature review, the exploratory study and main insights from expert interviews. The variables were grouped into different sets of indicators based on the theoretical model of innovation system in the construction industry (Figure 1). The structural analysis procedure was then enriched in order to describe the system, quantify the strength of relationships between the system's components in relation to the construction innovation system and, to identify the essential variables (Godet, 2006). By doing so, a series of expert interviews was conducted with stakeholders from the three groups of actors using a two-way (double input) influence matrix linking all of the constitutive factors through the MICMAC multiplication ranking approach.

The variables were ranked with regard to their influences and dependencies based on the relationship evaluation which included the following intensities: no influence (0); weak influence (1); medium influence (2); and strong influence (3). As the next step, the direct and indirect influence graphs along with influence diagrams were generated using the MICMAC software (MICMAC, 2017). By doing so, the variables were classified into the following categories:

- Influential variables represent input variables that exert some influence on other elements and the system as a whole while changing. This group of variables must have priority when considering policy design and decision-making strategies.
- Relay variables impact the system and are dependent from input variables. What is more important, they are dynamic variables involved in the system's feedback loops as they have an unstable behaviour as they may change to be input or output variables.
- Dependent variables represent the system's output variables that are most influenced by other variables and the system.
- Autonomous variables are neither influential nor dependent and are not controlled by the dynamics of the system. Hence, these variables are associated with exogenous components that exist within the system.

Subsequently, the finalised qualitative model was created using a comprehensive analysis of the system's elements based on the influence diagrams generated, that illustrated the dynamic behaviour of the system under study, and, therefore, worked as a reference for the logical building of the associated Causal Loop Diagram (CLD). The visualization of the systems conceptual model is illustrated in Figure 5.

For the further participatory modelling purposes, a CLD has been built using different shapes and colours, highlighting major classes of variables: hexagons represent construction innovation outputs; green, orange, blue and purple boxes represent system's resources, activities, enablers, and the broader environment, respectively; and last but not least, the circle represents innovation performance. For extended details of this modelling research stage, the reader is referred to the publication cited above (Suprun *et al.*, 2016).

The presented conceptual CLD has dual purposes, namely, (i) to provide the foundations for further SD modelling as it is a static model and the dynamics of the relationships are not included; and (ii) to visually communicate the problem of construction innovation performance to potential stakeholders. It is worth noting, that the presented model has been designed as a set of elements which included activities, outputs, and so on, but not the system's actors. Hence, the next step is to build a dynamic model represented by 4 interrelated sub-models such as government, academia, industry and innovation performance (Figure 2). In other words, we split the concept of construction innovation system into different sections to describe various activities taking place within a system in order to address the problem of the low level of innovation performance in the industry.

