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Developing a System Dynamics Model from Perceptions

A Case Study of Perspectives on Road Procurement in Sweden

Maksims Kornevs¹, Niki Kringos² and Sebastiaan Meijer³

^{1,3}Department of Health Systems Engineering
KTH Royal Institute of Technology
Teknikringen 72, 10044 Stockholm, Sweden

²Department of Civil and Architectural Engineering
KTH Royal Institute of Technology
Teknikringen 72, 10044 Stockholm, Sweden

Abstract— As a public organisation, road administrations have the responsibility to improve the road construction process. However, the changes in such process involve a number of the stakeholders, who have different perceptions about what is most important in the road construction process. Perspectives on the necessity and nature of change will differ too. In order to provide an environment in which the potential consequences of changes in procurement can be tested, it is important to develop a model that simulates the process, especially the social part of the system. To achieve this, the model requires perceptions of stakeholders. The paper presents a new framework that obtains worldviews of the stakeholders in the complex adaptive system and transforms them into a System Dynamics model. As a result, a computational model is developed to observe the behaviour of stakeholders in the system. The model can become a tool for testing policies in the complex adaptive system.

Keywords— *Q methodology, system dynamics, SD model, modelling and simulation, sociotechnical systems*

I. INTRODUCTION

Modelling and simulation tools are used in many fields nowadays. Simulation models allow imitating reality for design, experimentation and decision-making [1]. They provide a safe environment to experiment without harming real system or its elements; it is cheaper to experiment with models; they consume less time to produce results; they provide better control of the experimental conditions etc [2].

Modelling and simulation are extremely helpful for dealing with complex systems. Complexity can come from a large number of elements in the system or/and dynamic interaction of the elements over the time [3].

Modelling the complexity and dynamics of such systems over time is valuable as an insight into the sensitivity towards certain parameters that can be influenced by policy or management. However, it is complicated to model social aspects because they are usually not well defined and can highly depend on individuals. The tools, that do it, heavily rely on a formulation of the social dimension in alternatives, value functions, or other abstractions from human subjective knowledge.

Such subjectivity in aspects can be researched using Q methodology. It allows researching different people worldviews and perceptions [4].

Using the results of Q methodology with the combination of modelling and simulation tools can provide a better understanding of dynamic patterns in the system, see behaviour that characterises factors over time and provide an environment for experimentation and testing potential solutions and policies.

This paper proposes and describes a framework on how to combine Q methodology and its techniques with system dynamics in order to better understand complex systems.

The remainder of the paper is organised as follows: in Section 2, we provide a description of the case study and the reasoning behind why combining subjectivity with system dynamics can benefit research of road procurement. Section 3 introduces the framework, while Section 4 describes in more detailed how the framework was applied. Section 5 presents results that are found from the mode. Finally, we conclude the paper in Section 5.

II. PROBLEM STATEMENT

The Swedish Road Administration is responsible for the overall long-term infrastructure planning: construction, operation and maintenance of state roads and railways [5]. As a public organisation, the road administration has a responsibility to create a robust and efficient transport system. However, such system cannot be achieved only by efforts of the road administration. It requires cooperation with all parties in the road construction sector.

One of most effective way to ensure participations of different parties or stakeholders is with the help of procurement [6]. Procurement is the act of buying a product, service or work. Government institutions have to use the procurement process for most of their projects. Procurement contains specifications on how the finished project should look like and also criteria how the winning tender will be selected. Thus, all the changes for the road construction sector need to be included procurement process.

The issue often arises, when procurement is seen as a linear process. This is a case, when procurement starts with the specific project specification and ends either with the awarding

the winning bid or with the completion of the construction or another service that has been procured. However, the effect that procurement has made on a market, the process itself, a level of technologies and effect on other aspects is not considered.

This makes procurement more vulnerable to risks and unknowns. As seen in Fig. 1, a requirement that the road administration can have to make the road more innovative or 'green' will lead to risks related to the usage of new materials or processes, but it is hard to predict how these risks will affect the system.

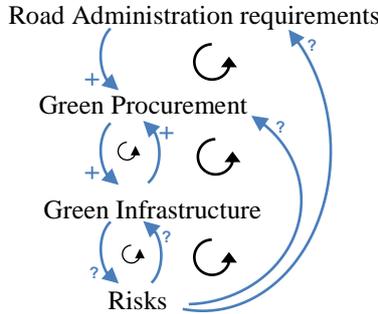


Fig. 1 Second order effect of innovation

One of the main sources of the issue is the social aspect of procurement. Since it is not purely a decision of one person or stakeholder group, it is important to know what each of the stakeholders thinks about the system. So in order to have a better understanding of the procurement, it is important to define what perspectives have different stakeholders in the road construction industry [7].

Since the views of stakeholders are subjective, Q methodology is used as the main method to analyse the answers. In addition, it is important to show how the system changes over the time; so SD modelling is chosen. In this way, we can see how different variables behave, and experiment with the models of different stakeholders groups. Such procurement model will give a chance to see what results will have long-term changes in procurement policies to all stakeholders in the industry.

III. PROPOSED FRAMEWORK

This paper proposes a framework to transform subjectivity or perceptions that stakeholders have to system dynamic models, and it is depicted in Fig. 2. The framework is made out of 8 steps, and it starts with defining variables for the research and ends with obtaining the results the model.

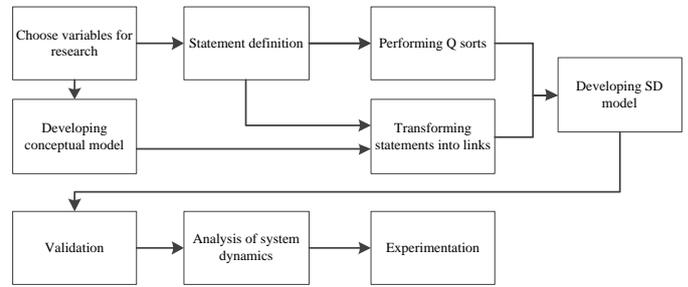


Fig. 2 Scheme of proposed framework

The framework is made out of 8 steps, and it starts with defining variables for the research and ends with obtaining the results the model:

- choose variables that are important to research questions;
- develop a conceptual model that describes important elements of the system;
- define statements for Q methodology;
- perform Q methodology;
- transform statements into casual links for the system dynamic model;
- simulate SD (system dynamics) model based on conceptual model and transformed links;
- confirm that model work properly;
- analyse gained results from the model and;
- perform experiments with the model if needed.

IV. MODEL DEVELOPMENT

A. Choose variables for research

The first step in order to develop the model is to determine what variables or parameters need to be used. They can be found by analysing a system and the purpose of the modelling.

In order to determine what variables are important in road procurement, a list of actions related to road life was analysed. These actions can be grouped into following categories: preparing procurement document, evaluation and awarding, project management, design, material supply, construction, maintenance and operations. A total number of actions that has been used is 69. Based on literature review results [7], 20 variables were found and each of them was compared to each of the actions to see if a variable can be applied to describe the action in road procurement. 11 variables with the highest applicability were chosen for further research. Selected variables are: innovation, cost, durability, environment, risks, market balance, recycling, procurement process, safety, prediction, and warranty.

B. Developing conceptual model

A conceptual model is a draft of the final model. It contains main ideas and relationships that exist in the system. It is used to determine the scope of the model and to make sure to include all important elements in the model.

System dynamics, which is used in this paper, is a computer-aided approach to policy analysis and design. It

applies to dynamic problems arising in complex social, managerial, economic, ecological systems, or any other dynamic systems characterised by interdependence, mutual interaction, information feedback, and circular causality (Richardson, 1999).

A general example of system dynamics can be seen in Fig. 3. On the left, we can see connections between eggs and chicken: the more eggs we have, the more chickens we will get. The same is true in the opposite direction: more chickens lay more eggs. This positive connection (more – more) also works in negative case (less – less): fewer chickens have fewer eggs. The loop, which is formed by elements and links between them, is a reinforcing loop: over time the value is only increasing for both of the eggs and chickens in geometry progression.

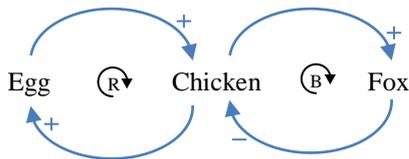


Fig. 3 System Dynamics example

The right side of the model shows chickens and foxes relationship. Since foxes eat chickens, and a number of foxes depends on an amount of food (chicken), the increasing amount of chickens increases the population of foxes, similarly as eggs increase an amount of adult chickens. The value of the link will be different, but the connection is the same. But increasing amount of foxes kills more chickens, and so the more there are foxes, the less is number of chickens (or negative to it: fewer foxes leads to more chickens). This loop is balancing. With time, it stabilises the stock level to a value or to a specific range.