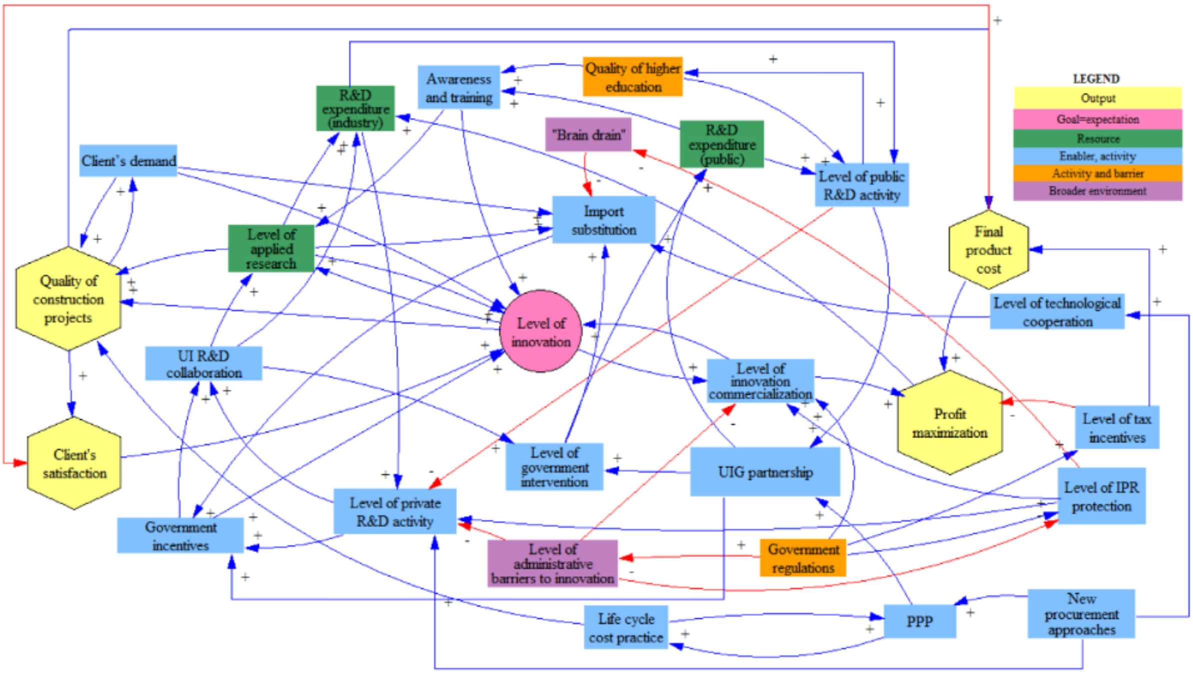

Figure 5. Conceptual model of construction innovation system based on structural analysis

SD model development

The intended conceptual model was designed in static form. However, it is relevant only as an initial step in a modelling process, because it is not capable of identifying stocks and flows among the variables. Consequently, the next modelling step is to quantify and translate the CLD, showing elements such as activities, resources and outputs into a dynamic model of the relationships between government, industry and academia based on stakeholder engagement. Participatory modelling is crucial for this step considering the complex nature of the innovation system consisting of many qualitative relationships that are difficult to be expressed trustworthily by a mathematical equation.

As mentioned above, participatory model development mostly focuses on portraying system structure but not model simulations (Vennix *et al.*, 1996; Van den Belt *et al.*, 2004). Hence, once the stock and flow model is developed it can be simulated by populating it with data in order to reveal system behaviour.

Once the initial round of pilot workshops was conducted, a preliminary draft model was constructed as a starting point. Then, the next two facilitated workshops were organised in order to review the preliminary model and its sub-models (Richardson and Andersen, 1995; Van den Belt *et al.*, 2004). The workshops procedure is presented in Table 1.

As a result of the participatory modelling workshops, a first version of a system dynamics model represented the construction innovation system in Russia has been built. The model consists of four sub-models, i.e. government, industry, academia and innovation performance sub-models.

Table 1. Workshops stages overview

Tasks	Purpose	Comments	Question examples	
Introduction and overview	Research objectives and methodology			Introductory Part
SD concepts	Brief explanation in order to introduce the language of system dynamics (trying to use non-technical language).	It is important to introduce the stock, flow, and causal link icons to be used throughout the workshop.		
System sectors (sub-models)	To initiate discussion about the structure and behaviour of the real system.	A preliminarily (draft) qualitative model was developed to assist stakeholders with their existing understanding.	What is the priority issue that emerges from the preliminary model that you would like to investigate further?	Interactive Part
Stocks and flows	Identification and confirmation of key stock and flow structure for the system under study before adding full feedback complexity to the system diagram.	The facilitator started with a basic stock and flow diagram and then asked participants to identify and confirm variables that influenced the transition rates or flows between these stocks.	What variables are accumulated levels that produce the behaviour in a system over time? And what variables are rates that change the level variables?	
Feedback loop analysis and time lags	Collection of feedbacks on the system's components and any missing parts.	Usually, various stakeholders are experts in one portion of the system and they take the lead when their portion of the system is under discussion.	Do you believe this process is correct? If not, why not? What importance do you currently give to this loop (process)? Do you expect this importance to increase, remain the same, or decrease in the future?	
Model refinement	To initiate discussion about the structure and behaviour of the real system	The initial qualitative stock and flow model of construction innovation system is about to be developed by participants of the workshop. It should contain the elements considered important by stakeholders and illustrate the connections between them.	What are the motives to continue R&D investment and what are the criteria used to make a decision to increase or decrease R&D investment?	
Equation writing and parametrization	To begin building a formal simulation model	This step involved presentation of some preliminary quantified parts of the model. Brain-storming technique was applied to express the relationships between the connected variables logically (not necessary mathematically).	In your opinion, what is the best way to evaluate thus variable? What units would you suggest to use in order to quantify model elements?	
Discussion	To suggest strategies for management, potential leverage points, recommendations and scenarios	It is very important to take into account expert's suggestions from participants represented all three groups of the system's actors.	Within the current system, what management and/or decision-making interventions are available to you (and how/where are these connected to the existing elements within the emerging system)?	