When the system has more than one loop, as a full system in the figure, it leads to more complex behaviour. In this case, the reinforcing loop between eggs and chickens will lead to a growth of chicken population, until the period when there are so many foxes that they first slow down and after decrease population of chickens. A number of chickens will go down fast in the beginning, but then it will slow down. The reason is that foxes are dying (a link from chickens to foxes suggests more chickens lead to more foxes, but also that fewer chickens lead to fewer foxes). Then there will be a moment when the chickens will be growing once again repeating all the previous experience. Such waves or periods are common in the complex dynamic systems with feedback loops.

Road procurement is also a complex dynamic system. The variables are chosen as elements for the model, where each variable can be connected to all other variables (Fig. 4). It generates a large amount of loops, but at this stage, there is no need to determine if the loops are reinforcing or balancing, because it will be partly also related to Q sorts.

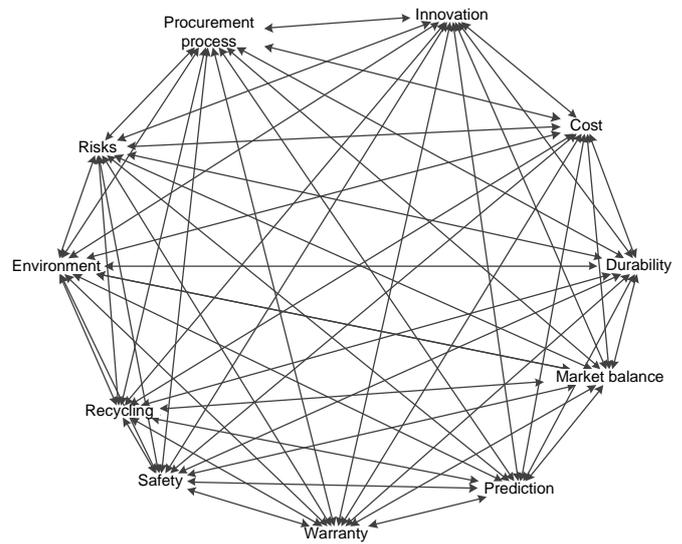


Fig. 4 Elements of road procurement

C. Statement definition

The concurrence for a final Q sort is based on all possible combinations of the variables. Although there are different ways how to do it, including representing statements with objects or pictures, structured statements are used [4], [8], [9]. This is done because later a model needs to be generated, and it is important to know how one variable affects others. The structured statements, in this case, can be formulated as following:

variable 1	more – more	variable 1
variable 2	(less – less)	variable 2
...	more – less	...
variable n	(less – more)	variable n

An example of such structured statement can be “The more is a value of cost the more is a value of durability”, or rephrasing it “Contracts with higher durability cost more”. It represents the same connection but makes the statement more understandable. Since a statement “Contracts with lower durability are cheaper” represents the same idea, it generally would have the same value, as a previous statement. Thus, these statements can be considered copies and can be used to give more varieties to structures.

Depending on a number of original variables, the concurrence can be extremely large, and it is important to decrease its size, that becomes a final Q set for the study.

In the case study, 11 variables would form 121 statements. The resizing of the concurrence was done based on several assumptions.

First of all, all statements, that connect variable to itself (self-loop), were excluded from research. Even if it is possible to define, it would not be as important as other statements for a model development in most cases.

Also, it is important to remember that not all links exist in the real system. Although it is possible to connect every variable to all other variables, it is often not needed. Some links

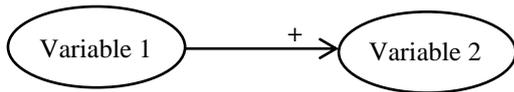
Based on factor matrix, one can find the factor array, or 'the perfect sort' for this factor. This array helps to find common characteristics of the people who participated in Q sorting. Since all statements have been related to variables, it is possible to make a conclusion about the each of the group (factor) based on these connections. In the same time, the sorts of each of the factors are providing values for links for developing the SD model.

E. Transforming statements into links

Beside Q sorts, another important process of preparation to simulation is a statement transformation into the links, which are used in the model.

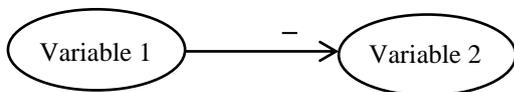
If all statements have been done using the same structure, this step can be relatively easy to perform:

More	variable 1	leads to	more	variable 2
Less			less	



or

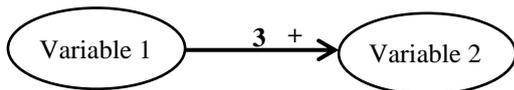
More	variable 1	leads to	less	variable 2
Less			more	



At this stage, it is also important to make a decision about the weight of the links. Usually, the groups, in which statements are sorted in, have value scale from negative to positive, or only positive. For example if we have 9 groups from strongly disagree to strongly agree, in the first case, strongly disagree will have value -4 every next group will increase its value by one and strongly agree will have value of +4. In the second case strongly disagree will have value 0 or 1, and strongly agree will have a value 9 or 10 respectively.

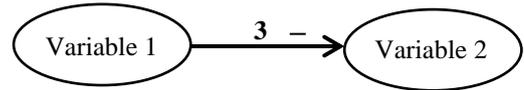
Only positive values for group mean that all links exist all the time, and, based on replies, the weight of influence differs. With negative and positive replies links with positive values (from neutral to strongly agree) will have different effects on variables:

- positive value during sorting gives its value to the weight of the link. For example, if a statement says "variable 1 increases variable 2" and it has value +3 from the Q sorting, then link will be as follows:



- zero value or neutral during sorting indicates that the link does not exist (participant do not care about this link in his/her worldview);
- negative value during sorting can be omitted as well, since it shows that person disagrees with the statement and the link, or a positive causal link can be changed

it to negative link (and opposite), while absolute value becomes the weight. If a previously mentioned statement will get value -3 from the Q sorting, the results can be like this:



In the project, the replies to the statements were converted into the range of -3 for strongly disagree to gradually increasing to +3 for strongly agree.

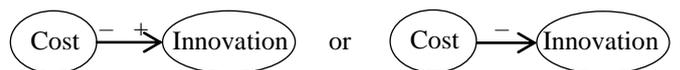
Transforming statements into links had few complications in the process, mainly because a) not all variables were properly included and b) not all statements were formulated based on the structure statement scheme.

One of the variables, that were originally used is procurement (the process how government institutions buy products or services). However, procurement by itself cannot be measurable, or in other words, one cannot have more or less of procurement. For this reason, procurement was split into three sub-variables: freedom of specification (how much of specifications can be adapted by bidders), number of awarding criteria, and chance to be awarded. These new variables can increase or decrease their value; thus, they are suitable for SD model. The statements, that had to deal with procurement, were used at this stage as links to one of these three new variables.

Similarly to procurement, the variable Market is again not countable. And so it was split into "changes in market balance", where the top value shows that the market goes through serious changes, while low value shows that market is stable and does not change, and into "individual market position", where high value shows that individual entrepreneurs have a high opportunity to improve their position on the market, and low value shows lack of such opportunity.

Also, it was observed that some statements that had to deal with innovation actually do not work with innovation as such, but rather looking at the things that can prevent innovation. Therefore new variable "blockage to innovation" was introduced where it is more applicable than innovation itself.

Transformation of most of the statement was easy due the structure. For example statement "Contracts with lowest costs stimulate innovation" deals with costs and innovation. It has the following structure:



However, some of the statements have not followed the pattern. For example, the statement "The current market balance is the result of the push for lowest costs" asked for an extra evaluation. First of all, we needed to define what a current market balance is. It is a market structure that has been achieved by changes in market balance. So it makes the sentence look like "More changes in market balance are the result of more pushing for lowest cost". Word result in the statement shows that the cause and effect have changed, so the

sentence should be “more pushing for lowest cost leads to more changes in market balance”. Next step here is to understand the more pushing for the lowest cost. Costs do not affect market directly, but rather they affect the chance for a tender to be awarded. Hence, the structure now is: cost→chance to be awarded→changes in market balance. This leads to a state, where the transformation has not generated just a unique link based on this statement, but rather a chain that is used in the model as two separate links with the same effect.

One statement was formulated as “Tenders should be awarded by both lowest costs and CO₂ emissions”. In this case, the structure is costs → chance to be awarded and environment → chance to be awarded. Since it is impossible to put such structure with a conjunction between the both of statements without overcomplicating the model, the statement is separated into two individual links with the same value. Although it might give misleading results in some case, based on replies of participants we saw that this separation is precise enough.

Most of the participants during Q sorts expressed that they would agree with statements, that are opposite of the statements they had disagreed with. Basically, if the statement says “Innovative roads cost more” and the person disagrees with it, the same person most likely would agree with the statement “Innovative roads cost less”. Hence, if someone disagreed with the statement, that has a positive causal link, we changed it to negative link, and opposite.

F. Developing the model

Model is developed using Vensim Software [12] and is based on casual loop diagram as seen in Fig. 7. Each link has its positive or negative casual value, and the number of the corresponding statement is recorded. Since not all statements match values of casual links, some of the links might have a different direction in the model than it is mention in the figure.