The detailed after-workshops stock and flow diagrams representing four sub-models are illustrated in Figures 6-9. Given the nature of the innovation process and source of innovation in the construction sector, two core linked dynamic hypotheses are presented in the model. The first one centres on how the industry, academia and the government can collaborate to most effectively diffuse innovations throughout the industry. A second problem centres on how to develop innovations by supporting domestic R&D which is especially relevant in the case of Russia and its current import substitution policy. An ongoing model development is to be performed step-by-step given the level of complexity and refinement of coming versions is expected through employing stakeholder engagement.

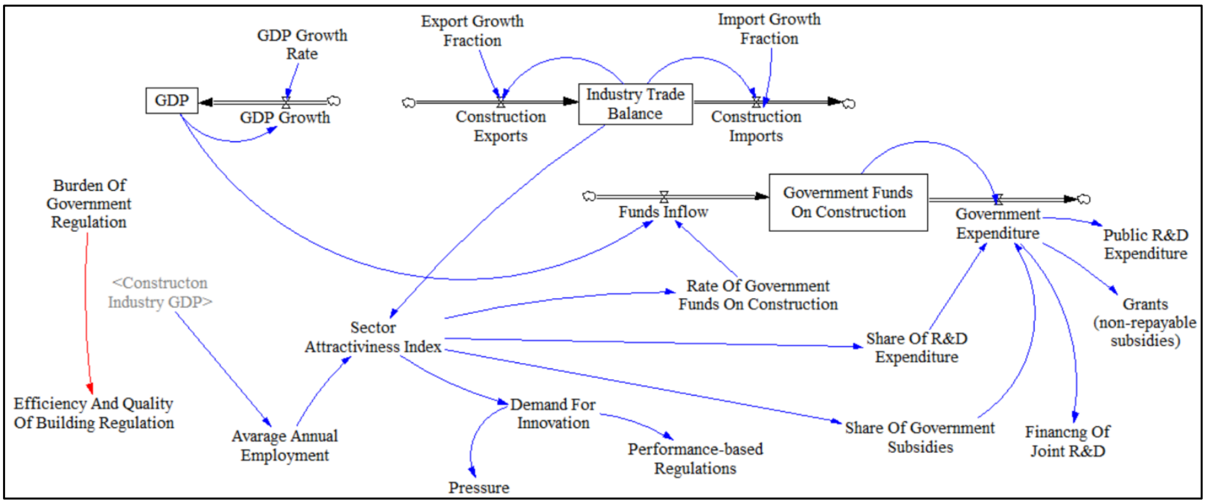

Figure 6. Detailed working stock-flow model of government subsystem

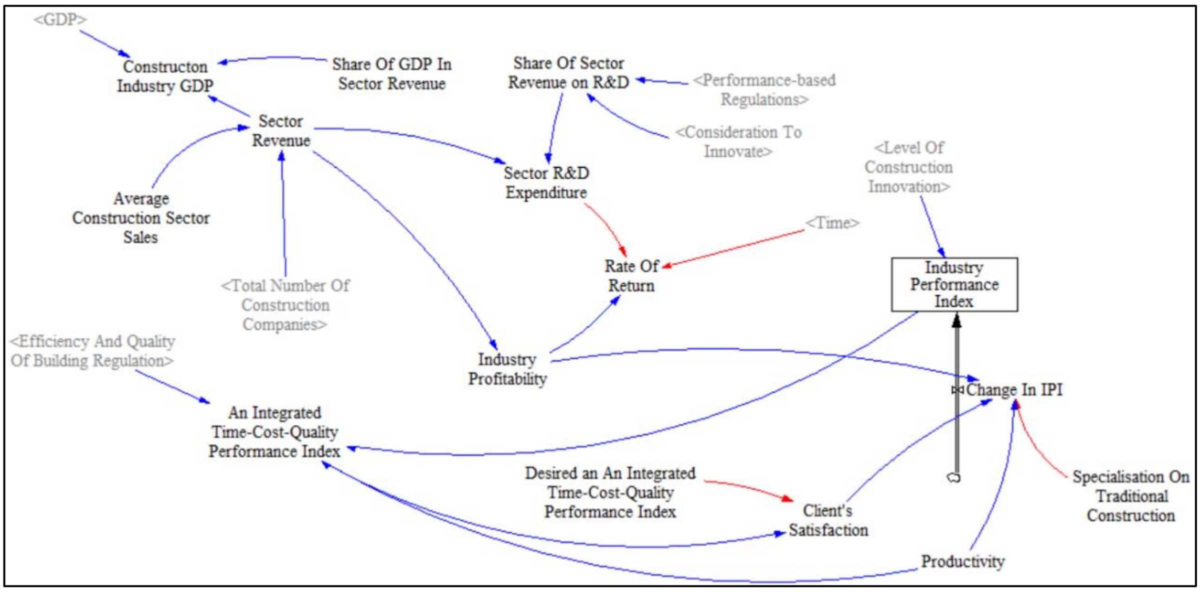

Figure 7. Detailed working stock-flow model of industry subsystem

5. Next research stage

The paper demonstrates a modelling framework for the construction innovation system which is capable of addressing various aspects of improving construction innovation performance within a holistic approach. The proposed methodology is being followed and implemented in an ongoing project and further activities and results are expected. The next stages involve a final model building where the research team aims to conduct a number of ad-hoc interviews with individual participants as a need to refine the eventual simulation model populated with data.