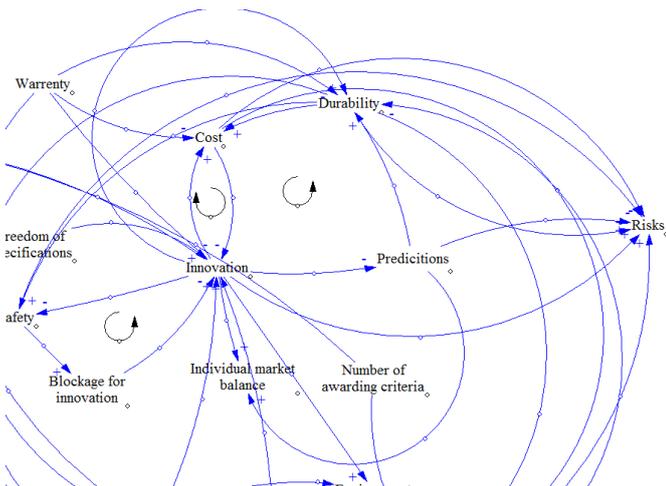


Fig. 7 Fragment of the system of procurement perspectives

Some links have a value of more than one statement. For example, statements 1 and 27 ask about a connection between costs and chance to be awarded. In this case, the average of the values is used as the value of the link.

For calculation purposes, all links are put in a matrix. This matrix is not symmetric because links are not bidirectional.

Every individual sort or factor will have the matrix with its own unique values based on the sort or factor array. Calculation matrix for factor 1 is given in Fig. 8 as an example.

	Market Balance	Number of Award Criteria	Chance to be Awarded	Warranty	Environment	Costs	Innovation	Individual Market Position	Predictions	Risks	Safety	Recycling	Blockage for innovation	Freedom of Specification	Success in History	Green Procurement	Durability
Market Balance										3							
Number of Award Criteria	2		-3														
Chance to be Awarded	0																
Warranty					0	1	1										-3
Environment																	
Costs						2		-1		-1	-2		-2				
Innovation	3						1	3									3
Individual Market Position																	
Predictions									-2		-1						-1
Risks																	
Safety											2		1				
Recycling	-1											2					1
Blockage for innovation																	
Freedom of Specification													0				
Success in History																	
Green Procurement																	-1
Durability																	0

Fig. 8. Example of calculation matrix

G. Validation

The validation of the system often is impossible due the fact that the model represents worldviews of the individual participant or of the number of participants. In order to evaluate if the model provides proper results, results have been validated by comparing individual replies and asking participants to evaluate the results. Since the model is based on worldviews, it is important for validation not to use calculated values, but original replies of individuals, because his/her responsibility is to compare results with their own way of thinking.

The model was validated with participants by discussing and evaluating their results. Participants, whose answers are sorts 10, 11, 12, 14, 15, 16, 19 and 21, were asked to look at SD models results based on their individual sorts, and say if they agreed with results.

V. ANALYSIS OF RESULTS

VI. CONCLUSION

Road construction sector has a low level of innovation. It is related to the long life cycle of the roads and, thus, the process of implanting innovation is often long as well and a particular market structure often in a form of oligopoly since a number of suppliers is very limited. Nevertheless, the road administration has a responsibility to have an efficient and innovative infrastructure system. And achieving of such

system requires cooperation with all parties in the road construction sector.

One of most effective way to ensure participations of different parties or stakeholders is with the help of procurement. Procurement regulates technical and functional specifications of the final product, and it can include the need for innovation.

However, procurement is a complex process, and changes in it can lead to different results. As a part of the complexity, procurement deals with different organisations (buyer, suppliers, consultants) and they have different perceptions on the procurement process and related aspects or variables.

Therefore, there is a need to investigate the behaviour of the changes in procurement before they are introduced. It can be done using modelling and simulation tools. Using a model of the procurement process, it is possible to predict better results of the changes or policies regarding procurement process.

The difficulty in creating such type of the model is the fact, that the data that is important for model development is worldviews of the stakeholders. Since worldviews are subjective, Q methodology can be used to extract these data.

This paper proposes the framework that gains and transforms perceptions of the stakeholders in a complex system to a system dynamics model, where the behaviour of values of perceptions over the time can be researched.

Such results give a better picture on the patterns that exist in the system, they help determine effects of policies and also they help to see the difference in timeframes for different groups in the system.

The framework uses road procurement in Sweden as a case study, however, the findings can be applicable to other cases researching complex adaptive systems where perceptions are important.

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