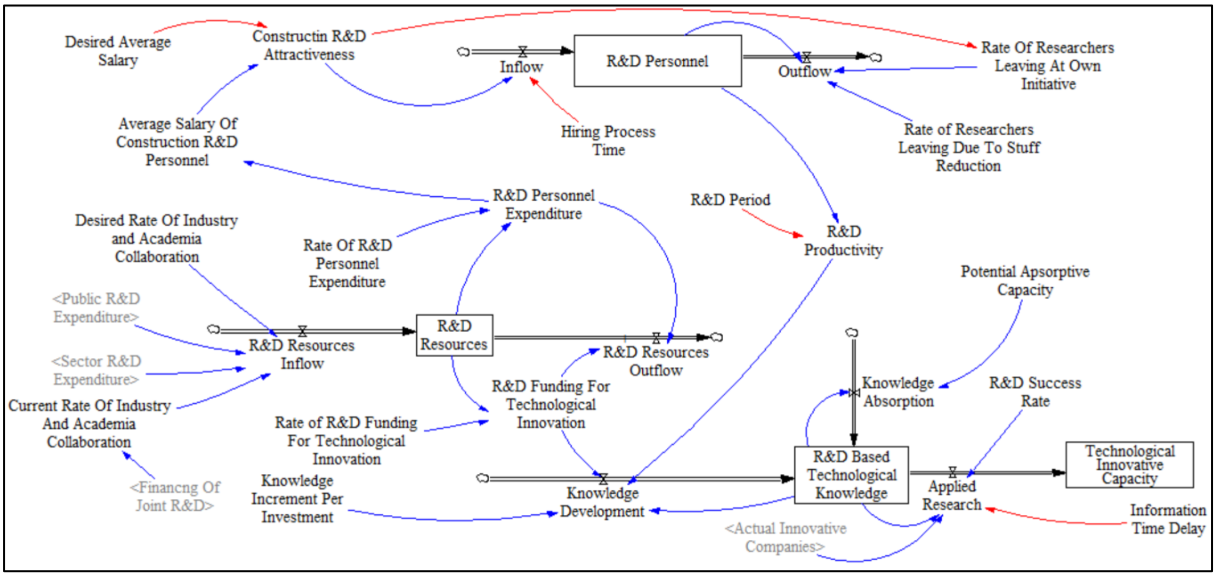

Figure 8. Detailed working stock-flow model of academia subsystem

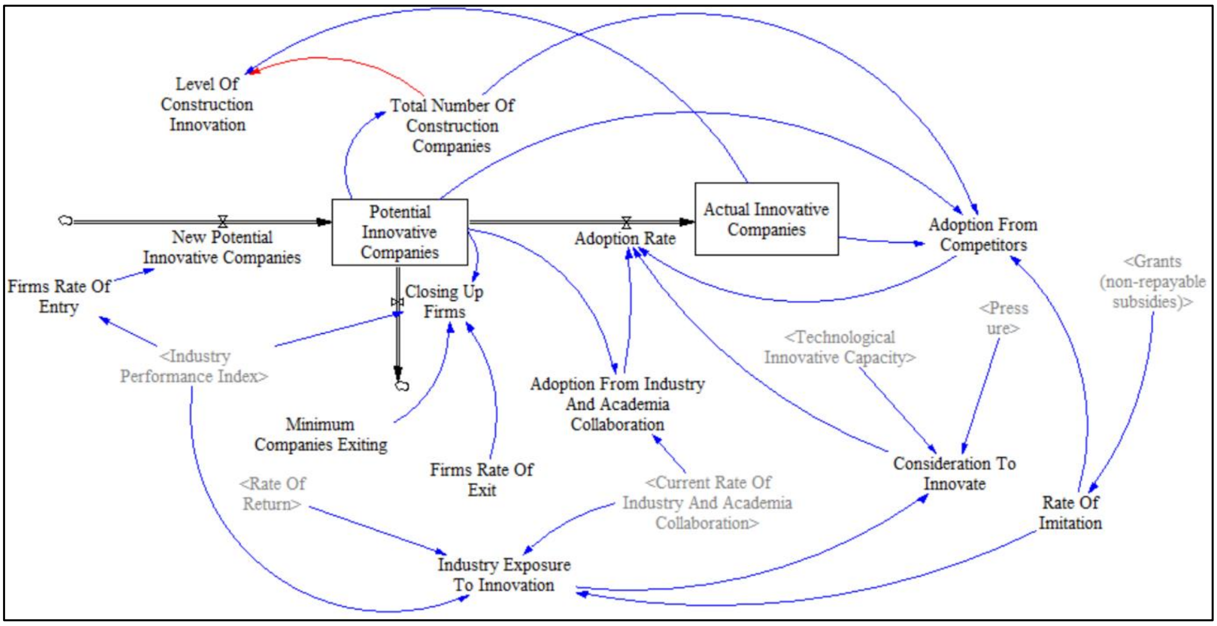

Figure 9. Detailed working stock-flow model of innovation performance subsystem

Subsequently, the verification of the model has to be tested and finalised through validation, verification and calibration processes prior to any decision-making process, because innovation performance is mainly improved based on future predictions and simulation. In fact, at this level of complexity decision-making cannot be automated, however, it can be substantially supported by generated models. Hence, this step again requires an active participation of stakeholders to check if the function of the entire modelling corresponds to real world behaviour. Throughout final participation-based actions, such as consultation meetings with experts, model outcomes can be confirmed through the perception and judgement of participants. The results also need to be examined in order to determine whether the model works effectively in simulating the system behaviour over time. A sensitivity analysis will be performed to explore how the model responds to various changes in input values, parameter values and other assumptions, as well as, to ensure the model is sensible enough and robust.

6. *Conclusion*

The goal of this paper was to present construction innovation system that had a completely dynamic complexity as a systems model representing correct and continuous interaction between government, the construction industry and academia. The problem that motivated this research can be stated as the lack of comprehensive understanding of both poor innovation performance of the Russian construction industry and an insufficient rate of collaboration among government, industry and academia. In an attempt to create a suitable SD model, an integrated systemic and participatory approach was applied and demonstrated to be effective in building an initial conceptual model followed by an ongoing model development, as well as, refinement of earlier versions.

In particular, we have demonstrated that coupling participatory modelling and structural analysis is the key for in-depth comprehension of a conceptual model for generating the required information about interrelations between essential system's factors in order to identify causal loops between them. As a result of stakeholder engagement, we have created a first version of a SD model demonstrating the relationships between actors which makes up the system given the intangible nature of capabilities and their effect on the construction innovation process. The model structure highlights that industry and academia representatives along with policy-makers need to both acknowledge innovation as a process of development and estimate the benefits of a high-level innovation performance. By doing so, academics and government authorities should support industrialists and encourage them to consider R&D investments as the core of their business strategy.

To sum up, the complex nature of the construction innovation system justifies the proposed approach as an appropriate method for modelling the construction innovation process and studying the dynamic behaviour under different scenarios. Further modelling is to be done using SD simulations in order to show the possible impacts and effectiveness of the collaboration between the three actors.

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